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APPENDICES

Appendix A Water-Air Flow for the Pipe Diameter of 19 mm

Table A1 Determination of bubble size for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the bubble size:

1. Make a movie of the bubble flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the bubble size by Scion Image software program.

Equivalent diameter (D_e) of the bubble is defined as the diameter of a sphere that has the same volume as the bubble.

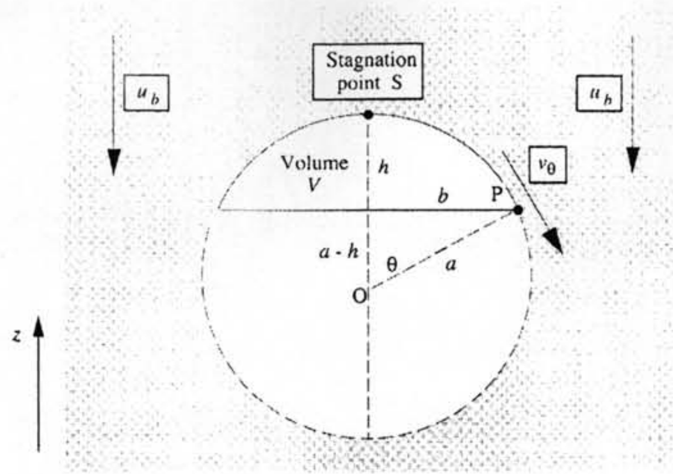


Figure A1 Flow around a spherical cap bubble (Wilkes, 1999).

$$\text{Equivalent diameter } (D_e) = \sqrt[3]{3.94h\left[\frac{h^2+b^2}{2h}\right]^2 - 1.94b^2\left[\left(\frac{h^2+b^2}{2h}\right) - h\right]} \qquad \text{(A1)}$$

Re_{water}	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble width, W_b (mm)			Average bubble width (mm)	Equivalent diameter, D_e (mm)			Average equivalent diameter, De (mm)
		1	2	3		1	2	3		1	2	3	
0	3.17	12.5	12.2	12.9	12.5 ± 0.3	13.6	14.9	14.4	14.3 ± 0.7	15.4	15.6	16.0	15.6 ± 0.3
0	4.40	13.3	13.5	13.3	13.4 ± 0.1	14.7	14.4	13.8	14.3 ± 0.5	16.4	16.5	16.1	16.3 ± 0.2
0	5.64	15.6	15.3	15.0	15.3 ± 0.3	14.7	14.0	14.0	14.2 ± 0.4	18.4	17.9	17.6	18.0 ± 0.4
0	6.88	16.2	16.4	16.3	16.3 ± 0.1	14.3	14.7	15.0	14.7 ± 0.4	18.8	19.1	19.1	19.0 ± 0.2
0	8.12	17.4	18.2	17.4	17.6 ± 0.5	15.0	15.5	15.2	15.2 ± 0.3	20.0	21.0	20.1	20.3 ± 0.5
1010	3.17	15.9	17.1	15.6	16.2 ± 0.8	15.4	15.0	14.5	15.0 ± 0.5	18.9	19.7	18.3	19.0 ± 0.7
1010	5.64	16.6	18.5	18.3	17.8 ± 1.1	14.3	14.3	14.1	14.2 ± 0.1	19.1	20.8	20.6	20.2 ± 0.9
1010	8.12	23.3	20.7	22.4	22.1 ± 1.3	14.6	14.6	14.8	14.7 ± 0.1	25.3	22.9	24.5	24.2 ± 1.2
1010	10.59	24.0	23.2	23.2	23.5 ± 0.5	15.2	13.8	15.3	14.8 ± 0.8	26.1	25.0	25.3	25.5 ± 0.6
1010	13.07	23.6	25.2	23.9	24.2 ± 0.8	14.5	15.6	15.0	15.0 ± 0.6	25.5	27.2	25.9	26.2 ± 0.9
2740	3.17	10.9	9.5	9.7	10.0 ± 0.7	13.8	12.8	12.6	13.1 ± 0.6	14.1	12.6	12.7	13.1 ± 0.8
2740	5.64	11.3	11.1	10.7	11.0 ± 0.3	14.8	14.9	13.7	14.5 ± 0.7	14.8	14.7	13.9	14.5 ± 0.5
2740	8.12	11.4	11.8	11.5	11.6 ± 0.2	14.8	14.5	14.7	14.6 ± 0.2	14.9	15.1	15.0	15.0 ± 0.1
2740	10.59	13.9	13.9	12.8	13.5 ± 0.6	13.7	13.7	14.1	13.8 ± 0.2	16.6	16.6	15.8	16.3 ± 0.5
2740	13.07	14.7	14.2	13.9	14.3 ± 0.4	14.1	14.5	14.5	14.3 ± 0.2	17.4	17.1	16.8	17.1 ± 0.3
2740	15.54	15.3	15.7	16.0	15.7 ± 0.3	15.0	14.8	15.7	15.2 ± 0.5	18.3	18.5	19.0	18.6 ± 0.4
2740	18.02	16.4	16.1	17.5	16.7 ± 0.7	16.3	15.1	15.0	15.5 ± 0.7	19.7	19.0	20.2	19.6 ± 0.6
2740	20.49	18.3	17.3	18.2	17.9 ± 0.5	15.0	13.8	15.2	14.6 ± 0.7	20.8	19.6	20.8	20.4 ± 0.7
2740	22.95	19.7	18.2	17.7	18.5 ± 1.0	15.3	14.8	15.2	15.1 ± 0.3	22.2	20.7	20.4	21.1 ± 1.0
2740	28.08	20.4	19.3	20.6	20.1 ± 0.7	15.4	15.1	15.3	15.2 ± 0.2	22.8	21.8	23.0	22.5 ± 0.7
2740	33.21	22.2	22.2	22.3	22.2 ± 0.1	15.6	15.0	15.1	15.2 ± 0.3	24.5	24.4	24.5	24.4 ± 0.1

Re_{water}	Re_{air}	Bubble height / Pipe diameter			Average, R_b/D	Bubble Width / Pipe diameter			Average, W_b/D	Equivalent diameter / Pipe diameter			Average equivalent diameter, De/D
		1	2	3		1	2	3		1	2	3	
0	3.17	0.66	0.64	0.68	0.66 ± 0.02	0.72	0.78	0.76	0.75 ± 0.03	0.81	0.82	0.84	0.82 ± 0.02
0	4.40	0.70	0.71	0.70	0.70 ± 0.01	0.77	0.76	0.72	0.75 ± 0.02	0.86	0.87	0.85	0.86 ± 0.01
0	5.64	0.82	0.81	0.79	0.81 ± 0.02	0.77	0.74	0.74	0.75 ± 0.02	0.97	0.94	0.93	0.95 ± 0.02
0	6.88	0.85	0.86	0.86	0.86 ± 0.01	0.75	0.77	0.79	0.77 ± 0.02	0.99	1.00	1.01	1.00 ± 0.01
0	8.12	0.91	0.96	0.91	0.93 ± 0.03	0.79	0.82	0.80	0.80 ± 0.01	1.05	1.10	1.06	1.07 ± 0.03
1010	3.17	0.84	0.90	0.82	0.85 ± 0.04	0.81	0.79	0.76	0.79 ± 0.02	0.99	1.04	0.96	1.00 ± 0.04
1010	5.64	0.87	0.98	0.96	0.94 ± 0.06	0.75	0.75	0.74	0.75 ± 0.01	1.01	1.10	1.08	1.06 ± 0.05
1010	8.12	1.23	1.09	1.18	1.17 ± 0.07	0.77	0.77	0.78	0.77 ± 0.01	1.33	1.20	1.29	1.27 ± 0.06
1010	10.59	1.26	1.22	1.22	1.24 ± 0.02	0.80	0.73	0.80	0.78 ± 0.04	1.37	1.31	1.33	1.34 ± 0.03
1010	13.07	1.24	1.32	1.26	1.28 ± 0.04	0.76	0.82	0.79	0.79 ± 0.03	1.34	1.43	1.37	1.38 ± 0.05
2740	3.17	0.57	0.50	0.51	0.53 ± 0.04	0.73	0.68	0.66	0.69 ± 0.03	0.74	0.66	0.67	0.69 ± 0.04
2740	5.64	0.59	0.58	0.57	0.58 ± 0.01	0.78	0.79	0.72	0.76 ± 0.04	0.78	0.77	0.73	0.76 ± 0.02
2740	8.12	0.60	0.62	0.61	0.61 ± 0.01	0.78	0.76	0.77	0.77 ± 0.01	0.78	0.80	0.79	0.79 ± 0.01
2740	10.59	0.73	0.73	0.67	0.71 ± 0.03	0.72	0.72	0.74	0.73 ± 0.01	0.87	0.87	0.83	0.86 ± 0.02
2740	13.07	0.86	0.85	0.92	0.88 ± 0.04	0.74	0.76	0.76	0.75 ± 0.01	0.99	0.99	1.05	1.01 ± 0.04
2740	15.54	0.96	0.91	0.96	0.94 ± 0.03	0.79	0.78	0.82	0.80 ± 0.02	1.10	1.05	1.10	1.08 ± 0.03
2740	18.02	1.04	0.96	0.93	0.98 ± 0.05	0.86	0.79	0.79	0.82 ± 0.04	1.18	1.09	1.07	1.12 ± 0.06
2740	20.49	1.07	1.02	1.08	1.06 ± 0.04	0.79	0.73	0.80	0.77 ± 0.04	1.19	1.13	1.21	1.18 ± 0.04
2740	22.95	1.04	0.96	0.93	0.98 ± 0.05	0.81	0.78	0.80	0.79 ± 0.01	1.17	1.09	1.07	1.11 ± 0.05
2740	28.08	1.07	1.02	1.08	1.06 ± 0.04	0.81	0.79	0.80	0.80 ± 0.01	1.20	1.15	1.21	1.19 ± 0.03
2740	33.21	1.17	1.17	1.17	1.17 ± 0.00	0.82	0.79	0.79	0.80 ± 0.02	1.29	1.28	1.29	1.29 ± 0.00

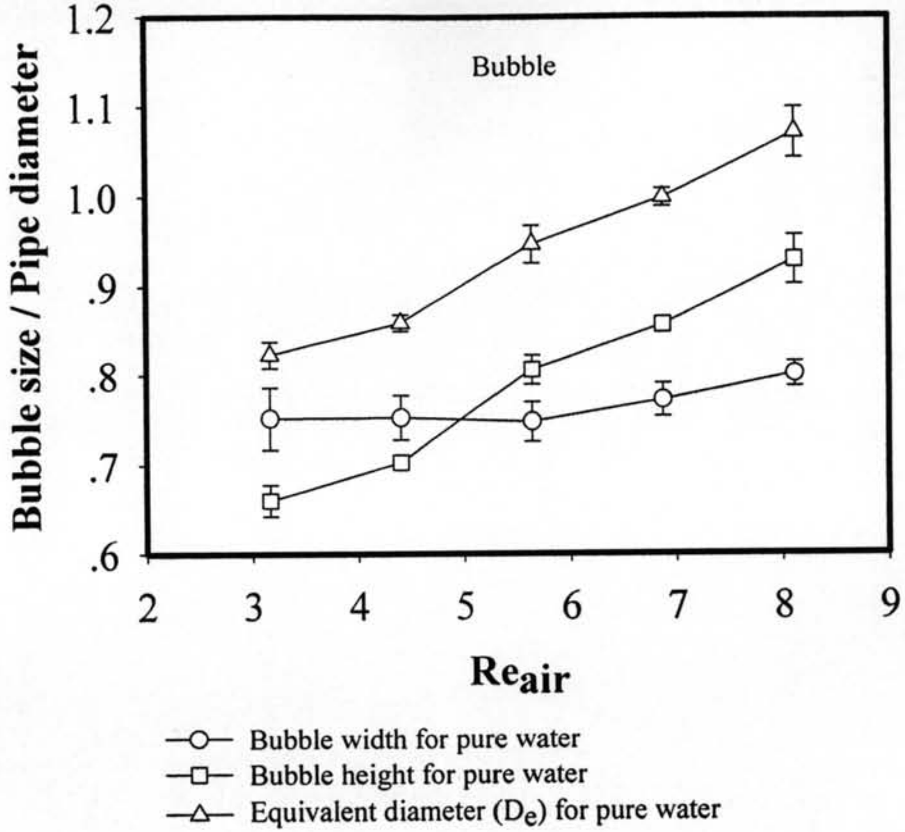


Figure A2 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of pure water at $Re_{water} = 0$ by using pipe diameter 19 mm.

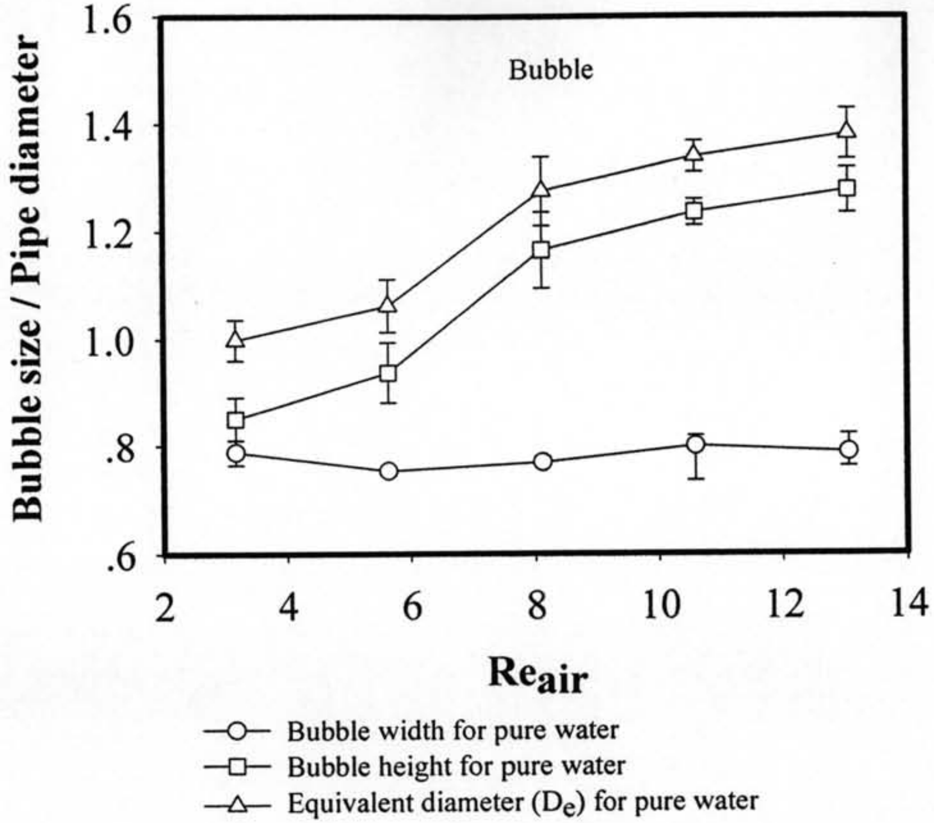


Figure A3 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of pure water at Re_{water} = 1010 by using pipe diameter 19 mm.

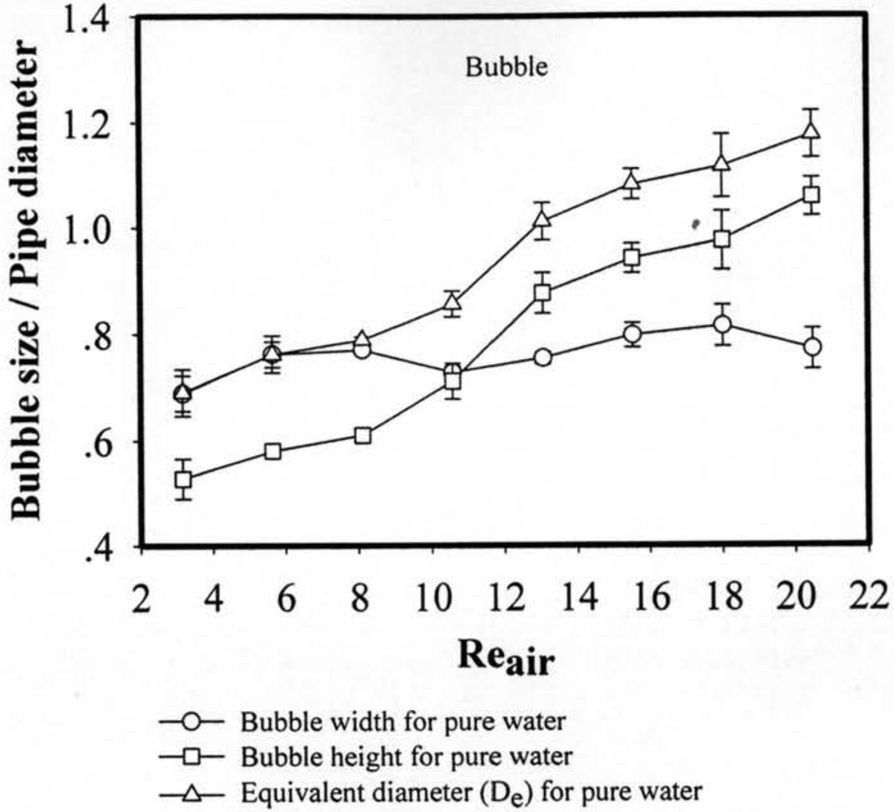


Figure A4 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of pure water at $Re_{water} = 2740$ by using pipe diameter 19 mm.

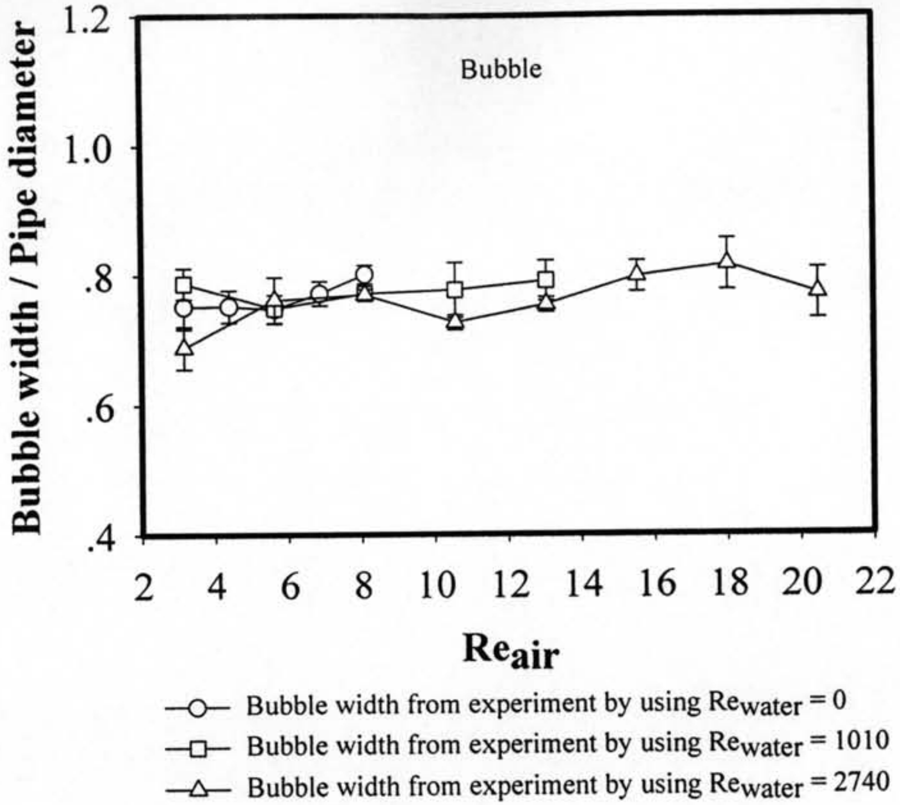


Figure A5 Bubble width from experiment vs. air Reynolds number of pure water by using pipe diameter 19 mm.

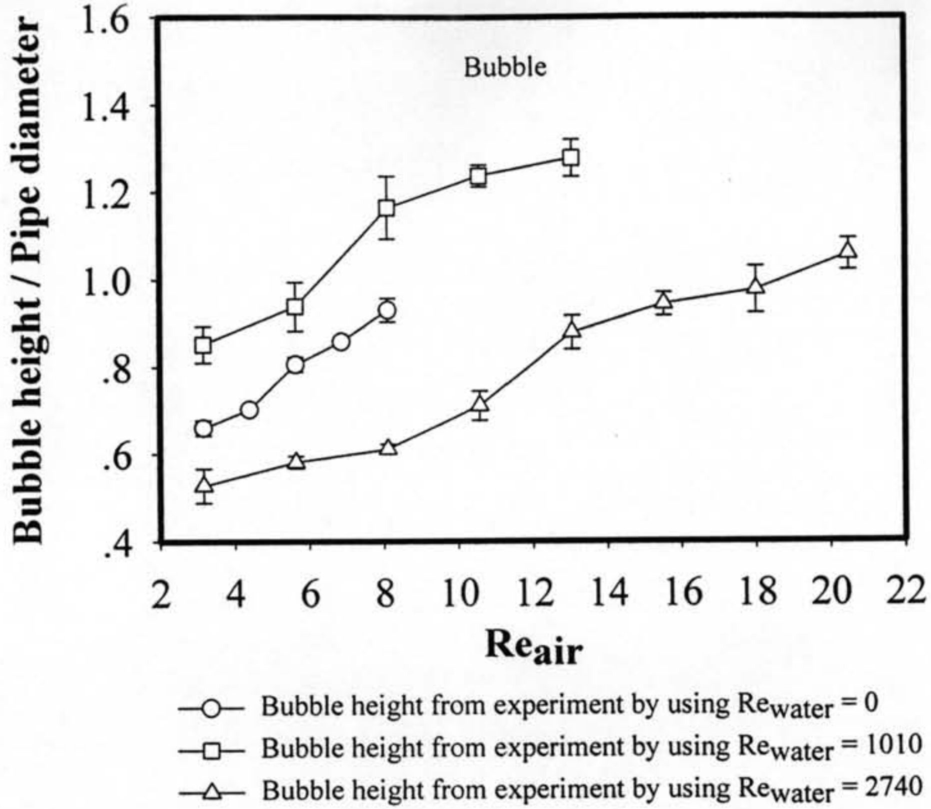


Figure A6 Bubble height from experiment vs. air Reynolds number of pure water by using pipe diameter 19 mm.

Table A2 Determination of slug height for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the slug height:

1. Make a movie of the slug flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the slug height by Scion Image software program.

Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
0	22.95	31.4	35.5	30.3	32.4 ± 2.8	1.7	1.9	1.6	1.7 ± 0.14
0	28.08	39.7	50.0	47.9	45.9 ± 5.4	2.1	2.6	2.5	2.4 ± 0.29
0	33.21	53.3	45.3	52.0	50.2 ± 4.3	2.8	2.4	2.7	2.6 ± 0.22
0	38.33	55.9	58.2	54.9	56.3 ± 1.7	2.9	3.1	2.9	3.0 ± 0.09
0	43.46	57.1	65.5	57.6	60.1 ± 4.7	3.0	3.4	3.0	3.2 ± 0.25
0	48.59	59.3	75.8	62.3	65.8 ± 8.7	3.1	4.0	3.3	3.5 ± 0.46
0	58.85	82.7	75.9	79.1	79.2 ± 3.4	4.4	4.0	4.2	4.2 ± 0.18
0	69.10	83.3	82.2	84.6	83.4 ± 1.2	4.4	4.3	4.5	4.4 ± 0.06
0	79.36	84.9	89.7	90.1	88.2 ± 2.9	4.5	4.7	4.7	4.6 ± 0.15
0	89.62	90.1	88.8	102.2	93.7 ± 7.4	4.7	4.7	5.4	4.9 ± 0.39
0	99.87	101.0	101.4	115.9	106.1 ± 8.5	5.3	5.3	6.1	5.6 ± 0.45
0	177	196.8	193.0	196.8	195.5 ± 2.2	10.4	10.2	10.4	10.3 ± 0.12
1010	33.21	37.1	38.8	41.4	39.1 ± 2.2	2.0	2.0	2.2	2.1 ± 0.11
1010	38.33	44.0	42.0	41.0	42.3 ± 1.5	2.3	2.2	2.2	2.2 ± 0.08
1010	43.46	48.1	49.0	46.2	47.8 ± 1.5	2.5	2.6	2.4	2.5 ± 0.08
1010	48.59	53.0	51.5	50.8	51.8 ± 1.2	2.8	2.7	2.7	2.7 ± 0.06
1010	58.85	56.8	56.8	60.2	58.0 ± 2.0	3.0	3.0	3.2	3.1 ± 0.10
1010	69.10	71.4	75.9	71.4	72.9 ± 2.6	3.8	4.0	3.8	3.8 ± 0.14
1010	79.36	73.6	87.3	81.2	80.7 ± 6.9	3.9	4.6	4.3	4.2 ± 0.36
1010	89.62	75.0	90.2	85.9	83.7 ± 7.8	3.9	4.7	4.5	4.4 ± 0.41
1010	99.87	101.3	108.8	86.3	98.8 ± 11.5	5.3	5.7	4.5	5.2 ± 0.60
1010	177	113.0	117.6	113.0	114.5 ± 2.7	5.9	6.2	5.9	6.0 ± 0.14
2740	48.59	37.5	40.9	36.4	38.3 ± 2.4	2.0	2.2	1.9	2.0 ± 0.12
2740	58.85	42.0	42.9	42.9	42.6 ± 0.5	2.2	2.3	2.3	2.2 ± 0.03
2740	69.10	49.1	52.8	59.3	53.7 ± 5.1	2.6	2.8	3.1	2.8 ± 0.27
2740	79.36	61.7	64.2	63.3	63.1 ± 1.3	3.2	3.4	3.3	3.3 ± 0.07

Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
2740	89.62	70.2	70.2	77.4	72.6 ± 4.2	3.7	3.7	4.1	3.8 ± 0.22
2740	99.87	81.3	80.4	80.5	80.7 ± 0.5	4.3	4.2	4.2	4.2 ± 0.03
2740	177	126.0	120.0	124.0	123.3 ± 3.1	6.6	6.3	6.5	6.5 ± 0.16
2740	296	206.0	209.0	211.0	208.7 ± 2.5	10.8	11.0	11.1	11.0 ± 0.13

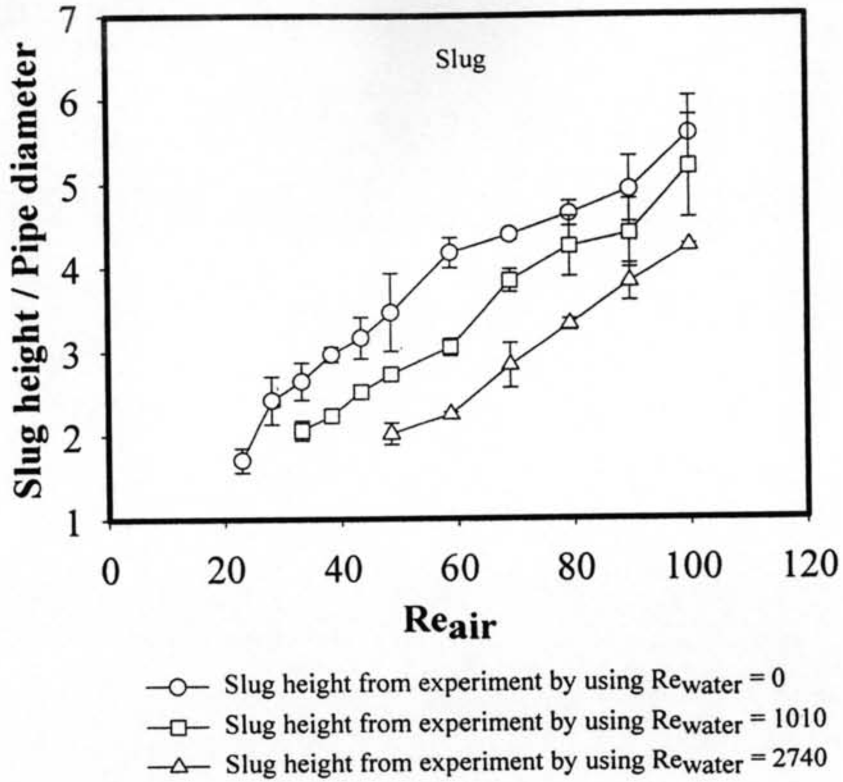


Figure A7 Slug height from experiment vs. air Reynolds number of pure water by using pipe diameter 19 mm.

Table A3 Determination of bubble and slug velocity for pure water from Nicklin's theory and experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Bubble velocity from theory, $$u_s = 1.2(\frac{Q_{qir} + Q_{liquid}}{A}) + 0.35\sqrt{gD} \qquad \text{(A2)}$$

Determination of bubble velocity from experiment by timing the bubble at known distance (0.7m)

Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
0	3.17	4.86	4.74	4.78	4.73	4.72	4.77 ± 0.06	0.14	0.15	0.15	0.15	0.15	0.15 ± 0.002	0.15
0	4.40	4.59	4.62	4.63	4.63	4.60	4.61 ± 0.02	0.15	0.15	0.15	0.15	0.15	0.15 ± 0.001	0.16
0	5.64	4.51	4.70	4.57	4.34	4.62	4.55 ± 0.14	0.16	0.15	0.15	0.16	0.15	0.15 ± 0.005	0.16
0	6.88	4.52	4.58	4.57	4.54	4.56	4.55 ± 0.02	0.15	0.15	0.15	0.15	0.15	0.15 ± 0.001	0.16
0	8.11	4.42	4.51	4.45	4.57	4.55	4.50 ± 0.06	0.16	0.16	0.16	0.15	0.15	0.16 ± 0.002	0.16
0	10.59	4.41	4.43	4.45	4.37	4.48	4.43 ± 0.04	0.16	0.16	0.16	0.16	0.16	0.16 ± 0.001	0.16
0	13.06	4.37	4.21	4.37	4.26	4.31	4.30 ± 0.07	0.16	0.17	0.16	0.16	0.16	0.16 ± 0.003	0.16
0	15.53	4.25	4.29	4.29	4.26	4.26	4.27 ± 0.02	0.16	0.16	0.16	0.16	0.16	0.16 ± 0.001	0.17
0	18.01	4.16	4.12	4.15	4.27	4.20	4.18 ± 0.06	0.17	0.17	0.17	0.16	0.17	0.17 ± 0.002	0.17
0	20.48	4.00	4.15	3.95	4.12	4.02	4.05 ± 0.08	0.18	0.17	0.18	0.17	0.17	0.17 ± 0.004	0.17
0	22.94	3.98	3.91	3.99	4.00	3.99	3.97 ± 0.04	0.18	0.18	0.18	0.18	0.18	0.18 ± 0.002	0.17

Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
0	28.06	3.73	3.81	3.85	3.88	3.79	3.81 ± 0.06	0.19	0.18	0.18	0.18	0.18	0.18 ± 0.003	0.18
0	33.19	3.74	3.74	3.71	3.74	3.76	3.74 ± 0.02	0.19	0.19	0.19	0.19	0.19	0.19 ± 0.001	0.18
0	38.31	3.63	3.66	3.56	3.71	3.57	3.63 ± 0.06	0.19	0.19	0.20	0.19	0.20	0.19 ± 0.003	0.19
0	43.44	3.65	3.52	3.56	3.56	3.61	3.58 ± 0.05	0.19	0.20	0.20	0.20	0.19	0.20 ± 0.003	0.19
0	48.57	3.55	3.52	3.58	3.40	3.49	3.51 ± 0.07	0.20	0.20	0.20	0.21	0.20	0.20 ± 0.004	0.20
0	58.82	3.34	3.37	3.33	3.38	3.34	3.35 ± 0.02	0.21	0.21	0.21	0.21	0.21	0.21 ± 0.001	0.21
0	69.07	3.30	3.16	3.20	3.20	3.23	3.22 ± 0.05	0.21	0.22	0.22	0.22	0.22	0.22 ± 0.003	0.22
0	79.32	3.06	3.05	3.06	3.01	3.09	3.05 ± 0.03	0.23	0.23	0.23	0.23	0.23	0.23 ± 0.002	0.23
0	89.57	2.82	2.90	3.04	2.96	2.93	2.93 ± 0.08	0.25	0.24	0.23	0.24	0.24	0.24 ± 0.007	0.24
0	99.82	2.88	2.85	2.91	2.88	2.90	2.88 ± 0.02	0.24	0.25	0.24	0.24	0.24	0.24 ± 0.002	0.25
0	177	2.24	2.21	2.28	2.20	2.21	2.23 ± 0.03	0.31	0.32	0.31	0.32	0.32	0.31 ± 0.005	0.33
1010	3.17	3.38	3.41	3.44	3.37	3.41	3.40 ± 0.03	0.21	0.21	0.20	0.21	0.21	0.21 ± 0.002	0.21
1010	5.64	3.28	3.40	3.34	3.32	3.43	3.35 ± 0.06	0.21	0.21	0.21	0.21	0.20	0.21 ± 0.004	0.21
1010	8.12	3.34	3.34	3.31	3.28	3.34	3.32 ± 0.03	0.21	0.21	0.21	0.21	0.21	0.21 ± 0.002	0.21
1010	10.59	3.22	3.32	3.34	3.31	3.22	3.28 ± 0.06	0.22	0.21	0.21	0.21	0.22	0.21 ± 0.004	0.22
1010	13.07	3.28	3.25	3.35	3.28	3.31	3.29 ± 0.04	0.21	0.22	0.21	0.21	0.21	0.21 ± 0.002	0.22
1010	15.54	3.22	3.22	3.25	3.22	3.25	3.23 ± 0.02	0.22	0.22	0.22	0.22	0.22	0.22 ± 0.001	0.22
1010	18.02	3.15	3.07	3.10	3.12	3.10	3.11 ± 0.03	0.22	0.23	0.23	0.22	0.23	0.23 ± 0.002	0.22
1010	20.49	3.13	3.09	3.10	3.06	3.09	3.09 ± 0.03	0.22	0.23	0.23	0.23	0.23	0.23 ± 0.002	0.23
1010	22.95	3.07	3.07	3.10	3.06	3.09	3.08 ± 0.02	0.23	0.23	0.23	0.23	0.23	0.23 ± 0.001	0.23
1010	28.08	2.97	3.00	2.97	2.97	2.97	2.98 ± 0.01	0.24	0.23	0.24	0.24	0.24	0.24 ± 0.001	0.23
1010	33.21	2.93	2.88	2.88	2.87	2.97	2.91 ± 0.04	0.24	0.24	0.24	0.24	0.24	0.24 ± 0.004	0.24
1010	38.33	2.93	2.85	2.93	2.87	2.87	2.89 ± 0.04	0.24	0.25	0.24	0.24	0.24	0.24 ± 0.003	0.24
1010	43.46	2.78	2.81	2.78	2.72	2.72	2.76 ± 0.04	0.25	0.25	0.25	0.26	0.26	0.25 ± 0.004	0.25
1010	48.59	2.75	2.75	2.72	2.69	2.78	2.74 ± 0.03	0.25	0.25	0.26	0.26	0.25	0.26 ± 0.003	0.25
1010	58.85	2.56	2.56	2.59	2.59	2.59	2.58 ± 0.02	0.27	0.27	0.27	0.27	0.27	0.27 ± 0.002	0.26
1010	69.10	2.47	2.47	2.53	2.54	2.47	2.50 ± 0.04	0.28	0.28	0.28	0.28	0.28	0.28 ± 0.004	0.27

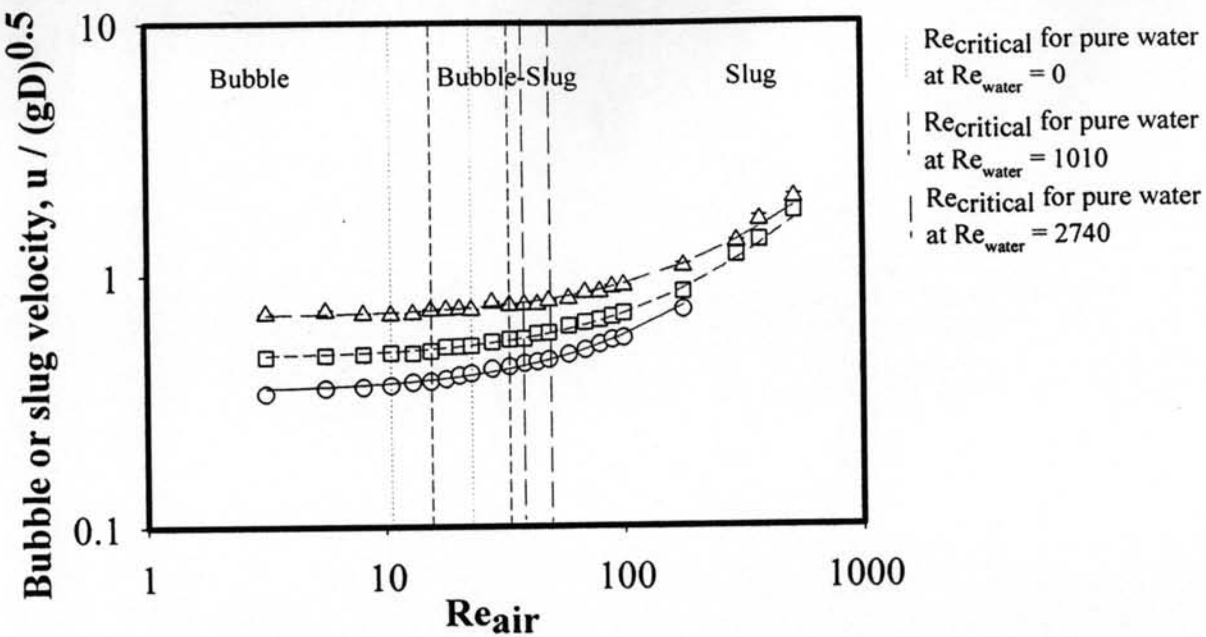
Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
1010	79.36	2.44	2.43	2.47	2.43	2.41	2.44 ± 0.02	0.29	0.29	0.28	0.29	0.29	0.29 ± 0.003	0.28
1010	89.62	2.37	2.34	2.37	2.41	2.34	2.37 ± 0.03	0.30	0.30	0.30	0.29	0.30	0.30 ± 0.004	0.29
1010	99.87	2.28	2.31	2.32	2.31	2.28	2.30 ± 0.02	0.31	0.30	0.30	0.30	0.31	0.30 ± 0.002	0.30
1010	177	1.84	1.81	1.96	1.94	1.91	1.89 ± 0.06	0.38	0.39	0.36	0.36	0.37	0.37 ± 0.013	0.38
1010	296	1.34	1.37	1.38	1.38	1.31	1.36 ± 0.03	0.52	0.51	0.51	0.51	0.53	0.52 ± 0.012	0.50
1010	369	1.19	1.25	1.19	1.10	1.19	1.18 ± 0.05	0.59	0.56	0.59	0.64	0.59	0.59 ± 0.028	0.57
1010	515	0.84	0.93	0.97	0.87	0.94	0.91 ± 0.05	0.83	0.75	0.72	0.80	0.74	0.77 ± 0.046	0.72
2740	3.17	2.28	2.28	2.31	2.32	2.31	2.30 ± 0.02	0.31	0.31	0.30	0.30	0.30	0.30 ± 0.002	0.30
2740	5.64	2.22	2.28	2.25	2.28	2.22	2.25 ± 0.03	0.32	0.31	0.31	0.31	0.32	0.31 ± 0.004	0.30
2740	8.11	2.29	2.28	2.31	2.34	2.31	2.31 ± 0.02	0.31	0.31	0.30	0.30	0.30	0.30 ± 0.003	0.31
2740	10.59	2.28	2.31	2.28	2.37	2.34	2.32 ± 0.04	0.31	0.30	0.31	0.30	0.30	0.30 ± 0.005	0.31
2740	13.06	2.32	2.28	2.31	2.29	2.28	2.30 ± 0.02	0.30	0.31	0.30	0.31	0.31	0.30 ± 0.002	0.31
2740	15.53	2.21	2.19	2.25	2.25	2.25	2.23 ± 0.03	0.32	0.32	0.31	0.31	0.31	0.31 ± 0.004	0.31
2740	18.01	2.19	2.22	2.22	2.21	2.25	2.22 ± 0.02	0.32	0.32	0.32	0.32	0.31	0.32 ± 0.003	0.32
2740	20.48	2.21	2.25	2.19	2.16	2.22	2.21 ± 0.03	0.32	0.31	0.32	0.32	0.32	0.32 ± 0.005	0.32
2740	22.94	2.22	2.25	2.22	2.22	2.22	2.23 ± 0.01	0.32	0.31	0.32	0.32	0.32	0.31 ± 0.002	0.32
2740	28.06	2.09	2.06	2.09	2.10	2.06	2.08 ± 0.02	0.33	0.34	0.33	0.33	0.34	0.34 ± 0.003	0.33
2740	33.19	2.15	2.12	2.12	2.12	2.15	2.13 ± 0.02	0.33	0.33	0.33	0.33	0.33	0.33 ± 0.003	0.33
2740	38.31	2.13	2.10	2.13	2.10	2.13	2.12 ± 0.02	0.33	0.33	0.33	0.33	0.33	0.33 ± 0.003	0.34
2740	43.44	2.10	2.13	2.12	2.12	2.13	2.12 ± 0.01	0.33	0.33	0.33	0.33	0.33	0.33 ± 0.002	0.34
2740	48.57	2.03	2.06	2.06	2.07	2.03	2.05 ± 0.02	0.34	0.34	0.34	0.34	0.34	0.34 ± 0.003	0.35
2740	58.82	2.03	2.06	1.97	2.03	2.00	2.02 ± 0.03	0.34	0.34	0.36	0.34	0.35	0.35 ± 0.006	0.36
2740	69.07	1.91	1.91	1.91	1.88	1.94	1.91 ± 0.02	0.37	0.37	0.37	0.37	0.36	0.37 ± 0.004	0.37
2740	79.32	1.87	1.94	1.91	1.87	1.91	1.90 ± 0.03	0.37	0.36	0.37	0.37	0.37	0.37 ± 0.006	0.38
2740	89.57	1.78	1.81	1.85	1.85	1.81	1.82 ± 0.03	0.39	0.39	0.38	0.38	0.39	0.38 ± 0.006	0.39
2740	99.82	1.81	1.78	1.78	1.78	1.81	1.79 ± 0.02	0.39	0.39	0.39	0.39	0.39	0.39 ± 0.004	0.40
2740	177	1.50	1.43	1.54	1.53	1.53	1.51 ± 0.05	0.47	0.49	0.45	0.46	0.46	0.47 ± 0.014	0.47

Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
2740	296	1.22	1.18	1.19	1.22	1.22	1.21 ± 0.02	0.57	0.59	0.59	0.57	0.57	0.58 ± 0.009	0.59
2740	369	1.00	0.94	1.06	0.96	1.00	0.99 ± 0.05	0.70	0.74	0.66	0.73	0.70	0.71 ± 0.032	0.66
2740	515	0.81	0.78	0.82	0.84	0.78	0.81 ± 0.03	0.86	0.90	0.85	0.83	0.90	0.87 ± 0.028	0.81

Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
0	3.17	0.33	0.34	0.34	0.34	0.34	0.34 ± 0.004	0.36
0	4.40	0.35	0.35	0.35	0.35	0.35	0.35 ± 0.001	0.36
0	5.64	0.36	0.34	0.35	0.37	0.35	0.36 ± 0.011	0.36
0	6.88	0.36	0.35	0.35	0.36	0.36	0.36 ± 0.002	0.37
0	8.11	0.37	0.36	0.36	0.35	0.36	0.36 ± 0.005	0.37
0	10.59	0.37	0.37	0.36	0.37	0.36	0.37 ± 0.003	0.37
0	13.06	0.37	0.39	0.37	0.38	0.38	0.38 ± 0.006	0.38
0	15.53	0.38	0.38	0.38	0.38	0.38	0.38 ± 0.002	0.39
0	18.01	0.39	0.39	0.39	0.38	0.39	0.39 ± 0.005	0.39
0	20.48	0.41	0.39	0.41	0.39	0.40	0.40 ± 0.008	0.40
0	22.94	0.41	0.41	0.41	0.41	0.41	0.41 ± 0.004	0.40
0	28.06	0.43	0.43	0.42	0.42	0.43	0.43 ± 0.006	0.41
0	33.19	0.43	0.43	0.44	0.43	0.43	0.43 ± 0.002	0.43
0	38.31	0.45	0.44	0.46	0.44	0.45	0.45 ± 0.008	0.44
0	43.44	0.44	0.46	0.46	0.46	0.45	0.45 ± 0.006	0.45
0	48.57	0.46	0.46	0.45	0.48	0.46	0.46 ± 0.009	0.46
0	58.82	0.49	0.48	0.49	0.48	0.49	0.48 ± 0.003	0.48
0	69.07	0.49	0.51	0.51	0.51	0.50	0.50 ± 0.008	0.51
0	79.32	0.53	0.53	0.53	0.54	0.52	0.53 ± 0.005	0.53
0	89.57	0.57	0.56	0.53	0.55	0.55	0.55 ± 0.015	0.56
0	99.82	0.56	0.57	0.56	0.56	0.56	0.56 ± 0.005	0.58
0	177	0.72	0.73	0.71	0.74	0.73	0.73 ± 0.011	0.76
1010	3.17	0.48	0.48	0.47	0.48	0.48	0.48 ± 0.004	0.48
1010	5.64	0.49	0.48	0.49	0.49	0.47	0.48 ± 0.009	0.49
1010	8.12	0.49	0.49	0.49	0.49	0.49	0.49 ± 0.004	0.49
1010	10.59	0.50	0.49	0.49	0.49	0.50	0.49 ± 0.009	0.50

Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
1010	13.07	0.49	0.50	0.48	0.49	0.49	0.49 ± 0.006	0.51
1010	15.54	0.50	0.50	0.50	0.50	0.50	0.50 ± 0.003	0.51
1010	18.02	0.51	0.53	0.52	0.52	0.52	0.52 ± 0.005	0.52
1010	20.49	0.52	0.52	0.52	0.53	0.52	0.52 ± 0.004	0.52
1010	22.95	0.53	0.53	0.52	0.53	0.52	0.53 ± 0.003	0.53
1010	28.08	0.55	0.54	0.55	0.55	0.55	0.54 ± 0.002	0.54
1010	33.21	0.55	0.56	0.56	0.56	0.55	0.56 ± 0.008	0.55
1010	38.33	0.55	0.57	0.55	0.56	0.56	0.56 ± 0.007	0.56
1010	43.46	0.58	0.58	0.58	0.60	0.60	0.59 ± 0.009	0.58
1010	48.59	0.59	0.59	0.60	0.60	0.58	0.59 ± 0.007	0.59
1010	58.85	0.63	0.63	0.63	0.63	0.63	0.63 ± 0.004	0.61
1010	69.10	0.66	0.66	0.64	0.64	0.66	0.65 ± 0.009	0.63
1010	79.36	0.66	0.67	0.66	0.67	0.67	0.67 ± 0.006	0.66
1010	89.62	0.68	0.69	0.68	0.67	0.69	0.69 ± 0.008	0.68
1010	99.87	0.71	0.70	0.70	0.70	0.71	0.70 ± 0.006	0.71
1010	177	0.88	0.90	0.83	0.84	0.85	0.86 ± 0.030	0.88
1010	296	1.21	1.18	1.17	1.17	1.24	1.20 ± 0.027	1.15
1010	369	1.36	1.30	1.36	1.47	1.36	1.37 ± 0.064	1.32
1010	515	1.93	1.74	1.67	1.86	1.72	1.79 ± 0.107	1.66
2740	3.17	0.71	0.71	0.70	0.70	0.70	0.70 ± 0.006	0.70
2740	5.64	0.73	0.71	0.72	0.71	0.73	0.72 ± 0.010	0.70
2740	8.11	0.71	0.71	0.70	0.69	0.70	0.70 ± 0.007	0.71
2740	10.59	0.71	0.70	0.71	0.68	0.69	0.70 ± 0.012	0.72
2740	13.06	0.70	0.71	0.70	0.71	0.71	0.71 ± 0.006	0.72
2740	15.53	0.73	0.74	0.72	0.72	0.72	0.73 ± 0.009	0.73
2740	18.01	0.74	0.73	0.73	0.73	0.72	0.73 ± 0.007	0.73

Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
2740	20.48	0.73	0.72	0.74	0.75	0.73	0.74 ± 0.011	0.74
2740	22.94	0.73	0.72	0.73	0.73	0.73	0.73 ± 0.004	0.74
2740	28.06	0.78	0.79	0.78	0.77	0.79	0.78 ± 0.007	0.76
2740	33.19	0.75	0.76	0.76	0.76	0.75	0.76 ± 0.006	0.77
2740	38.31	0.76	0.77	0.76	0.77	0.76	0.77 ± 0.006	0.78
2740	43.44	0.77	0.76	0.76	0.76	0.76	0.76 ± 0.004	0.79
2740	48.57	0.80	0.79	0.79	0.78	0.80	0.79 ± 0.007	0.80
2740	58.82	0.80	0.79	0.82	0.80	0.81	0.80 ± 0.014	0.83
2740	69.07	0.85	0.85	0.85	0.86	0.84	0.85 ± 0.009	0.85
2740	79.32	0.87	0.84	0.85	0.87	0.85	0.85 ± 0.013	0.87
2740	89.57	0.91	0.90	0.88	0.88	0.90	0.89 ± 0.015	0.90
2740	99.82	0.90	0.91	0.91	0.91	0.90	0.90 ± 0.008	0.92
2740	177	1.08	1.13	1.05	1.06	1.06	1.08 ± 0.033	1.10
2740	296	1.33	1.37	1.36	1.33	1.33	1.34 ± 0.022	1.37
2740	369	1.62	1.72	1.53	1.69	1.62	1.64 ± 0.075	1.54
2740	515	2.00	2.08	1.98	1.93	2.08	2.01 ± 0.065	1.87



○ Bubble and slug velocity from experiment by using $Re_{water} = 0$

——— Bubble and slug velocity from Nicklin's, Wilkes's, and Davidson's theory by using $Re_{water} = 0$

□ Bubble and slug velocity from experiment by using $Re_{water} = 1010$

------ Bubble and slug velocity from Nicklin's, Wilkes's, and Davidson's theory by using $Re_{water} = 1010$

△ Bubble and slug velocity from experiment by using $Re_{water} = 2740$

— — — Bubble and slug velocity from Nicklin's, Wilkes's, and Davidson's theory by using $Re_{water} = 2740$

Figure A8 Comparison bubble and slug velocity from experiment vs. air Reynolds number of pure water comparing with Nicklin's theory by using pipe diameter 19 mm.

Table A4 Determination of the pressure gradient for the bubble flow regime from Nicklin's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Superficial liquid velocity, $j_{liquid} = \dfrac{Q_{liquid}}{A}$ (A3)

Superficial air velocity, $j_{air} = \dfrac{Q_{air}}{A}$ (A4)

Reynolds number of liquid, $\mathrm{Re}_{liquid} = \dfrac{\rho\, j_{liquid} D}{\mu_{liquid}}$ (A5)

Reynolds number of air, $\mathrm{Re}_{air} = \dfrac{\rho\, j_{air} D}{\mu_{air}}$ (A6)

Bubble velocity rising in stagnant liquid, $u_b = 1.00\sqrt{g R_b}$ (A7)

where R_b is equivalent radius of the bubble which defined as the radius of a sphere that has the same volume as the bubble

Void fraction, $\varepsilon = \dfrac{Q_{air}}{Q_{air} + Q_{liquid} + u_b A}$ (A8)

Pressure gradient for bubble flow regime, $\dfrac{dp}{dz} = -\rho_l g(1-\varepsilon)$ (A9)

Q_{water} (ml/min)	Sup. water velocity j_{water} (m/s)	Q_{water} (m^3/sec)	Re_{water}	Q_{air} (L/min)	Sup. Air velocity j_{air} (m/s)	Q_{air} (m^3/sec)	Re_{air}	Flow regime	U_b (m/s)	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
0	0	0	0	0.0444	0.0026	7.40567E-07	3.17	bubble	0.2770	0.0093	9.6697
0	0	0	0	0.0792	0.0047	1.31925E-06	5.64	bubble	0.2970	0.0154	9.6103
0	0	0	0	0.1139	0.0067	1.89793E-06	8.12	bubble	0.3159	0.0208	9.5583
771	0.0453	1.28451E-05	1011	0.0444	0.0026	7.40567E-07	3.17	bubble	0.3051	0.0074	9.6887
771	0.0453	1.28451E-05	1011	0.0792	0.0047	1.31925E-06	5.64	bubble	0.3147	0.0128	9.6363
771	0.0453	1.28451E-05	1011	0.1139	0.0067	1.90E-06	8.12	bubble	0.3446	0.0169	9.5961
771	0.0453	1.28451E-05	1011	0.1486	0.0087	2.47662E-06	10.59	bubble	0.3533	0.0215	9.5516
771	0.0453	1.28451E-05	1011	0.1833	0.0108	3.0553E-06	13.07	bubble	0.3587	0.0260	9.5073
2090	0.1229	3.48294E-05	2740	0.0444	0.0026	7.40567E-07	3.1670	bubble	0.2536	0.0069	9.6937
2090	0.1229	3.48294E-05	2740	0.0792	0.0047	1.31925E-06	5.6418	bubble	0.2664	0.0118	9.6456
2090	0.1229	3.48294E-05	2740	0.1139	0.0067	1.89793E-06	8.1165	bubble	0.2711	0.0167	9.5978
2090	0.1229	3.48294E-05	2740	0.1486	0.0087	2.47662E-06	10.5912	bubble	0.2827	0.0211	9.5550
2090	0.1229	3.48294E-05	2740	0.1833	0.0108	3.0553E-06	13.0659	bubble	0.3070	0.0245	9.5221
2090	0.1229	3.48294E-05	2740	0.2180	0.0128	3.63398E-06	15.5407	bubble	0.3175	0.0283	9.4848
2090	0.1229	3.48294E-05	2740	0.2528	0.0149	4.21267E-06	18.0154	bubble	0.3226	0.0323	9.4457
2090	0.1229	3.48294E-05	2740	0.2875	0.0169	4.79135E-06	20.4901	bubble	0.3312	0.0359	9.4105
2090	0.1229	3.48294E-05	2740	0.3220	0.0189	5.3665E-06	22.9498	bubble	0.3216	0.0409	9.3621
2090	0.1229	3.48294E-05	2740	0.3939	0.0232	6.56567E-06	28.0780	bubble	0.3324	0.0484	9.2884
2090	0.1229	3.48294E-05	2740	0.4659	0.0274	7.76483E-06	33.2062	bubble	0.3463	0.0552	9.2223

Table A5 Determination of the pressure gradient for the slug flow regime from Nicklin's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Mean liquid velocity, $u_l = \dfrac{Q_{air} + Q_{liquid}}{A}$ (A10)

Reynolds number of the liquid slug, $\mathrm{Re}_{slug} = \dfrac{\rho_{liquid} u_l D}{\mu_{liquid}}$ (A11)

Fanning friction factor, $f_F = \dfrac{16}{\mathrm{Re}_{slug}}$ for laminar flow ($\mathrm{Re}_{slug} < 2000$) (A12)

$f_F = 0.079\,\mathrm{Re}_{slug}^{-1/4}$ for turbulent flow ($\mathrm{Re}_{slug} > 4000$) (A13)

Single-phase frictional pressure gradient for liquid only, $\left(\dfrac{dp}{dz}\right)_{sp} = \dfrac{2 f_F \rho_{liquid} u_l}{D}$ (A14)

Void fraction, $\varepsilon = \dfrac{Q_{air}}{1.2\left(Q_{air} + Q_{liquid}\right) + 0.35 A\sqrt{gD}}$ (A15)

Pressure gradient for slug flow regime, $\dfrac{dp}{dz} = (1 - \varepsilon)\left[-\rho_{liquid} g + \left(\dfrac{dp}{dz}\right)_{sp}\right]$ (A16)

Q_{water} (m^3/sec)	Re_{water}	Qair (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
0	0	5.367E-06	22.95	slug	0.0189	422	0.0379	1.4235	0.1089	8.6988
0	0	6.566E-06	28.08	slug	0.0232	517	0.0310	1.7416	0.1295	8.4983
0	0	7.765E-06	33.21	slug	0.0274	611	0.0262	2.0597	0.1489	8.3090
0	0	8.964E-06	38.33	slug	0.0316	705	0.0227	2.3777	0.1673	8.1298
0	0	1.016E-05	43.46	slug	0.0359	800	0.0200	2.6958	0.1847	7.9599
0	0	1.136E-05	48.59	slug	0.0401	894	0.0179	3.0139	0.2013	7.7988
0	0	1.376E-05	58.85	slug	0.0486	1083	0.0148	3.6501	0.2319	7.4999
0	0	1.616E-05	69.10	slug	0.0570	1271	0.0126	4.2862	0.2598	7.2287
0	0	1.856E-05	79.36	slug	0.0655	1460	0.0110	4.9224	0.2851	6.9815
0	0	2.096E-05	89.62	slug	0.0739	1649	0.0097	5.5586	0.3083	6.7552
0	0	2.335E-05	99.87	slug	0.0824	1837	0.0087	6.1947	0.3297	6.5473
0	0	4.134E-05	176.80	slug	0.1459	3252	0.0049	10.9660	0.4473	5.4011
1.285E-05	1010	7.765E-06	33.21	slug	0.0727	1621	0.0099	5.4669	0.1149	8.6438
1.285E-05	1010	8.964E-06	38.33	slug	0.0770	1716	0.0093	5.7849	0.1299	8.4977
1.285E-05	1010	1.016E-05	43.46	slug	0.0812	1810	0.0088	6.1030	0.1443	8.3576
1.285E-05	1010	1.136E-05	48.59	slug	0.0854	1904	0.0084	6.4211	0.1581	8.2231
1.285E-05	1010	1.376E-05	58.85	slug	0.0939	2093	0.0076	7.0573	0.1841	7.9697
1.285E-05	1010	1.616E-05	69.10	slug	0.1023	2282	0.0070	7.6935	0.2082	7.7351
1.285E-05	1010	1.856E-05	79.36	slug	0.1108	2470	0.0065	8.3296	0.2305	7.5172
1.285E-05	1010	2.096E-05	89.62	slug	0.1193	2659	0.0060	8.9658	0.2513	7.3144
1.285E-05	1010	2.335E-05	99.87	slug	0.1277	2848	0.0056	9.6020	0.2707	7.1252
1.285E-05	1010	4.134E-05	176.80	slug	0.1912	4263	0.0098	37.4397	0.3834	6.0422

Q_{water} (m^3/sec)	Re_{water}	Qair (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
1.285E-05	1010	6.922E-05	296.03	slug-churn	0.2896	6456	0.0088	77.4159	0.4899	5.0185
1.285E-05	1010	8.631E-05	369.11	slug-churn	0.3499	7801	0.0084	107.7919	0.5334	4.6045
1.285E-05	1010	0.0001205	515.27	slug-churn	0.4705	10489	0.0078	180.9944	0.5941	4.0357
1.285E-05	1010	0.0001718	734.50	slug-churn	0.6514	14522	0.0072	319.8312	0.6498	3.5308
3.483E-05	2740	1.136E-05	48.59	slug	0.1630	3634	0.0044	12.2525	0.1156	8.6430
3.483E-05	2740	1.376E-05	58.85	slug	0.1715	3823	0.0042	12.8887	0.1361	8.4439
3.483E-05	2740	1.616E-05	69.10	slug	0.1799	4011	0.0099	33.6587	0.1554	8.2729
3.483E-05	2740	1.856E-05	79.36	slug	0.1884	4200	0.0098	36.4780	0.1736	8.0964
3.483E-05	2740	2.096E-05	89.62	slug	0.1969	4389	0.0097	39.3939	0.1909	7.9293
3.483E-05	2740	2.335E-05	99.87	slug	0.2053	4577	0.0096	42.4054	0.2073	7.7708
3.483E-05	2740	4.134E-05	176	slug	0.2688	5992	0.0090	67.9443	0.3080	6.8016
3.483E-05	2740	6.922E-05	296	slug	0.3672	8186	0.0083	117.2778	0.4128	5.8003
3.483E-05	2740	8.631E-05	369	slug-churn	0.4275	9530	0.0080	153.0319	0.4586	5.3670
3.483E-05	2740	0.0001205	515	slug-churn	0.5481	12219	0.0075	236.4062	0.5257	4.7419
3.483E-05	2740	0.0001718	734	slug-churn	0.7290	16252	0.0070	389.4364	0.5908	4.1537
3.483E-05	2740	0.0003399	1453	slug-churn	1.3224	29480	0.0060	1104.2015	0.6902	3.3664

Table A6 Determination of the pressure gradient for the slug flow regime from Sylvester's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

$$\beta = L_{TB}/L_{SU} \tag{A17}$$

where: L_{TB} is length of the Taylor bubble

L_{SU} is length of the slug unit

Friction factor associated with the Taylor bubble, $$f_{TB} = \frac{1}{\left[-2.0\log\left\{\frac{\left(1-\alpha_{TB}^{1/2}\right)}{7.4}\right\}\right]^2} \tag{A18}$$

Reynolds number of the liquid slug, $$\mathrm{Re}_{LS} = \frac{\rho_L U_{LLS} D}{\mu_L} \tag{A19}$$

where: velocity of the liquid in the liquid slug, $$U_{LLS} = U_{SG} + U_{SL} \tag{A20}$$

Friction factor associated with the liquid slug, $$f_{LS} = \frac{1}{\left[-2.0\log\left\{\frac{\varepsilon/D}{3.7} - \left(\frac{5.02}{\mathrm{Re}_{LS}}\right)\log\left(\frac{\varepsilon/D}{3.7} + \frac{13}{\mathrm{Re}_{LS}}\right)\right\}\right]^2} \tag{A21}$$

where: ε is the pipe roughness

Acceleration pressure drop, $$(\Delta P)_A = \rho_L(U_{LTB} + U_{TB})(1-\alpha_{TB})(U_{LTB} + U_{TB} + U_{LLS}) \tag{A22}$$

where: velocity of the liquid film around the Taylor bubble, $$U_{LTB} = 9.916\left[gD\left(1-\sqrt{\alpha_{TB}}\right)\right]^{1/2} \tag{A23}$$

velocity of the Taylor bubble, $U_{TB} = 1.2(U_{SG} + U_{SL}) + 0.35\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}$ (A24)

area average void fraction of the Taylor bubble, $\alpha_{TB} = \frac{\text{Average all area at Taylor bubble region}}{\text{Average area in Taylor bubble}}$ (A25)

Hydrostatic pressure drop, $(\Delta P)_H = \rho_L(1-\alpha_{LS})gL_{LS}$ (A26)

where: void fraction of the liquid slug, $\alpha_{LS} = \frac{U_{SG}}{0.425 + 2.65(U_{SG} + U_{SL})}$ (A27)

length of the liquid slug, L_{LS}

Frictional pressure drop of slug unit, $(\Delta P)_F = \frac{L_{LS}}{2D}\left[\frac{\rho_G \beta f_{TB} U_{TB}^2}{(1-\beta)\left[1-(1-\alpha_{TB}^{1/2}\right]} + U_{LLS}^2 \rho_L (1-\alpha_{LS}) f_{LS} (1-\beta)\right]$ (A28)

Total pressure drop in the slug unit, $(\Delta P)_T = (\Delta P)_A + (\Delta P)_H + (\Delta P)_F$ (A29)

Re_{water}	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
0	22.95	slug	0.1940	0.0579	422	0.0821	186	1261	0.0821	1447.6	1.4476	8.6692
0	28.08	slug	0.2551	0.0620	517	0.0764	252	1246	0.1052	1497.3	1.4973	8.3246
0	33.21	slug	0.2796	0.0620	611	0.0721	254	1193	0.1283	1447.5	1.4475	8.0619
0	38.33	slug	0.2977	0.0640	705	0.0686	293	1216	0.1617	1509.5	1.5095	7.9771
0	43.46	slug	0.2918	0.0620	800	0.0658	260	1325	0.2177	1585.3	1.5853	7.6986
0	48.59	slug	0.2994	0.0620	894	0.0634	263	1390	0.2714	1652.4	1.6524	7.5184
0	58.85	slug	0.3602	0.0640	1083	0.0595	305	1253	0.3091	1558.7	1.5587	7.0848
0	69.10	slug	0.3870	0.0640	1271	0.0564	311	1162	0.3593	1473.3	1.4733	6.8368
0	79.36	slug	0.4032	0.0620	1460	0.0540	279	1135	0.4305	1415.0	1.4150	6.4664
0	89.62	slug	0.4073	0.0620	1649	0.0520	285	1172	0.5408	1457.8	1.4578	6.3376
0	99.87	slug	0.4440	0.0620	1837	0.0502	291	1131	0.5890	1421.8	1.4218	5.9506
0	176	slug	0.5854	0.0640	3252	0.0423	379	1109	1.1543	1488.7	1.4887	4.4574
1010	33.21	slug	0.2305	0.0579	1621	0.0522	214	1217	0.6982	1431.9	1.4319	8.4455
1010	38.33	slug	0.2447	0.0579	1716	0.0513	216	1211	0.7507	1428.5	1.4285	8.2574
1010	43.46	slug	0.2463	0.0579	1810	0.0505	219	1347	0.9114	1566.4	1.5664	8.0780
1010	48.59	slug	0.2723	0.0600	1904	0.0497	256	1268	0.9036	1524.2	1.5242	8.0155
1010	58.85	slug	0.2782	0.0579	2093	0.0482	226	1362	1.1293	1588.9	1.5889	7.6269
1010	69.10	slug	0.3097	0.0620	2282	0.0470	304	1456	1.3388	1761.9	1.7619	7.4840
1010	79.36	slug	0.3657	0.0620	2470	0.0459	310	1242	1.2037	1553.0	1.5530	7.0382
1010	89.62	slug	0.4053	0.0640	2659	0.0449	358	1079	1.1149	1438.3	1.4383	6.9645
1010	99.87	slug	0.3792	0.0620	2848	0.0440	322	1408	1.7009	1731.5	1.7315	6.6490

Re_{water}	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
1010	176	slug	0.5761	0.0659	4263	0.0391	466	694	1.1650	1160.6	1.1606	5.8390
2740	48.59	slug	0.2367	0.0579	3634	0.0409	266	1148	2.5647	1415.7	1.4157	8.7605
2740	58.85	slug	0.2755	0.0579	3823	0.0403	271	1032	2.3893	1304.9	1.3049	8.4483
2740	69.10	slug	0.3443	0.0620	4011	0.0398	360	935	2.1347	1297.9	1.2979	8.3181
2740	79.36	slug	0.3955	0.0640	4200	0.0393	414	874	1.9954	1289.8	1.2898	8.0890
2740	89.62	slug	0.3497	0.0640	4389	0.0388	421	1214	3.2072	1638.1	1.6381	7.8933
2740	99.87	slug	0.3428	0.0640	4577	0.0383	428	1381	3.9618	1813.0	1.8130	7.7034
2740	176	slug	0.4405	0.0640	5992	0.0356	483	1333	5.2003	1821.2	1.8212	6.5045
2740	296	slug	0.5415	0.0640	8186	0.0327	577	1423	7.8721	2008.2	2.0082	5.2116

Table A7 Determination of the pressure gradient for the annular and mist flow regime from Wallis's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ PA.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Fanning friction factor, $f_F = \dfrac{16}{\text{Re}}$ for laminar flow (Re < 2000) (A30)

$f_F = 0.079\,\text{Re}^{-1/4}$ for turbulent flow (Re > 4000) (A31)

Pressure gradient for air, $\left(\dfrac{dp}{dz}\right)_{air} = \dfrac{2 f_F \rho_{air} j_{air}}{D}$ (A32)

Pressure gradient for liquid, $\left(\dfrac{dp}{dz}\right)_{liquid} = \dfrac{2 f_F \rho_{liquid} j_{liquid}}{D}$ (A33)

Martinelli parameter, X

from $\left(1+X^{2/3.61}\right)^{3.61}\left(\dfrac{dp}{dz}\right)_{air} - \rho_{air} g = \dfrac{\left(1+X^{2/3.61}\right)^{3.61}}{X^2}\left(\dfrac{dp}{dz}\right)_{liquid} - [\dfrac{1}{(1+0.0904X^{0.548})^{2.82}}\rho_{air} + (1-\dfrac{1}{(1+0.0904X^{0.548})^{2.82}})\rho_{liquid}]g$ (A34)

Void fraction, $\varepsilon = \dfrac{1}{\left(1+0.0904\,X^{0.548}\right)^{2.82}}$ (A35)

Gas two-phase flow multiplier, $\phi_g = \left(1+X^{2/3.61}\right)^{3.61/2}$ (A36)

Pressure gradient for two-phase flow, $\left(\frac{dp}{dz}\right) = \phi_g^2 \left(\frac{dp}{dz}\right)_{air} - \rho_{air} g$ (A37)

Q_{water} (ml/min)	Re_{water}	Q_{air} (L/min)	Re_{air}	Flow regime	f_F of air	f_F of water	$(-dp/dz)_{air}$ (Pa/m)	$(-dp/dz)_{water}$ (Pa/m)	Martinelli parameter (X)	Void fraction (ε)	Φ_g^2	Pressue gradient $(-dp/dz)_{tp}$ (kPa/m)
771	1010	400	28510	Annular	0.0061	0.0158	418	3.4072	0.1574	0.9130	3.0265	1.2764
771	1010	500	35637	Annular	0.0057	0.0158	618	3.4072	0.0998	0.9313	2.4309	1.5128
771	1010	600	42765	Annular	0.0055	0.0158	850	3.4072	0.0765	0.9402	2.1786	1.8627
771	1010	700	49892	Annular	0.0053	0.0158	1113	3.4072	0.0632	0.9459	2.0292	2.2697
771	1010	800	57020	mist	0.0051	0.0158	1406	3.4072	0.0544	0.9501	1.9267	2.7200
771	1010	900	64147	mist	0.0050	0.0158	1728	3.4072	0.0480	0.9533	1.8504	3.2081
771	1010	1000	71275	mist	0.0048	0.0158	2077	3.4072	0.0431	0.9559	1.7905	3.7309
2090	2740	400	28510	Annular	0.0061	0.0058	418	9.2386	0.2511	0.8895	3.9692	1.6704
2090	2740	500	35637	Annular	0.0057	0.0058	618	9.2386	0.1655	0.9107	3.1083	1.9312
2090	2740	600	42765	Annular	0.0055	0.0058	850	9.2386	0.1273	0.9220	2.7186	2.3215
2090	2740	700	49892	Annular	0.0053	0.0058	1113	9.2386	0.1051	0.9294	2.4870	2.7791
2090	2740	800	57020	mist	0.0051	0.0058	1406	9.2386	0.0903	0.9348	2.3292	3.2858
2090	2740	900	64147	mist	0.0050	0.0058	1728	9.2386	0.0796	0.9390	2.2126	3.8338
2090	2740	1000	71275	mist	0.0048	0.0058	2077	9.2386	0.0714	0.9423	2.1219	4.4193

Table A8 Determination of the pressure gradient from experiment for pure water

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m;

cross-sectional area of pipe, A = 0.00028 m^2; pressure taps difference = 0.4 m

Procedure to determine of pressure gradient from experiment:

1. Read the highest and lowest difference level from manometer.
2. Put the value of difference level in $-\frac{dp}{dz} = \frac{\rho_w g(100 - level_{water,L}) - (100 - level_{water,R})}{100x0.4x1000}$ (A38)

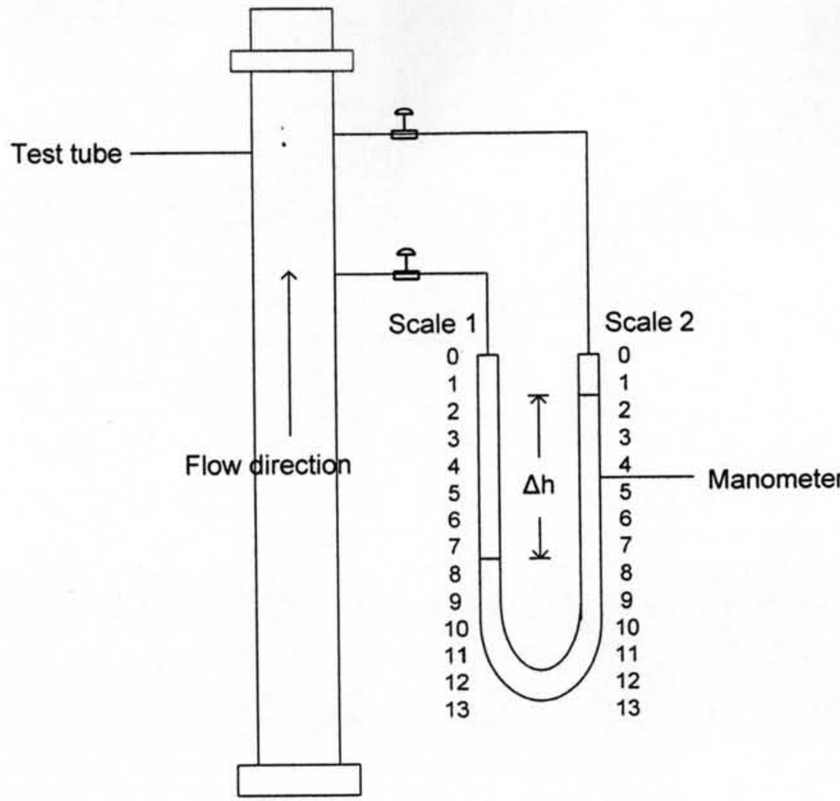


Figure A9 Appearance scale and water level in manometer.

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
0	3.17	Bubble	88.1	88.1	88.1	88.1	88.1	48.2	48.2	48.2	48.2	48.2
0	5.64	Bubble	88.2	88.2	88.2	88.2	88.2	48.4	48.4	48.4	48.4	48.4
0	8.12	Bubble	88	88	88	88	88	48.3	48.3	48.3	48.3	48.3
0	10.59	Bubble-Slug	87.6	87.6	87.6	87.6	87.6	49	49	49	49	49
0	13.07	Bubble-Slug	87.3	87.3	87.3	87.3	87.3	49.5	49.4	49.2	49.2	49.4
0	15.54	Bubble-Slug	87	87	87	87	87	49.2	49.3	49.3	49.3	49.2
0	18.02	Bubble-Slug	86.5	86.5	86.5	86.5	86.5	50	50	50	50	50
0	20.49	Bubble-Slug	86.2	86.2	86.3	86.3	86.3	50.2	50.3	50.2	50.2	50.2
0	22.95	Slug	85.5	85.5	85.5	85.5	85.5	50.8	50.8	50.9	50.9	50.8
0	28.08	Slug	80.6	80.7	80.6	80.6	80.5	45.5	45.3	45.5	45.5	45.6
0	33.21	Slug	80	80	80	80	80	46	46	46	46	46
0	38.33	Slug	79.5	79.5	79.4	79.4	79.5	46.5	46.5	46.6	46.6	46.5
0	43.46	Slug	77	77	76.9	76.9	76.9	44.8	44.7	44.8	44.3	44.5
0	48.59	Slug	76.8	76.8	77	77	77	44.5	44.5	44.2	44.2	44
0	58.85	Slug	76.2	76.2	76.2	76.2	76.2	44.5	44.5	44.5	44.5	44.5
0	69.10	Slug	75	75	75	75	75	45.8	45.5	45.3	44.8	45.3
0	79.36	Slug	74	74	74.5	74	74	44.8	44.3	43.8	44.8	44.2
0	89.62	Slug	73.7	73.7	73.7	73.7	73.7	45	45	45	45	45
0	99.87	Slug	73	73	73	72.8	72	44.8	45	44.5	44.5	44.5
0	177	Slug	67	67	67	67	67	44	44	44	44	44
1010	3.17	Bubble	85.4	85.4	85.4	85.4	85.4	45.8	45.7	45.8	45.7	45.8
1010	5.64	Bubble	85	85	85	85	85	45.5	45.5	45.5	45.5	45.5
1010	8.12	Bubble	84.5	84.5	84.5	84.5	84.5	45.5	45.4	45.4	45.4	45.4
1010	10.59	Bubble	84	84	84	84	84	45.3	45.3	45.3	45.3	45.3
1010	13.07	Bubble	83.9	83.9	83.9	83.9	83.9	45.5	45.5	45.5	45.5	45.5
1010	15.54	Bubble-Slug	83.4	83.5	83.5	83.5	83.5	45.8	45.8	45.9	46	45.8

Re$_{water}$	Re$_{air}$	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
1010	18.02	Bubble-Slug	82.9	83	83	83	83	46.5	46.4	46.4	46.1	46.1
1010	20.49	Bubble-Slug	82.6	82.6	82.7	82.6	82.7	46.5	46.6	46.4	46.8	46.5
1010	22.95	Bubble-Slug	82.5	82.5	82.4	82.4	82.5	46.9	46.7	46.8	47	46.7
1010	28.08	Bubble-Slug	82.5	82.2	82.3	82.3	82.3	47	47.1	47.2	47.1	47.1
1010	33.21	Slug	81.8	81.8	81.8	81.7	81.7	47.3	47.4	47.3	47.5	47.5
1010	38.33	Slug	81.5	81.5	81.4	81.3	81.5	47.8	47.8	47.9	47.9	47.8
1010	43.46	Slug	81	81	80.9	80.8	80.8	48	48.1	48.3	48.3	48.2
1010	48.59	Slug	80.8	80.8	80.8	80.8	80.7	48.1	48.3	48.5	48.5	48.6
1010	58.85	Slug	80.4	80.4	80.3	80.1	80.1	49	49.2	49.3	49	49.4
1010	69.10	Slug	79.9	79.7	79.7	79.7	80	49.5	49.7	49.8	49.7	49.6
1010	79.36	Slug	79.6	79.8	79.8	79.8	79.6	49.8	50	49.8	49.5	50
1010	89.62	Slug	79.5	79.5	80	79.7	79	50	49.9	49.8	49.9	50.2
1010	99.87	Slug	74.4	74.3	74	74.3	74.3	47.9	47.7	47.2	47.5	47.5
1010	177	Slug	71.8	71.8	71.5	71.5	71.5	48	48.1	48.5	48	48.5
1010	296	Slug-Churn	59.5	60.5	59.5	60.5	60	40.8	40	40.8	39.5	40
1010	369	Slug-Churn	50.5	50.3	50.5	50	49.5	31.5	31.3	31.4	31.5	30.8
1010	515	Slug-Churn	44.5	44	43.5	43	39.8	29.5	30	28.7	28.2	23
1010	735	Slug-Churn	32	30	30	28	28	16	16	15.8	15	14.8
1010	1454	Churn	61	61	59.5	59	58.8	51	50.8	49.5	49	49
1010	2474	Churn	57.8	57.5	57.8	57.8	57.5	48.9	49	48.8	49	49.3
1010	3495	Churn	56.5	56.8	56.8	56.8	56.3	49.2	49.1	49.2	49.8	49.3
1010	4516	Churn	56	56	56	56	56	50	50.1	50.2	50.2	50.1
1010	5537	Churn	56.6	56.7	56.7	56.7	56.8	50.5	50.4	50.3	50.4	50.2
1010	14255	Churn	55.2	55.2	55.2	55.2	55.2	51.4	51.3	51.3	51.3	51.3
1010	21382	Churn	55.7	55.7	55.7	55.7	55.7	51.2	51.2	51.2	51.2	51.2
1010	28510	Annular	56.3	56.3	56.3	56.3	56.3	50.6	50.6	50.6	50.6	50.6

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
1010	35637	Annular	57	57	57	57	57	49.9	49.9	49.9	49.9	49.9
1010	42765	Annular	54.7	54.7	54.7	54.7	54.7	44.3	44.3	44.3	44.3	44.3
1010	49892	Annular	56.2	56.2	56.2	56.2	56.2	42.6	42.6	42.6	42.6	42.6
1010	57020	Mist	53.5	53.5	53.5	53.5	53.5	38.4	38.4	38.4	38.4	38.4
1010	64147	Mist	54	54	54	54	54	36.6	36.6	36.6	36.6	36.6
1010	71275	Mist	56.5	56.5	56.5	56.5	56.5	38.3	38.3	38.3	38.3	38.3
2740	3.17	Bubble	85.5	85.5	85.5	85.5	85.5	45.6	45.6	45.6	45.6	45.6
2740	5.64	Bubble	85.4	85.4	85.4	85.4	85.4	45.5	45.5	45.5	45.5	45.5
2740	8.12	Bubble	85.4	85.4	85.4	85.4	85.4	45.5	45.5	45.5	45.5	45.5
2740	10.59	Bubble	85.4	85.4	85.4	85.4	85.4	45.6	45.6	45.6	45.6	45.6
2740	13.07	Bubble	85.1	85.1	85.1	85.1	85.1	45.6	45.6	45.6	45.6	45.6
2740	15.54	Bubble	85	84.9	84.9	84.9	84.9	45.8	45.8	45.9	45.9	45.9
2740	18.02	Bubble	84.8	84.8	84.8	84.8	84.8	46.1	46.1	46.1	46.1	46.1
2740	20.49	Bubble	84.6	84.5	84.5	84.5	84.5	46.1	46.4	46.1	46.2	46.1
2740	22.95	Bubble	84.3	84.3	84.4	84.5	84.4	46.6	46.5	46.4	46.5	46.6
2740	28.08	Bubble	83.9	84	84	83.9	84	47	46.8	47	47	47
2740	33.21	Bubble	83.5	83.6	83.5	83.5	83.5	47.4	47.1	47.3	47.3	47.3
2740	38.33	Bubble-Slug	83.4	83.5	83.5	83.5	83.5	47.1	47.5	47.5	47.4	47.6
2740	43.46	Bubble-Slug	83.2	83.2	83.3	83.3	83.3	47.7	47.8	47.8	47.6	47.6
2740	48.59	Slug	82.6	82.5	82.5	82.6	82.6	47.9	48	48	47.9	48
2740	58.85	Slug	82.3	82.5	82.4	82.4	82.4	48.1	48.3	48.2	48.1	48.4
2740	69.10	Slug	82	82	82.3	82	82	48.8	49	48.6	48.8	48.8
2740	79.36	Slug	81.6	81.6	81.6	81.6	81.7	49.2	49.1	49.1	49.2	49.2
2740	89.62	Slug	81.5	81.6	81.5	81.5	81.4	49.5	49.3	49.1	49.5	49.4
2740	99.87	Slug	81	81.5	81.5	81.6	81.5	49.2	49.4	49.5	49.4	49.5
2740	177	Slug	64	64	64.5	64.2	64	37.2	37.2	38	37	37

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2740	296	Slug	67	66.5	66	66	66.5	43.5	44.5	44	44	43.5
2740	369	Slug-Churn	62	61.5	61.5	61.5	61.5	42	41	41	41	41
2740	515	Slug-Churn	58	57	57.5	57.5	57.5	40	39	39	39	39
2740	735	Slug-Churn	54.5	54	54	54	54.5	39	39	39.2	38.5	38
2740	1454	Slug-Churn	60.5	58.5	58.5	58	58	45.5	47	46.5	46.5	45.8
2740	2474	Churn	51.5	52.5	51	51	51	40.5	40	40.5	40	39.8
2740	3495	Churn	50	50	50	50	50	40	40	40	40	40
2740	4516	Churn	49.5	49.5	49.5	49.5	49.5	40.2	40.2	40.2	40.2	40.2
2740	5537	Churn	57	56	56	56	56	45.2	44.5	44.5	44.5	44.5
2740	14255	Churn	54.4	54.4	54.4	54.4	54.4	45.2	45.2	45.2	45.2	45.2
2740	21382	Churn	54.7	54.7	54.7	54.7	54.7	44.6	44.6	44.6	44.6	44.6
2740	28510	Annular	53	53	53	53	53	39.6	39.6	39.6	39.6	39.6
2740	35637	Annular	52	52	52	52	52	35	35	35	35	35
2740	42765	Annular	50.6	50.6	50.6	50.6	50.6	30.8	30.8	30.8	30.8	30.8
2740	49892	Annular	47.6	47.6	47.6	47.6	47.6	25.8	25.8	25.8	25.8	25.8
2740	57020	Mist	46.2	46.2	46.2	46.2	46.2	21.8	21.8	21.8	21.8	21.8
2740	64147	Mist	46.8	46.8	46.8	46.8	46.8	18.8	18.8	18.8	18.8	18.8
2740	71275	Mist	46.8	46.8	46.8	46.8	46.8	16.5	16.5	16.5	16.5	16.5

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
0	3.17	Bubble	88.5	88.5	88.5	88.5	88.5	48.6	48.6	48.6	48.6	48.6
0	5.64	Bubble	88.3	88.3	88.3	88.3	88.3	48.5	48.5	48.5	48.5	48.5
0	8.12	Bubble	88	88	88	88	88	48.6	48.6	48.6	48.6	48.6
0	10.59	Bubble-Slug	87	87	87	87	87	49.5	49.5	49.5	49.5	49.5
0	13.07	Bubble-Slug	86.5	86.7	86.7	86.7	86.7	50	49.8	49.7	49.8	49.7
0	15.54	Bubble-Slug	86	86	86	86	86	50.2	50.2	50.2	50.3	50.3
0	18.02	Bubble-Slug	85.8	85.8	85.8	85.8	85.8	50.6	50.5	50.5	50.5	50.5
0	20.49	Bubble-Slug	85.6	85.6	85.5	85.5	85.5	51	51	51.1	51	51
0	22.95	Slug	84.6	84.6	84.5	84.6	84.6	51.8	52	51.8	52	52
0	28.08	Slug	78.8	79	79	79	79	47.2	47	47	47	47
0	33.21	Slug	78	78	78.1	78.1	78.1	47.5	47.4	47.5	47.4	47.4
0	38.33	Slug	77.9	77.9	77.8	77.9	77.8	47.7	47.6	47.6	47.6	47.7
0	43.46	Slug	75.3	75	75	75	75	46	46.3	46.5	46.8	46.3
0	48.59	Slug	74.8	75	75	74.8	74.8	46.5	46.2	46.2	46	46.3
0	58.85	Slug	73.8	73.5	73	73	73.2	46.5	47	47	46.8	46.8
0	69.10	Slug	72.3	72.3	72.3	72.3	72.3	46.8	47	47	46.8	47
0	79.36	Slug	71.5	71	71	71	71	47	48	47.5	47	47
0	89.62	Slug	70.8	71	71	70.8	70.8	47	47	47	47	47
0	99.87	Slug	69.5	69	69.5	69.5	69	47.5	48.5	47	47	48
0	177	Slug	62	62	62	62	62	47.5	47.5	47.5	47.5	47.5
1010	3.17	Bubble	85.4	85.4	85.4	85.4	85.4	45.7	45.8	45.7	45.7	45.7
1010	5.64	Bubble	85	85	85	85	85	45.6	45.8	45.8	45.8	45.8
1010	8.12	Bubble	84.5	84.5	84.5	84.5	84.5	45.8	45.7	45.8	45.8	45.8
1010	10.59	Bubble	83.6	83.6	83.6	83.6	83.6	45.8	45.9	45.9	45.8	45.9
1010	13.07	Bubble	83.5	83.5	83.5	83.5	83.5	45.8	45.8	45.8	45.9	45.9
1010	15.54	Bubble-Slug	83.2	83.1	83.1	83.1	83.1	46	46.1	46.1	46	46

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
1010	18.02	Bubble-Slug	82.6	82.6	82.6	82.7	82.5	46.4	46.5	46.6	46.4	46.5
1010	20.49	Bubble-Slug	82.3	81.8	82	82	82	46.9	47	47	47.1	47
1010	22.95	Bubble-Slug	81.8	81.8	81.7	81.6	81.6	47.2	47.2	47.3	47.5	47.3
1010	28.08	Bubble-Slug	81.5	81.2	81	81.4	81.3	47.4	47.8	48	47.8	47.9
1010	33.21	Slug	81.1	81	81	79.9	81	47.9	48	48	48.1	48
1010	38.33	Slug	80.5	80.5	80.3	80.3	80.2	48.6	48.5	48.7	48.6	48.8
1010	43.46	Slug	80	80.1	80.1	80	80.1	49	48.8	48.9	49	49
1010	48.59	Slug	80	80.2	79.9	79.9	80	49	48.8	49	49.1	49.1
1010	58.85	Slug	79.2	79.2	79.3	79	79.3	49.8	49.8	49.7	50	49.8
1010	69.10	Slug	78.8	78.7	77	79	78.5	50.5	50.3	51	50	50
1010	79.36	Slug	78.5	78.5	78	78.3	78.2	50.3	50.2	50.8	50.3	50.6
1010	89.62	Slug	77.8	77.5	77.8	77.2	77.5	51	51.5	51.3	51.3	51.2
1010	99.87	Slug	72.2	72.5	72.5	72.5	71.8	48.2	48	48.5	48.6	48.8
1010	177	Slug	69.2	69.2	69.3	69.3	69	49.8	49.5	49	49.8	49.8
1010	296	Slug-Churn	55	54.5	54.5	52	53	42.5	42	41.8	43.3	41.8
1010	369	Slug-Churn	44.5	44.8	45	45	45	34	33.5	33	34.2	33.9
1010	515	Slug-Churn	34.5	33	34.5	32	32	26.8	25.5	25.5	25.3	26
1010	735	Slug-Churn	23	23	22.8	22	22.2	19	18.5	19.5	18.8	19
1010	1454	Churn	56	56	56	56	57	52.5	52	51	51.5	50
1010	2474	Churn	56.3	56	56	56	56.2	49.8	50	50.5	50.3	49.8
1010	3495	Churn	55.8	56.2	56	56	56	49.8	50	50	50.3	50.2
1010	4516	Churn	55.5	55.5	55.5	55.5	55.5	50.5	50.5	50.5	50.5	50.4
1010	5537	Churn	56.2	56.4	56.2	56.3	56.3	50.8	50.8	50.4	50.2	50.2
1010	14255	Churn	54.8	54.7	54.8	54.7	54.7	51.6	51.7	51.7	51.6	51.6
1010	21382	Churn	55.5	55.5	55.5	55.5	55.5	51.4	51.4	51.4	51.4	51.4
1010	28510	Annular	56.2	56.2	56.2	56.2	56.2	50.6	50.6	50.6	50.6	50.6
1010	35637	Annular	57	57	57	57	57	50.1	50.1	50.1	50.1	50.1

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
1010	42765	Annular	54.6	54.6	54.6	54.6	54.6	44.4	44.4	44.4	44.4	44.4
1010	49892	Annular	56.1	56.1	56.1	56.1	56.1	42.7	42.7	42.7	42.7	42.7
1010	57020	Mist	53.3	53.3	53.3	53.3	53.3	38.5	38.5	38.5	38.5	38.5
1010	64147	Mist	54	54	54	54	54	36.6	36.6	36.6	36.6	36.6
1010	71275	Mist	56.5	56.5	56.5	56.5	56.5	38.3	38.3	38.3	38.3	38.3
2740	3.17	Bubble	85.5	85.5	85.5	85.5	85.5	45.6	45.6	45.6	45.6	45.6
2740	5.64	Bubble	85.4	85.4	85.4	85.4	85.4	45.5	45.5	45.5	45.5	45.5
2740	8.12	Bubble	85.3	85.3	85.3	85.3	85.3	45.5	45.5	45.5	45.5	45.5
2740	10.59	Bubble	85	85	85	85	85	45.7	45.7	45.7	45.7	45.7
2740	13.07	Bubble	84.8	84.8	84.8	84.8	84.8	45.8	45.8	45.8	45.8	45.8
2740	15.54	Bubble	84.5	84.6	84.6	84.6	84.6	46	45.9	46	45.9	46
2740	18.02	Bubble	84.5	84.5	84.5	84.5	84.5	46.2	46.3	46.3	46.3	46.3
2740	20.49	Bubble	84.1	84.2	84.2	84.2	84.1	46.7	46.7	46.6	46.6	46.6
2740	22.95	Bubble	83.8	83.8	83.7	83.7	83.8	47.1	47.2	47.3	47.1	47.1
2740	28.08	Bubble	83.5	83.5	83.5	83.5	83.5	47.2	47.3	47.2	47.3	47.3
2740	33.21	Bubble	83.2	83.2	83.2	83.3	83.3	47.6	47.6	47.6	47.6	47.6
2740	38.33	Bubble-Slug	82.8	82.8	82.8	82.6	82.8	48	47.8	48	48	47.9
2740	43.46	Bubble-Slug	82.5	82.5	82.5	82.4	82.5	48.3	48.3	48.4	48.1	48.3
2740	48.59	Slug	82	82	81.8	81.8	81.8	49	48.5	48.5	48.6	48.4
2740	58.85	Slug	81.3	81.3	81.4	81.3	81.2	49.2	49.8	49.5	49.2	49.2
2740	69.10	Slug	81	81.1	81.3	81.2	81.2	50	49.8	49.7	49.8	49.8
2740	79.36	Slug	80.8	80.8	80.7	80.7	80.7	50	50	50.2	50.1	50.1
2740	89.62	Slug	80.4	80.2	80.3	80.3	80.1	50.3	50.7	50.5	50.2	50.7
2740	99.87	Slug	80	80.1	80.1	80.1	79.8	50.6	50.6	50.6	51	51
2740	177	Slug	61.8	62	62	62	62	38.8	39.1	39.1	39	39
2740	296	Slug	63.5	62.8	62.5	62.8	61	45.8	46.5	47	46.5	46.8
2740	369	Slug-Churn	60	59	59.5	59	59	46.5	46.5	45.5	45	44

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2740	515	Slug-Churn	53	53	53	52	53	42	42	41.5	42	43
2740	735	Slug-Churn	51.5	51	50	49.8	50	40	40.8	41	41	40
2740	1454	Slug-Churn	55.5	55.5	54	57	54	47.8	48	47	47.2	46.5
2740	2474	Churn	53.5	53	52	52	51.5	45.2	44.5	45.5	44.5	43
2740	3495	Churn	48.2	48.5	49	49	49	42	40.5	40.8	40.8	40.8
2740	4516	Churn	48.8	48.8	48.8	48.8	48.8	41	41	41	41	41
2740	5537	Churn	54.3	54	54	54	54	45	45.2	45.2	45.3	45.5
2740	14255	Churn	53.8	53.7	53.7	53.7	53.7	45.5	45.6	45.6	45.6	45.6
2740	21382	Churn	54.5	54.5	54.5	54.5	54.5	44.8	44.8	44.8	44.8	44.8
2740	28510	Annular	52.9	52.9	52.9	52.9	52.9	39.7	39.7	39.7	39.7	39.7
2740	35637	Annular	51.9	51.9	51.9	51.9	51.9	35	35	35	35	35
2740	42765	Annular	50.5	50.5	50.5	50.5	50.5	30.9	30.9	30.9	30.9	30.9
2740	49892	Annular	47.3	47.3	47.3	47.3	47.3	25.6	25.6	25.6	25.6	25.6
2740	57020	Mist	46.2	46.2	46.2	46.2	46.2	21.8	21.8	21.8	21.8	21.8
2740	64147	Mist	46.8	46.8	46.8	46.8	46.8	18.8	18.8	18.8	18.8	18.8
2740	71275	Mist	46.8	46.8	46.8	46.8	46.8	16.5	16.5	16.5	16.5	16.5

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
0	3.17	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	5.64	Bubble	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121 ± 0.00
0	8.12	Bubble	9.6877	9.6877	9.6877	9.6877	9.6877	9.2729	9.2729	9.2729	9.2729	9.2729	9.4803 ± 0.22
0	10.59	Bubble-Slug	9.4193	9.4193	9.4193	9.4193	9.4193	9.1509	9.1509	9.1509	9.1509	9.1509	9.2851 ± 0.14
0	13.07	Bubble-Slug	9.2241	9.2485	9.2973	9.2973	9.2485	8.9069	9.0045	9.0289	9.0045	9.0289	9.1289 ± 0.15
0	15.54	Bubble-Slug	9.2241	9.1997	9.1997	9.1997	9.2241	8.7361	8.7361	8.7361	8.7116	8.7116	8.9679 ± 0.25
0	18.02	Bubble-Slug	8.9069	8.9069	8.9069	8.9069	8.9069	8.5896	8.6140	8.6140	8.6140	8.6140	8.7580 ± 0.16
0	20.49	Bubble-Slug	8.7849	8.7605	8.8093	8.8093	8.8093	8.4432	8.4432	8.3944	8.4188	8.4188	8.6092 ± 0.20
0	22.95	Slug	8.4676	8.4676	8.4432	8.4432	8.4676	8.0040	7.9552	7.9796	7.9552	7.9552	8.2138 ± 0.26
0	28.08	Slug	8.5652	8.6384	8.5652	8.5652	8.5164	7.7112	7.8088	7.8088	7.8088	7.8088	8.1797 ± 0.41
0	33.21	Slug	8.2968	8.2968	8.2968	8.2968	8.2968	7.4427	7.4671	7.4671	7.4915	7.4915	7.8844 ± 0.43
0	38.33	Slug	8.0528	8.0528	8.0040	8.0040	8.0528	7.3695	7.3939	7.3695	7.3939	7.3451	7.7038 ± 0.35
0	43.46	Slug	7.8576	7.8820	7.8332	7.9552	7.9064	7.1499	7.0035	6.9547	6.8815	7.0035	7.4427 ± 0.47
0	48.59	Slug	7.8820	7.8820	8.0040	8.0040	8.0528	6.9059	7.0279	7.0279	7.0279	6.9547	7.4769 ± 0.52
0	58.85	Slug	7.7356	7.7356	7.7356	7.7356	7.7356	6.6618	6.4666	6.3446	6.3934	6.4422	7.0987 ± 0.68
0	69.10	Slug	7.1255	7.1987	7.2475	7.3695	7.2475	6.2226	6.1738	6.1738	6.2226	6.1738	6.7155 ± 0.55
0	79.36	Slug	7.1255	7.2475	7.4915	7.1255	7.2719	5.9786	5.6125	5.7346	5.8566	5.8566	6.5301 ± 0.77
0	89.62	Slug	7.0035	7.0035	7.0035	7.0035	7.0035	5.8078	5.8566	5.8566	5.8078	5.8078	6.4154 ± 0.62
0	99.87	Slug	6.8815	6.8327	6.9547	6.9059	6.7107	5.3685	5.0025	5.4905	5.4905	5.1245	6.0762 ± 0.84
0	177	Slug	5.6125	5.6125	5.6125	5.6125	5.6125	3.5383	3.5383	3.5383	3.5383	3.5383	4.5754 ± 1.09
1010	3.17	Bubble	9.6633	9.6877	9.6633	9.6877	9.6633	9.6877	9.6633	9.6877	9.6877	9.6877	9.6780 ± 0.01
1010	5.64	Bubble	9.6389	9.6389	9.6389	9.6389	9.6389	9.6145	9.5657	9.5657	9.5657	9.5657	9.6072 ± 0.04
1010	8.12	Bubble	9.5169	9.5413	9.5413	9.5413	9.5413	9.4437	9.4681	9.4437	9.4437	9.4437	9.4925 ± 0.05
1010	10.59	Bubble	9.4437	9.4437	9.4437	9.4437	9.4437	9.2241	9.1997	9.1997	9.2241	9.1997	9.3266 ± 0.12
1010	13.07	Bubble	9.3705	9.3705	9.3705	9.3705	9.3705	9.1997	9.1997	9.1997	9.1753	9.1753	9.2802 ± 0.10
1010	15.54	Bubble-Slug	9.1753	9.1997	9.1753	9.1509	9.1997	9.0777	9.0289	9.0289	9.0533	9.0533	9.1143 ± 0.07

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
1010	18.02	Bubble-Slug	8.8825	8.9313	8.9313	9.0045	9.0045	8.8337	8.8093	8.7849	8.8581	8.7849	8.8825 ± 0.08
1010	20.49	Bubble-Slug	8.8093	8.7849	8.8581	8.7361	8.8337	8.6384	8.4920	8.5408	8.5164	8.5408	8.6750 ± 0.14
1010	22.95	Bubble-Slug	8.6872	8.7361	8.6872	8.6384	8.7361	8.4432	8.4432	8.3944	8.3212	8.3700	8.5457 ± 0.17
1010	28.08	Bubble-Slug	8.6628	8.5652	8.5652	8.5896	8.5896	8.3212	8.1504	8.0528	8.1992	8.1504	8.3847 ± 0.23
1010	33.21	Slug	8.4188	8.3944	8.4188	8.3456	8.3456	8.1016	8.0528	8.0528	7.7600	8.0528	8.1943 ± 0.22
1010	38.33	Slug	8.2236	8.2236	8.1748	8.1504	8.2236	7.7844	7.8088	7.7112	7.7356	7.6623	7.9698 ± 0.25
1010	43.46	Slug	8.0528	8.0284	7.9552	7.9308	7.9552	7.5647	7.6379	7.6135	7.5647	7.5891	7.7892 ± 0.21
1010	48.59	Slug	7.9796	7.9308	7.8820	7.8820	7.8332	7.5647	7.6623	7.5403	7.5159	7.5403	7.7331 ± 0.19
1010	58.85	Slug	7.6623	7.6135	7.5647	7.5891	7.4915	7.1743	7.1743	7.2231	7.0767	7.1987	7.3768 ± 0.23
1010	69.10	Slug	7.4183	7.3207	7.2963	7.3207	7.4183	6.9059	6.9303	6.3446	7.0767	6.9547	7.0987 ± 0.33
1010	79.36	Slug	7.2719	7.2719	7.3207	7.3939	7.2231	6.8815	6.9059	6.6374	6.8327	6.7351	7.0474 ± 0.28
1010	89.62	Slug	7.1987	7.2231	7.3695	7.2719	7.0279	6.5398	6.3446	6.4666	6.3202	6.4178	6.8180 ± 0.43
1010	99.87	Slug	6.4666	6.4910	6.5398	6.5398	6.5398	5.8566	5.9786	5.8566	5.8322	5.6125	6.1714 ± 0.37
1010	177	Slug	5.8078	5.7834	5.6125	5.7346	5.6125	4.7341	4.8073	4.9537	4.7585	4.6853	5.2490 ± 0.49
1010	296	Slug-Churn	4.5632	5.0025	4.5632	5.1245	4.8805	3.0503	3.0503	3.0991	2.1230	2.7331	3.8190 ± 1.11
1010	369	Slug-Churn	4.6365	4.6365	4.6609	4.5144	4.5632	2.5622	2.7575	2.9283	2.6355	2.7087	3.6604 ± 1.00
1010	515	Slug-Churn	3.6604	3.4163	3.6116	3.6116	4.0996	1.8790	1.8302	2.1962	1.6350	1.4641	2.7404 ± 1.02
1010	735	Slug-Churn	3.9044	3.4163	3.4651	3.1723	3.2211	0.9761	1.0981	0.8053	0.7809	0.7809	2.1621 ± 1.36
1010	1454	Churn	2.4402	2.4890	2.4402	2.4402	2.3914	0.8541	0.9761	1.2201	1.0981	1.7082	1.8058 ± 0.70
1010	2474	Churn	2.1718	2.0742	2.1962	2.1474	2.0010	1.5862	1.4641	1.3421	1.3909	1.5618	1.7936 ± 0.35
1010	3495	Churn	1.7814	1.8790	1.8546	1.7082	1.7082	1.4641	1.5129	1.4641	1.3909	1.4153	1.6179 ± 0.19
1010	4516	Churn	1.4641	1.4397	1.4153	1.4153	1.4397	1.2201	1.2201	1.2201	1.2201	1.2445	1.3299 ± 0.11
1010	5537	Churn	1.4885	1.5373	1.5618	1.5373	1.6106	1.3177	1.3665	1.4153	1.4885	1.4885	1.4812 ± 0.09
1010	14255	Churn	0.9273	0.9517	0.9517	0.9517	0.9517	0.7809	0.7321	0.7565	0.7565	0.7565	0.8516 ± 0.10
1010	21382	Churn	1.0981	1.0981	1.0981	1.0981	1.0981	1.0005	1.0005	1.0005	1.0005	1.0005	1.0493 ± 0.05
1010	28510	Annular	1.3909	1.3909	1.3909	1.3909	1.3909	1.3665	1.3665	1.3665	1.3665	1.3665	1.3787 ± 0.01
1010	35637	Annular	1.7326	1.7326	1.7326	1.7326	1.7326	1.6838	1.6838	1.6838	1.6838	1.6838	1.7082 ± 0.03

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
1010	42765	Annular	2.5378	2.5378	2.5378	2.5378	2.5378	2.4890	2.4890	2.4890	2.4890	2.4890	2.5134 ± 0.03
1010	49892	Annular	3.3187	3.3187	3.3187	3.3187	3.3187	3.2699	3.2699	3.2699	3.2699	3.2699	3.2943 ± 0.03
1010	57020	Mist	3.6848	3.6848	3.6848	3.6848	3.6848	3.6116	3.6116	3.6116	3.6116	3.6116	3.6482 ± 0.04
1010	64147	Mist	4.2460	4.2460	4.2460	4.2460	4.2460	4.2460	4.2460	4.2460	4.2460	4.2460	4.2460 ± 0.00
1010	71275	Mist	4.4412	4.4412	4.4412	4.4412	4.4412	4.4412	4.4412	4.4412	4.4412	4.4412	4.4412 ± 0.00
2740	3.17	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
2740	5.64	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
2740	8.12	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7121	9.7121	9.7121	9.7121	9.7121	9.7243 ± 0.01
2740	10.59	Bubble	9.7121	9.7121	9.7121	9.7121	9.7121	9.5901	9.5901	9.5901	9.5901	9.5901	9.6511 ± 0.06
2740	13.07	Bubble	9.6389	9.6389	9.6389	9.6389	9.6389	9.5169	9.5169	9.5169	9.5169	9.5169	9.5779 ± 0.06
2740	15.54	Bubble	9.5657	9.5413	9.5169	9.5169	9.5169	9.3949	9.4437	9.4193	9.4437	9.4193	9.4779 ± 0.06
2740	18.02	Bubble	9.4437	9.4437	9.4437	9.4437	9.4437	9.3461	9.3217	9.3217	9.3217	9.3217	9.3852 ± 0.06
2740	20.49	Bubble	9.3949	9.2973	9.3705	9.3461	9.3705	9.1265	9.1509	9.1753	9.1753	9.1509	9.2558 ± 0.11
2740	22.95	Bubble	9.1997	9.2241	9.2729	9.2729	9.2241	8.9557	8.9313	8.8825	8.9313	8.9557	9.0850 ± 0.16
2740	28.08	Bubble	9.0045	9.0777	9.0289	9.0045	9.0289	8.8581	8.8337	8.8581	8.8337	8.8337	8.9361 ± 0.10
2740	33.21	Bubble	8.8093	8.9069	8.8337	8.8337	8.8337	8.6872	8.6872	8.6872	8.7116	8.7116	8.7702 ± 0.08
2740	38.33	Bubble-Slug	8.8581	8.7849	8.7849	8.8093	8.7605	8.4920	8.5408	8.4920	8.4432	8.5164	8.6482 ± 0.16
2740	43.46	Bubble-Slug	8.6628	8.6384	8.6628	8.7116	8.7116	8.3456	8.3456	8.3212	8.3700	8.3456	8.5115 ± 0.18
2740	48.59	Slug	8.4676	8.4188	8.4188	8.4676	8.4432	8.0528	8.1748	8.1260	8.1016	8.1504	8.2822 ± 0.17
2740	58.85	Slug	8.3456	8.3456	8.3456	8.3700	8.2968	7.8332	7.6867	7.7844	7.8332	7.8088	8.0650 ± 0.29
2740	69.10	Slug	8.1016	8.0528	8.2236	8.1016	8.1016	7.5647	7.6379	7.7112	7.6623	7.6623	7.8820 ± 0.25
2740	79.36	Slug	7.9064	7.9308	7.9308	7.9064	7.9308	7.5159	7.5159	7.4427	7.4671	7.4671	7.7014 ± 0.23
2740	89.62	Slug	7.8088	7.8820	7.9064	7.8088	7.8088	7.3451	7.1987	7.2719	7.3451	7.1743	7.5550 ± 0.31
2740	99.87	Slug	7.7600	7.8332	7.8088	7.8576	7.8088	7.1743	7.1987	7.1987	7.1011	7.0279	7.4769 ± 0.36
2740	177	Slug	6.5398	6.5398	6.4666	6.6374	6.5886	5.6125	5.5881	5.5881	5.6125	5.6125	6.0786 ± 0.50
2740	296	Slug	5.7346	5.3685	5.3685	5.3685	5.6125	4.3192	3.9776	3.7824	3.9776	3.4651	4.6975 ± 0.87
2740	369	Slug-Churn	4.8805	5.0025	5.0025	5.0025	5.0025	3.2943	3.0503	3.4163	3.4163	3.6604	4.1728 ± 0.86

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2740	515	Slug-Churn	4.3924	4.3924	4.5144	4.5144	4.5144	2.6843	2.6843	2.8063	2.4402	2.4402	3.5383 ± 0.98
2740	735	Slug-Churn	3.7824	3.6604	3.6116	3.7824	4.0264	2.8063	2.4890	2.1962	2.1474	2.4402	3.0942 ± 0.74
2740	1454	Slug-Churn	3.6604	2.8063	2.9283	2.8063	2.9771	1.8790	1.8302	1.7082	2.3914	1.8302	2.4817 ± 0.66
2740	2474	Churn	2.6843	3.0503	2.5622	2.6843	2.7331	2.0254	2.0742	1.5862	1.8302	2.0742	2.3304 ± 0.47
2740	3495	Churn	2.4402	2.4402	2.4402	2.4402	2.4402	1.5129	1.9522	2.0010	2.0010	2.0010	2.1669 ± 0.32
2740	4516	Churn	2.2694	2.2694	2.2694	2.2694	2.2694	1.9034	1.9034	1.9034	1.9034	1.9034	2.0864 ± 0.19
2740	5537	Churn	2.8795	2.8063	2.8063	2.8063	2.8063	2.2694	2.1474	2.1474	2.1230	2.0742	2.4866 ± 0.36
2740	14255	Churn	2.2450	2.2450	2.2450	2.2450	2.2450	2.0254	1.9766	1.9766	1.9766	1.9766	2.1157 ± 0.14
2740	21382	Churn	2.4646	2.4646	2.4646	2.4646	2.4646	2.3670	2.3670	2.3670	2.3670	2.3670	2.4158 ± 0.05
2740	28510	Annular	3.2699	3.2699	3.2699	3.2699	3.2699	3.2211	3.2211	3.2211	3.2211	3.2211	3.2455 ± 0.03
2740	35637	Annular	4.1484	4.1484	4.1484	4.1484	4.1484	4.1240	4.1240	4.1240	4.1240	4.1240	4.1362 ± 0.01
2740	42765	Annular	4.8317	4.8317	4.8317	4.8317	4.8317	4.7829	4.7829	4.7829	4.7829	4.7829	4.8073 ± 0.03
2740	49892	Annular	5.3197	5.3197	5.3197	5.3197	5.3197	5.2953	5.2953	5.2953	5.2953	5.2953	5.3075 ± 0.01
2740	57020	Mist	5.9542	5.9542	5.9542	5.9542	5.9542	5.9542	5.9542	5.9542	5.9542	5.9542	5.9542 ± 0.00
2740	64147	Mist	6.8327	6.8327	6.8327	6.8327	6.8327	6.8327	6.8327	6.8327	6.8327	6.8327	6.8327 ± 0.00
2740	71275	Mist	7.3939	7.3939	7.3939	7.3939	7.3939	7.3939	7.3939	7.3939	7.3939	7.3939	7.3939 ± 0.00

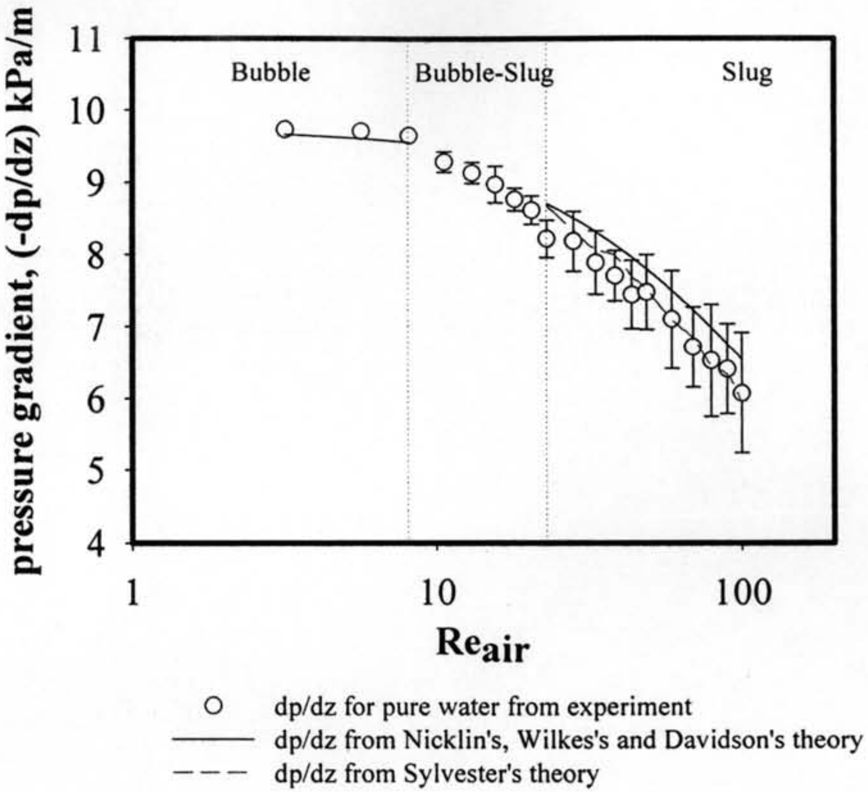
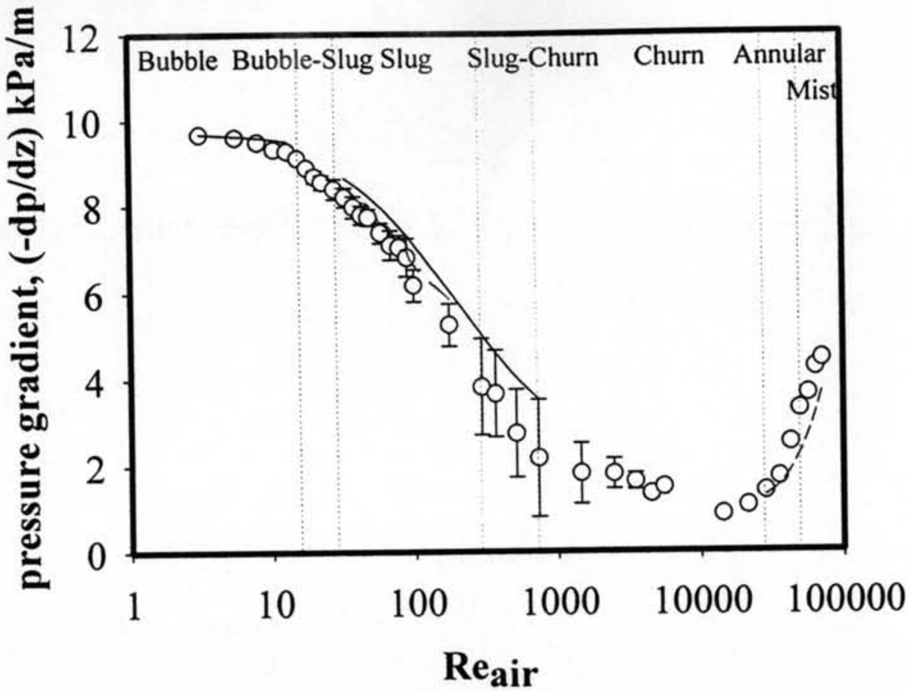


Figure A10 Comparison between Nicklin's theory, Sylvester's theory and experimental pressure gradient vs. air Reynolds number of pure water at $Re_{water} = 0$ by using pipe diameter 19 mm.



○ dp/dz for pure water from experiment

——— dp/dz from Nicklin's, Wilkes's and Davidson's theory

— — — dp/dz from Sylvester's theory

------ dp/dz from Wallis's theory

Figure A11 Comparison between Nicklin's theory, Sylvester's theory, Wallis's theory and experimental pressure gradient vs. air Reynolds number of pure water at Re_{water} = 1010 by using pipe diameter 19 mm.

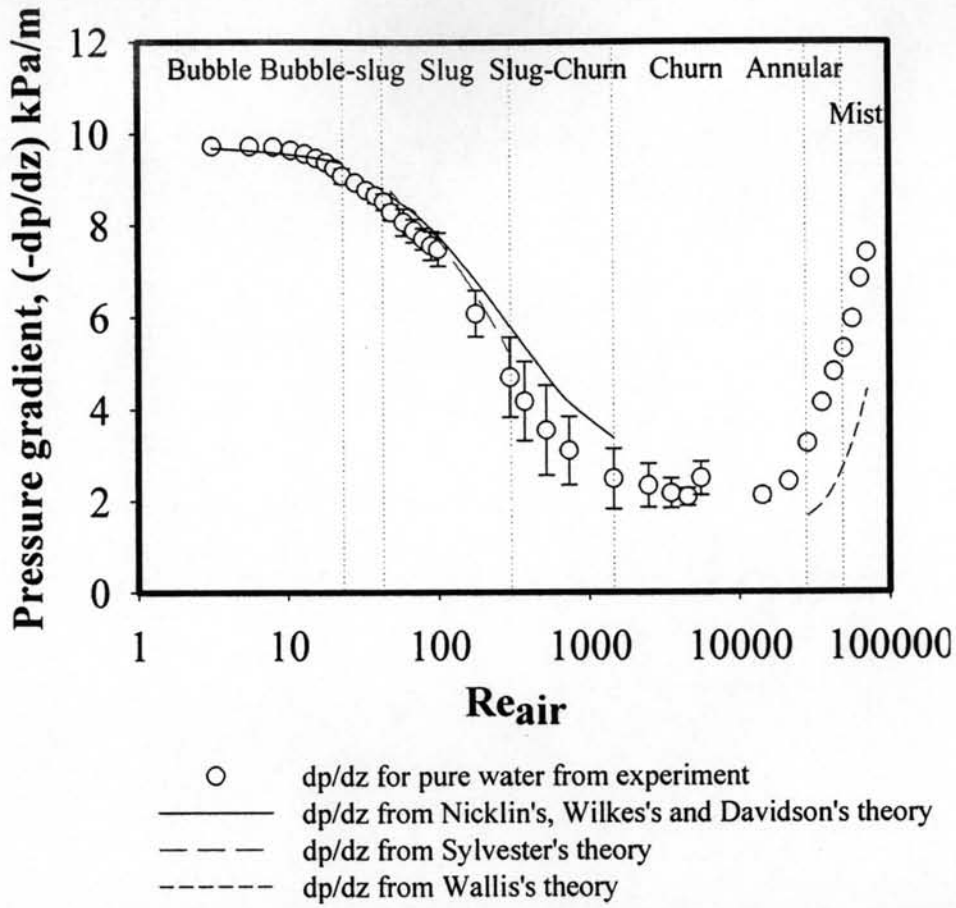


Figure A12 Comparison between Nicklin's theory, Sylvester's theory, Wallis's theory and experimental pressure gradient vs. air Reynolds number of pure water at Re_{water} = 2740 by using pipe diameter 19 mm.

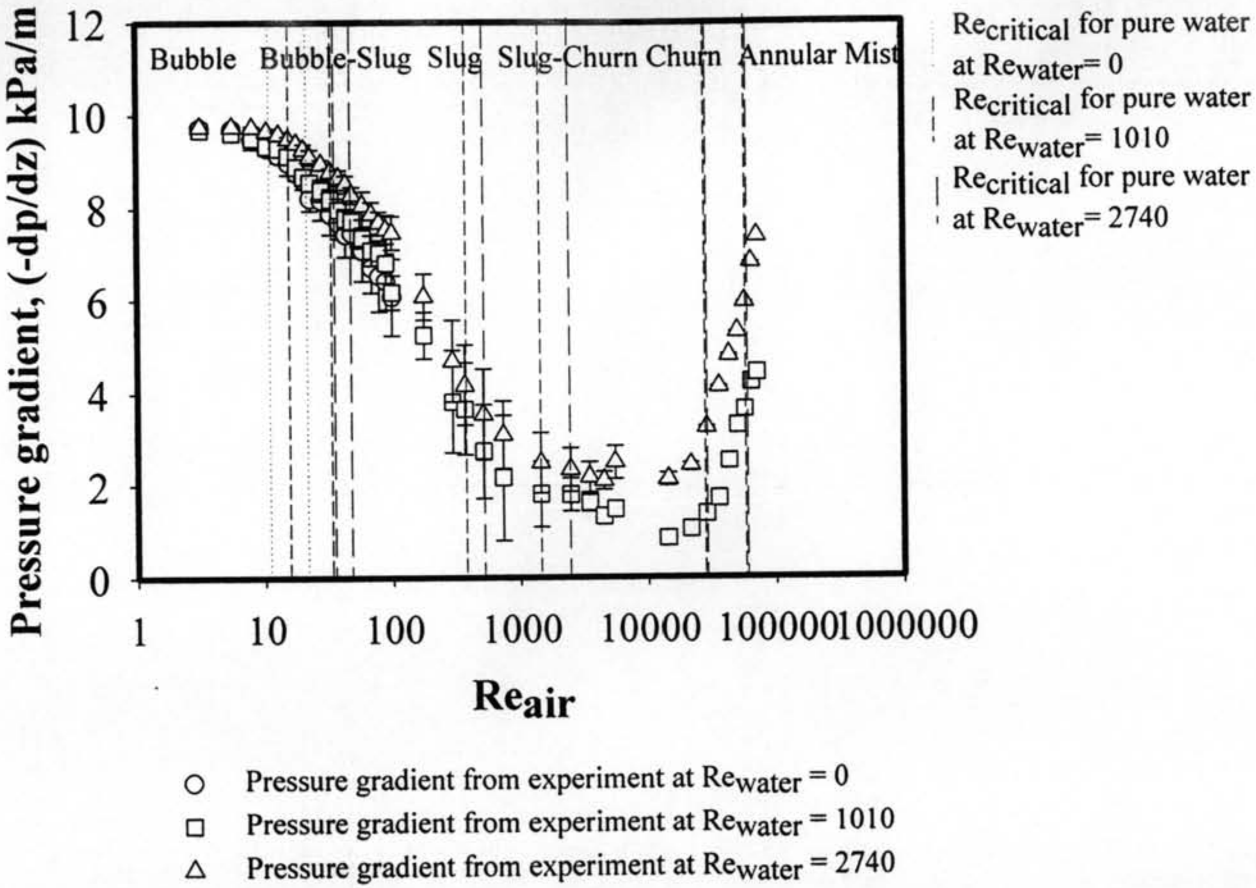


Figure A13 Comparison pressure gradient from experiment vs. air Reynolds number of pure water by using pipe diameter 19 mm.

Table A9 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes by using pipe diameter of 19 mm

Pipe diameter (mm)	Re_{water}	Re_{air}(critical) for each flow regime					
		Bubble-slug	Slug	Slug-churn	Churn	Annular	Mist
19	0	10.59	22.95	-	-	-	-
	1010	15.54	33.21	296	1454	28510	57020
	2740	38.33	48.59	369	2474	28510	57020

Appendix B Water-Air Flow for the Pipe Diameter of 53.15 mm

Table B1 Determination of bubble size for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

Procedure to determine the bubble size:

1. Make a movie of the bubble flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the bubble size by Scion Image software program.

Equivalent diameter (D_e) of the bubble is defined as the diameter of a sphere that has the same volume as the bubble.

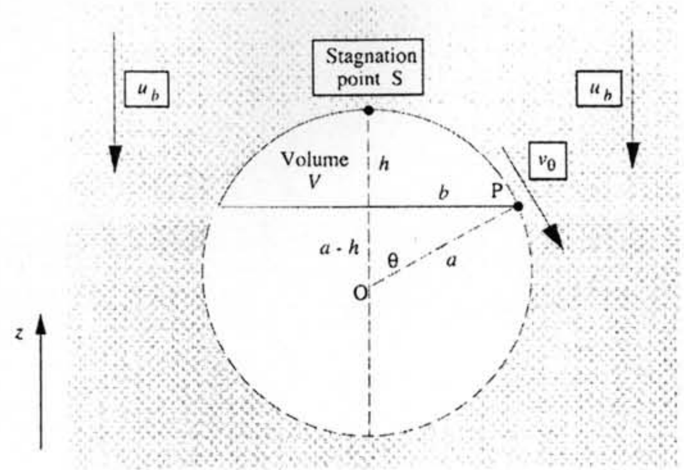


Figure B1 Flow around a spherical cap bubble (Wilkes, 1999).

$$\text{Equivalent diameter } (D_e) = \sqrt[3]{3.94h\left[\frac{h^2+b^2}{2h}\right]^2 - 1.94b^2\left[\left(\frac{h^2+b^2}{2h}\right) - h\right]} \qquad \text{(B1)}$$

Re_{water}	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble width, W_b (mm)			Average bubble width (mm)	Equivalent diameter, D_e (mm)			Average equivalent diameter, De (mm)
		1	2	3		1	2	3		1	2	3	
0	2.9	8.6	10.2	11.7	10.2 ± 1.5	14.0	15.4	14.4	14.6 ± 0.7	12.4	14.1	15.0	13.8 ± 1.3
0	5.6	11.2	10.8	12.4	11.5 ± 0.8	18.6	17.4	16.6	17.5 ± 1.0	16.2	15.4	16.4	16.0 ± 0.5
0	8.2	12.4	14.0	12.2	12.9 ± 1.0	25.7	28.3	23.1	25.7 ± 2.6	20.0	22.2	18.8	20.3 ± 1.8
0	10.0	13.5	16.8	15.7	15.3 ± 1.7	25.6	33.3	32.6	30.5 ± 4.3	20.7	26.4	25.2	24.1 ± 3.0
0	11.9	16.8	16.8	17.9	17.2 ± 0.6	33.2	27.3	31.5	30.7 ± 3.1	26.4	24.1	26.6	25.7 ± 1.4
0	13.7	18.3	16.7	22.7	19.3 ± 3.1	28.9	33.0	28.1	30.0 ± 2.6	25.9	26.2	29.1	27.1 ± 1.8
0	15.5	19.7	21.7	20.2	20.5 ± 1.0	28.9	31.9	31.0	30.6 ± 1.5	27.0	29.7	28.2	28.3 ± 1.4
0	17.4	21.0	20.2	21.4	20.9 ± 0.6	30.5	30.2	31.6	30.8 ± 0.7	28.6	27.9	29.4	28.6 ± 0.8
0	21.0	20.7	19.4	19.3	19.8 ± 0.8	28.9	38.3	29.3	32.2 ± 5.3	27.8	30.5	26.8	28.4 ± 1.9
0	22.9	23.1	25.1	21.1	23.1 ± 2.0	26.4	32.3	35.5	31.4 ± 4.6	28.8	32.7	30.7	30.7 ± 1.9
0	28.4	28.2	20.2	27.9	25.4 ± 4.5	35.9	31.3	29.7	32.3 ± 3.2	36.5	28.3	34.0	33.0 ± 4.2
0	33.9	25.8	25.2	23.8	24.9 ± 1.0	28.1	33.0	35.7	32.3 ± 3.9	31.8	33.0	32.9	32.5 ± 0.7
0	37.5	27.8	28.9	30.0	28.9 ± 1.1	34.8	34.9	33.6	34.4 ± 0.7	35.8	36.8	37.2	36.6 ± 0.7
0	43.0	26.2	30.0	30.4	28.9 ± 2.3	35.4	31.6	32.3	33.1 ± 2.0	34.7	36.5	37.1	36.1 ± 1.2
0	48.5	31.1	31.5	28.5	30.4 ± 1.6	34.6	37.4	35.7	35.9 ± 1.4	38.5	39.8	36.7	38.4 ± 1.6
0	59.5	36.1	33.6	28.5	32.8 ± 3.9	35.9	35.1	37.3	36.1 ± 1.1	43.2	40.8	37.3	40.4 ± 3.0
0	68.7	32.7	33.5	33.9	33.4 ± 0.6	37.0	44.1	45.0	42.0 ± 4.4	40.7	44.0	44.6	43.1 ± 2.1
0	79.7	33.2	26.4	33.7	31.1 ± 4.1	41.1	45.1	43.9	43.4 ± 2.1	42.6	38.6	44.0	41.8 ± 2.8
0	88.9	35.4	34.8	35.4	35.2 ± 0.3	42.7	43.5	41.7	42.6 ± 0.9	45.0	44.8	44.6	44.8 ± 0.2
0	99.9	39.6	41.4	40.2	40.4 ± 0.9	47.0	44.4	41.8	44.4 ± 2.6	50.1	50.6	48.7	49.8 ± 1.0
1028	2.9	7.8	6.9	8.0	7.5 ± 0.6	7.4	8.1	8.6	8.0 ± 0.6	9.2	8.7	9.7	9.2 ± 0.5
1028	5.6	8.9	9.0	10.8	9.5 ± 1.1	7.2	6.4	9.2	7.6 ± 1.4	10.1	9.9	12.4	10.8 ± 1.4
1028	8.2	17.5	15.5	17.8	16.9 ± 1.3	15.5	20.1	19.3	18.3 ± 2.5	20.3	20.2	21.9	20.8 ± 0.9
1028	10.0	16.0	19.4	18.8	18.0 ± 1.8	23.4	17.4	23.7	21.5 ± 3.6	21.9	22.5	24.3	22.9 ± 1.3
1028	11.9	20.0	19.5	14.2	17.9 ± 3.2	23.3	26.7	16.7	22.2 ± 5.1	25.1	26.0	17.9	23.0 ± 4.4
1028	13.7	19.0	16.1	16.4	17.2 ± 1.6	25.9	19.9	27.3	24.4 ± 3.9	25.2	20.7	23.7	23.2 ± 2.3
1028	15.5	21.8	20.3	22.4	21.5 ± 1.1	23.4	22.6	24.4	23.5 ± 0.9	26.7	25.1	27.6	26.5 ± 1.2
1028	17.4	17.8	20.8	19.7	19.5 ± 1.5	27.6	26.5	24.1	26.1 ± 1.8	25.0	27.0	25.2	25.7 ± 1.1

Re_{water}	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble width, W_b (mm)			Average bubble width (mm)	Equivalent diameter, D_e (mm)			Average equivalent diameter, De (mm)
		1	2	3		1	2	3		1	2	3	
1028	21.0	23.2	22.4	24.1	23.2 ± 0.8	30.4	28.1	22.7	27.1 ± 4.0	30.4	28.9	28.4	29.2 ± 1.1
1028	22.9	21.0	23.2	23.7	22.6 ± 1.4	23.5	27.1	29.4	26.7 ± 3.0	26.0	29.2	30.5	28.6 ± 2.3
1028	28.4	24.6	21.1	22.6	22.8 ± 1.7	31.1	29.9	28.8	30.0 ± 1.1	31.8	28.6	29.3	29.9 ± 1.7
1028	33.9	26.3	21.4	24.2	23.9 ± 2.5	29.8	34.6	31.4	31.9 ± 2.4	32.7	30.5	31.6	31.6 ± 1.1
1028	37.5	21.9	23.2	25.6	23.6 ± 1.8	34.7	27.2	33.0	31.6 ± 3.9	31.0	29.2	33.3	31.2 ± 2.1
1028	43.0	23.9	25.8	23.6	24.5 ± 1.2	33.0	32.2	30.0	31.7 ± 1.6	31.9	33.2	30.6	31.9 ± 1.3
1028	48.5	30.8	30.4	32.0	31.1 ± 0.8	37.5	34.6	33.0	35.0 ± 2.2	39.3	37.9	38.7	38.6 ± 0.7
1028	59.5	32.5	32.9	35.0	33.5 ± 1.3	36.2	36.2	36.4	36.2 ± 0.1	40.2	40.6	42.4	41.1 ± 1.2
1028	68.7	37.5	39.5	37.0	38.0 ± 1.3	39.1	40.3	36.1	38.5 ± 2.2	45.5	47.6	44.0	45.7 ± 1.8
1028	79.7	42.3	42.3	43.0	42.5 ± 0.4	33.3	36.7	41.2	37.1 ± 3.9	47.8	48.8	50.9	49.2 ± 1.6
1028	88.9	44.5	43.6	45.5	44.5 ± 0.9	39.8	41.1	37.8	39.6 ± 1.7	51.8	51.4	52.0	51.7 ± 0.3
1028	99.9	46.8	42.2	45.2	44.7 ± 2.3	38.1	43.6	38.8	40.2 ± 3.0	53.2	51.0	52.1	52.1 ± 1.1
1028	132	43.7	44.2	45.8	44.6 ± 1.1	36.6	35.6	45.8	39.3 ± 5.6	50.0	50.2	54.9	51.7 ± 2.8

Re_{water}	Re_{air}	Bubble height / Pipe diameter			Average, R_h/D	Bubble Width / Pipe diameter			Average, W_b/D	Equivalent diameter / Pipe diameter			Average equivalent diameter, De/D
		1	2	3		1	2	3		1	2	3	
0	2.90	0.16	0.19	0.22	0.19 ± 0.03	0.26	0.29	0.27	0.27 ± 0.01	0.23	0.27	0.28	0.26 ± 0.03
0	5.56	0.21	0.20	0.23	0.22 ± 0.02	0.35	0.33	0.31	0.33 ± 0.02	0.31	0.29	0.31	0.30 ± 0.01
0	8.20	0.23	0.26	0.23	0.24 ± 0.02	0.48	0.53	0.43	0.48 ± 0.05	0.38	0.42	0.35	0.38 ± 0.03
0	10.04	0.25	0.32	0.30	0.29 ± 0.03	0.48	0.63	0.61	0.57 ± 0.08	0.39	0.50	0.47	0.45 ± 0.06
0	11.87	0.32	0.32	0.34	0.32 ± 0.01	0.63	0.51	0.59	0.58 ± 0.06	0.50	0.45	0.50	0.48 ± 0.03
0	13.70	0.34	0.31	0.43	0.36 ± 0.06	0.54	0.62	0.53	0.56 ± 0.05	0.49	0.49	0.55	0.51 ± 0.03
0	15.54	0.37	0.41	0.38	0.39 ± 0.02	0.54	0.60	0.58	0.58 ± 0.03	0.51	0.56	0.53	0.53 ± 0.03
0	17.37	0.39	0.38	0.40	0.39 ± 0.01	0.57	0.57	0.59	0.58 ± 0.01	0.54	0.52	0.55	0.54 ± 0.01
0	21.04	0.39	0.37	0.36	0.37 ± 0.01	0.54	0.72	0.55	0.61 ± 0.10	0.52	0.57	0.50	0.53 ± 0.04
0	22.87	0.43	0.47	0.40	0.43 ± 0.04	0.50	0.61	0.67	0.59 ± 0.09	0.54	0.61	0.58	0.58 ± 0.04
0	28.37	0.53	0.38	0.52	0.48 ± 0.08	0.67	0.59	0.56	0.61 ± 0.06	0.69	0.53	0.64	0.62 ± 0.08
0	33.87	0.49	0.47	0.45	0.47 ± 0.02	0.53	0.62	0.67	0.61 ± 0.07	0.60	0.62	0.62	0.61 ± 0.01
0	37.54	0.52	0.54	0.56	0.54 ± 0.02	0.65	0.66	0.63	0.65 ± 0.01	0.67	0.69	0.70	0.69 ± 0.01
0	43.04	0.49	0.56	0.57	0.54 ± 0.04	0.67	0.59	0.61	0.62 ± 0.04	0.65	0.69	0.70	0.68 ± 0.02
0	48.54	0.59	0.59	0.54	0.57 ± 0.03	0.65	0.70	0.67	0.68 ± 0.03	0.72	0.75	0.69	0.72 ± 0.03
0	59.53	0.68	0.63	0.54	0.62 ± 0.07	0.68	0.66	0.70	0.68 ± 0.02	0.81	0.77	0.70	0.76 ± 0.06
0	68.70	0.62	0.63	0.64	0.63 ± 0.01	0.70	0.83	0.85	0.79 ± 0.08	0.77	0.83	0.84	0.81 ± 0.04
0	79.70	0.63	0.50	0.63	0.59 ± 0.08	0.77	0.85	0.83	0.82 ± 0.04	0.80	0.73	0.83	0.79 ± 0.05
0	88.87	0.67	0.66	0.67	0.66 ± 0.01	0.80	0.82	0.79	0.80 ± 0.02	0.85	0.84	0.84	0.84 ± 0.00
0	99.87	0.75	0.78	0.76	0.76 ± 0.02	0.89	0.84	0.79	0.84 ± 0.05	0.94	0.95	0.92	0.94 ± 0.02
1028	2.9	0.15	0.13	0.15	0.14 ± 0.01	0.14	0.15	0.16	0.15 ± 0.01	0.17	0.16	0.18	0.17 ± 0.01
1028	5.6	0.17	0.17	0.20	0.18 ± 0.02	0.14	0.12	0.17	0.14 ± 0.03	0.19	0.19	0.23	0.20 ± 0.03
1028	8.2	0.33	0.29	0.34	0.32 ± 0.02	0.29	0.38	0.36	0.34 ± 0.05	0.38	0.38	0.41	0.39 ± 0.02
1028	10.0	0.30	0.36	0.35	0.34 ± 0.03	0.44	0.33	0.45	0.40 ± 0.07	0.41	0.42	0.46	0.43 ± 0.02
1028	11.9	0.38	0.37	0.27	0.34 ± 0.06	0.44	0.50	0.31	0.42 ± 0.10	0.47	0.49	0.34	0.43 ± 0.08
1028	13.7	0.36	0.30	0.31	0.32 ± 0.03	0.49	0.37	0.51	0.46 ± 0.07	0.47	0.39	0.45	0.44 ± 0.04
1028	15.5	0.41	0.38	0.42	0.40 ± 0.02	0.44	0.43	0.46	0.44 ± 0.02	0.50	0.47	0.52	0.50 ± 0.02
1028	17.4	0.34	0.39	0.37	0.37 ± 0.03	0.52	0.50	0.45	0.49 ± 0.03	0.47	0.51	0.47	0.48 ± 0.02

Re_{water}	Re_{air}	Bubble height / Pipe diameter			Average, R_h/D	Bubble Width / Pipe diameter			Average, W_b/D	Equivalent diameter / Pipe diameter			Average equivalent diameter, De/D
		1	2	3		1	2	3		1	2	3	
1028	21.0	0.44	0.42	0.45	0.44 ± 0.02	0.57	0.53	0.43	0.51 ± 0.07	0.57	0.54	0.53	0.55 ± 0.02
1028	22.9	0.40	0.44	0.45	0.43 ± 0.03	0.44	0.51	0.55	0.50 ± 0.06	0.49	0.55	0.57	0.54 ± 0.04
1028	28.4	0.46	0.40	0.42	0.43 ± 0.03	0.58	0.56	0.54	0.56 ± 0.02	0.60	0.54	0.55	0.56 ± 0.03
1028	33.9	0.49	0.40	0.46	0.45 ± 0.05	0.56	0.65	0.59	0.60 ± 0.05	0.62	0.57	0.59	0.59 ± 0.02
1028	37.5	0.41	0.44	0.48	0.44 ± 0.03	0.65	0.51	0.62	0.59 ± 0.07	0.58	0.55	0.63	0.59 ± 0.04
1028	43.0	0.45	0.49	0.44	0.46 ± 0.02	0.62	0.61	0.56	0.60 ± 0.03	0.60	0.63	0.58	0.60 ± 0.02
1028	48.5	0.58	0.57	0.60	0.58 ± 0.02	0.70	0.65	0.62	0.66 ± 0.04	0.74	0.71	0.73	0.73 ± 0.01
1028	59.5	0.61	0.62	0.66	0.63 ± 0.03	0.68	0.68	0.68	0.68 ± 0.00	0.76	0.76	0.80	0.77 ± 0.02
1028	68.7	0.71	0.74	0.70	0.71 ± 0.02	0.74	0.76	0.68	0.72 ± 0.04	0.86	0.90	0.83	0.86 ± 0.03
1028	79.7	0.80	0.79	0.81	0.80 ± 0.01	0.63	0.69	0.78	0.70 ± 0.07	0.90	0.92	0.96	0.93 ± 0.03
1028	88.9	0.84	0.82	0.86	0.84 ± 0.02	0.75	0.77	0.71	0.74 ± 0.03	0.97	0.97	0.98	0.97 ± 0.01
1028	99.9	0.88	0.79	0.85	0.84 ± 0.04	0.72	0.82	0.73	0.76 ± 0.06	1.00	0.96	0.98	0.98 ± 0.02
1028	132	0.82	0.83	0.86	0.84 ± 0.02	0.69	0.67	0.86	0.74 ± 0.11	0.94	0.94	1.03	0.97 ± 0.05

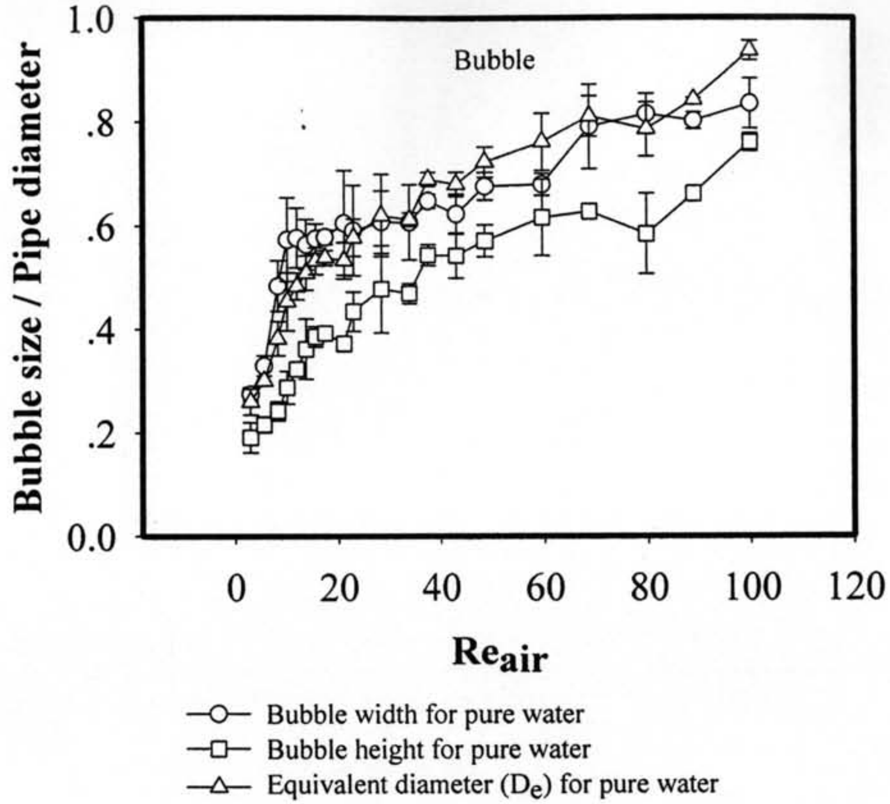


Figure B2 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of pure water at $Re_{water} = 0$ by using pipe diameter 53.15 mm.

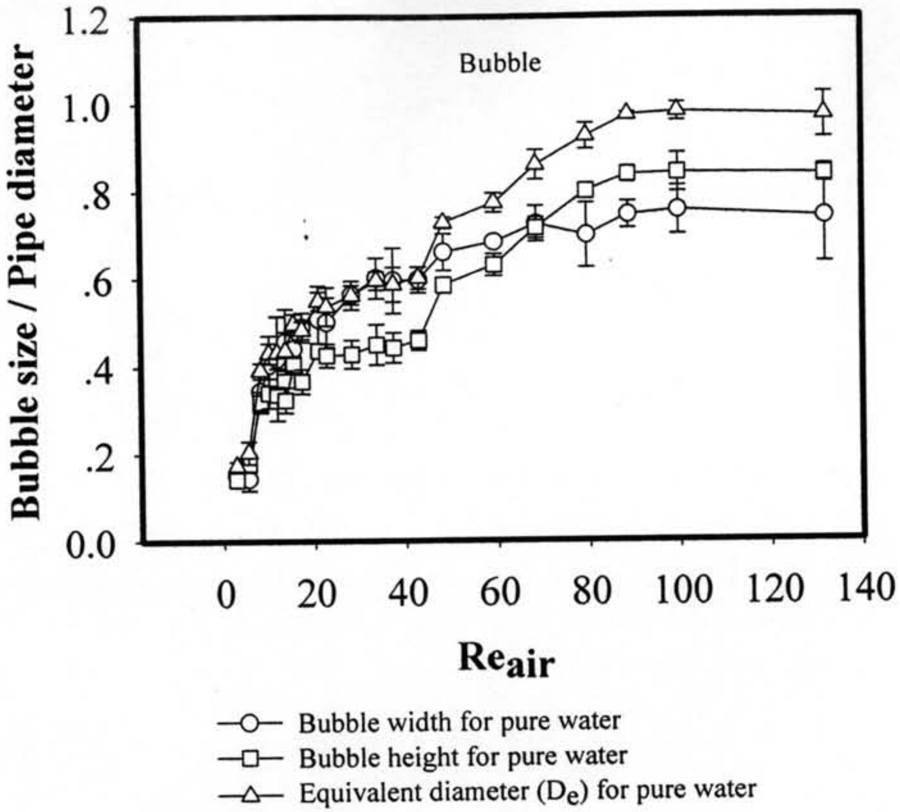


Figure B3 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of pure water at $Re_{water} = 1028$ by using pipe diameter 53.15 mm.

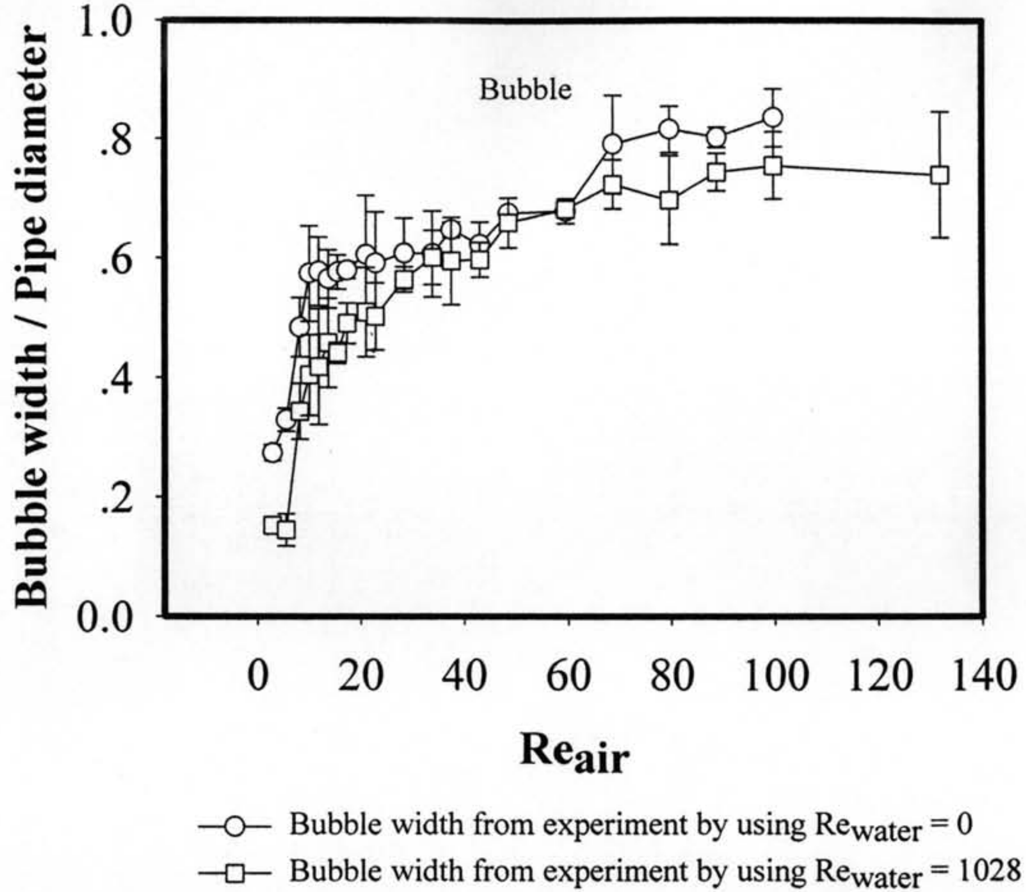


Figure B4 Bubble width from experiment vs. air Reynolds number of pure water by using pipe diameter 53.15 mm.

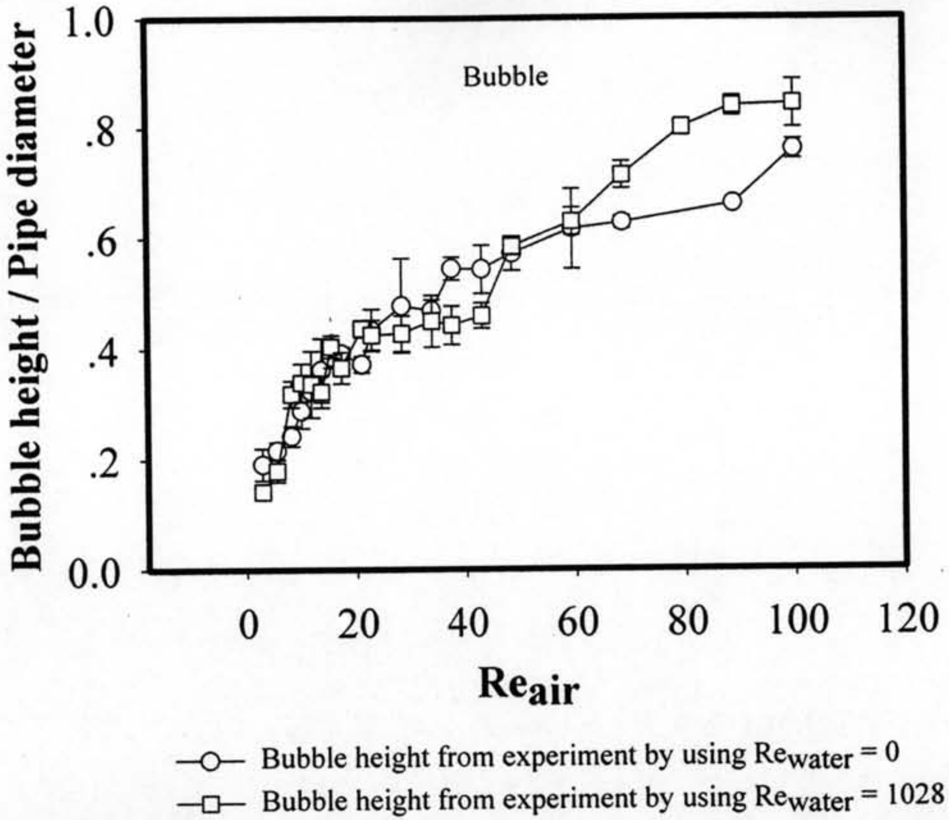


Figure B5 Bubble height from experiment vs. air Reynolds number of pure water by using pipe diameter 53.15 mm.

Table B2 Determination of slug height for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

Procedure to determine the slug height:

1. Make a movie of the slug flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the slug height by Scion Image software program.

Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
0	289	75.0	83.6	97.5	85.4 ± 11.4	1.4	1.6	1.8	1.6 ± 0.21
0	367	120.0	114.6	127.3	120.6 ± 6.4	2.3	2.2	2.4	2.3 ± 0.12
0	445	148.1	127.5	108.8	128.1 ± 19.7	2.8	2.4	2.0	2.4 ± 0.37
0	520	163.6	173.1	168.8	168.5 ± 4.8	3.1	3.3	3.2	3.2 ± 0.09
0	629	161.1	178.3	190.9	176.8 ± 14.9	3.0	3.4	3.6	3.3 ± 0.28
0	739	230.0	213.9	258.3	234.1 ± 22.5	4.3	4.0	4.9	4.4 ± 0.42
0	848	357.0	302.5	302.5	320.7 ± 31.5	6.7	5.7	5.7	6.0 ± 0.59
0	958	382.5	377.5	342.5	367.5 ± 21.8	7.2	7.1	6.4	6.9 ± 0.41
1028	445	115.9	126.7	121.7	121.4 ± 5.4	2.2	2.4	2.3	2.3 ± 0.10
1028	520	110.0	125.0	132.5	122.5 ± 11.5	2.1	2.4	2.5	2.3 ± 0.22
1028	629	164.4	208.7	172.5	181.9 ± 23.6	3.1	3.9	3.2	3.4 ± 0.44
1028	739	190.0	205.0	224.4	206.5 ± 17.2	3.6	3.9	4.2	3.9 ± 0.32
1028	848	226.4	225.0	240.0	230.5 ± 8.3	4.3	4.2	4.5	4.3 ± 0.16
1028	958	225.0	290.0	247.5	254.2 ± 33.0	4.2	5.5	4.7	4.8 ± 0.62
1028	1067	220.0	242.5	295.0	252.5 ± 38.5	4.1	4.6	5.6	4.8 ± 0.72

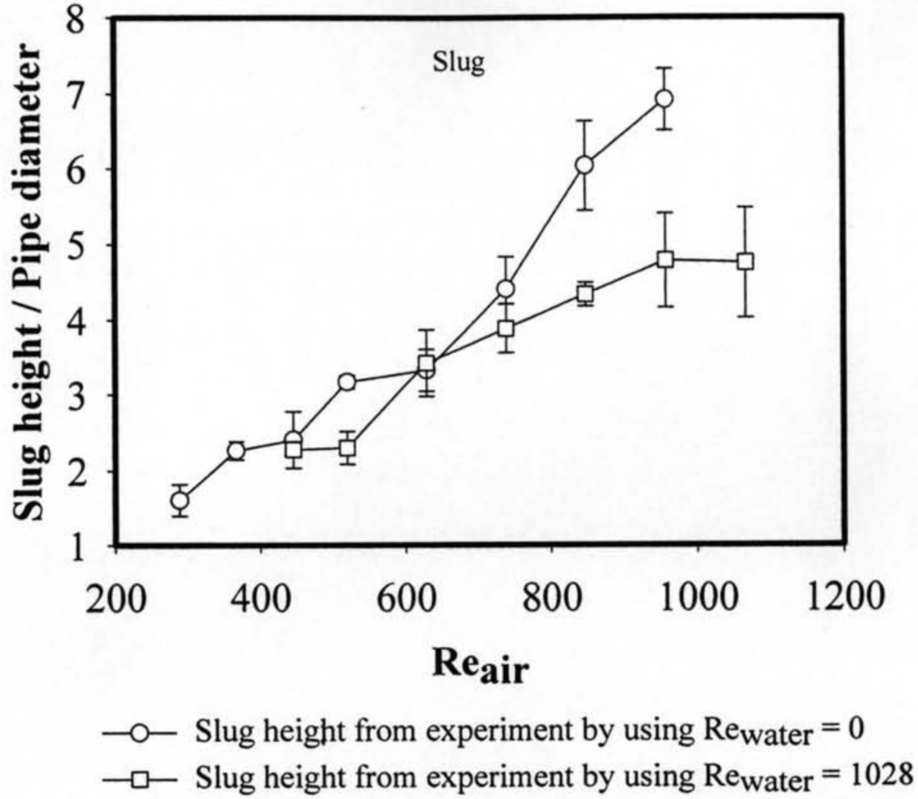


Figure B6 Slug height from experiment vs. air Reynolds number of pure water by using pipe diameter 53.15 mm.

Table B3 Determination of bubble and slug velocity for pure water from Nicklin's theory and experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

Bubble velocity from theory, $u_s = 1.2(\frac{Q_{qir} + Q_{liquid}}{A}) + 0.35\sqrt{gD}$ (B2)

Determination of bubble velocity from experiment by timing the bubble at known distance (0.7m)

Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
0	2.90	2.96	2.96	2.73	2.94	2.85	2.89 ± 0.10	0.24	0.24	0.26	0.24	0.25	0.24 ± 0.009	0.24
0	5.56	2.74	2.75	2.76	2.89	2.67	2.76 ± 0.08	0.26	0.25	0.25	0.24	0.26	0.25 ± 0.007	0.25
0	8.20	2.43	2.51	2.64	2.53	2.67	2.56 ± 0.10	0.29	0.28	0.27	0.28	0.26	0.27 ± 0.011	0.27
0	10.04	2.46	2.96	2.49	2.41	2.81	2.63 ± 0.24	0.28	0.24	0.28	0.29	0.25	0.27 ± 0.024	0.27
0	11.87	2.33	2.52	2.59	2.75	2.61	2.56 ± 0.15	0.30	0.28	0.27	0.25	0.27	0.27 ± 0.017	0.27
0	13.70	2.55	2.47	2.42	2.45	2.77	2.53 ± 0.14	0.27	0.28	0.29	0.29	0.25	0.28 ± 0.015	0.28
0	15.54	2.40	2.44	2.38	2.53	2.42	2.43 ± 0.06	0.29	0.29	0.29	0.28	0.29	0.29 ± 0.007	0.29
0	17.37	2.40	2.49	2.40	2.37	2.37	2.41 ± 0.05	0.29	0.28	0.29	0.30	0.30	0.29 ± 0.006	0.29
0	21.04	2.19	2.29	2.38	2.36	2.47	2.34 ± 0.10	0.32	0.31	0.29	0.30	0.28	0.30 ± 0.014	0.30
0	22.87	2.34	2.23	2.22	2.46	2.43	2.34 ± 0.11	0.30	0.31	0.32	0.28	0.29	0.30 ± 0.014	0.30
0	28.37	2.16	2.24	2.23	2.34	2.14	2.22 ± 0.08	0.32	0.31	0.31	0.30	0.33	0.32 ± 0.011	0.32

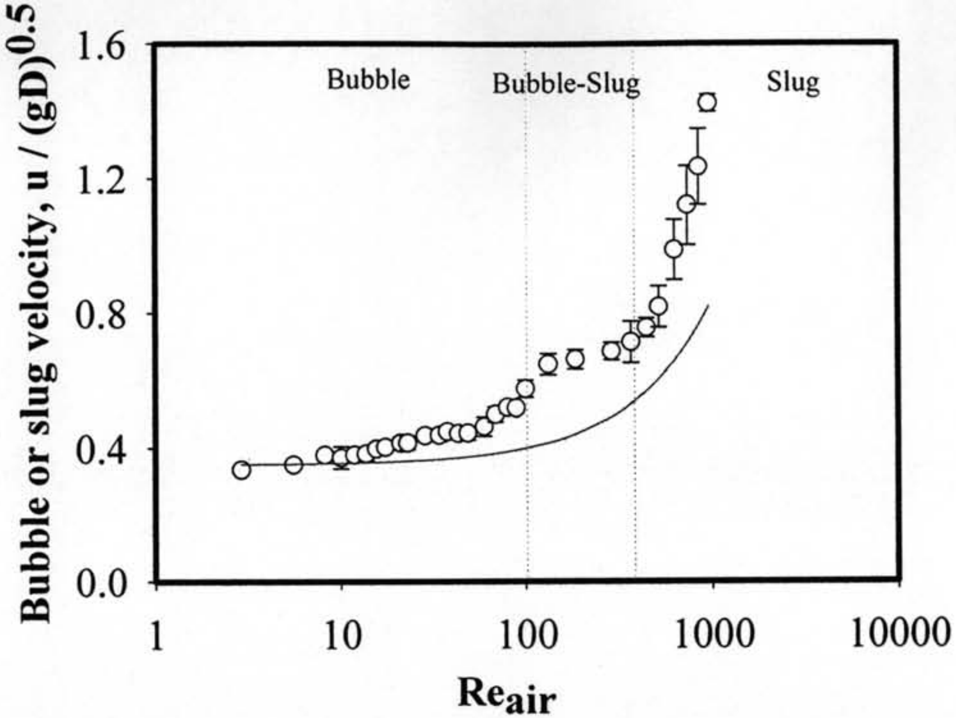
Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
0	33.87	2.19	2.20	2.13	2.38	2.17	2.21 ± 0.10	0.32	0.32	0.33	0.29	0.32	0.32 ± 0.013	0.32
0	37.54	2.23	2.21	2.16	2.11	2.09	2.16 ± 0.06	0.31	0.32	0.32	0.33	0.33	0.32 ± 0.009	0.32
0	43.04	2.17	2.23	2.13	2.19	2.22	2.19 ± 0.04	0.32	0.31	0.33	0.32	0.32	0.32 ± 0.006	0.32
0	48.54	2.07	2.08	2.25	2.25	2.27	2.18 ± 0.10	0.34	0.34	0.31	0.31	0.31	0.32 ± 0.015	0.32
0	59.53	2.12	2.13	2.27	2.05	1.92	2.10 ± 0.13	0.33	0.33	0.31	0.34	0.36	0.33 ± 0.021	0.33
0	68.70	2.06	1.92	1.97	1.95	1.82	1.94 ± 0.09	0.34	0.36	0.36	0.36	0.38	0.36 ± 0.016	0.36
0	79.70	1.87	1.85	1.87	1.95	1.78	1.86 ± 0.06	0.37	0.38	0.37	0.36	0.39	0.38 ± 0.012	0.38
0	88.87	1.87	1.88	1.81	1.85	1.94	1.87 ± 0.05	0.37	0.37	0.39	0.38	0.36	0.37 ± 0.009	0.37
0	99.87	1.60	1.70	1.72	1.63	1.79	1.69 ± 0.08	0.44	0.41	0.41	0.43	0.39	0.42 ± 0.018	0.42
0	132	1.46	1.43	1.49	1.50	1.63	1.50 ± 0.08	0.48	0.49	0.47	0.47	0.43	0.47 ± 0.023	0.47
0	184	1.40	1.47	1.53	1.41	1.53	1.47 ± 0.06	0.50	0.48	0.46	0.50	0.46	0.48 ± 0.020	0.48
0	289	1.50	1.40	1.44	1.37	1.37	1.42 ± 0.06	0.47	0.50	0.49	0.51	0.51	0.49 ± 0.019	0.49
0	367	1.22	1.28	1.40	1.50	1.44	1.37 ± 0.12	0.57	0.55	0.50	0.47	0.49	0.51 ± 0.044	0.51
0	445	1.22	1.33	1.30	1.25	1.32	1.28 ± 0.05	0.57	0.53	0.54	0.56	0.53	0.55 ± 0.020	0.55
0	520	1.29	1.16	1.06	1.22	1.22	1.19 ± 0.09	0.54	0.60	0.66	0.57	0.57	0.59 ± 0.044	0.59
0	629	0.97	0.89	0.92	1.09	1.07	0.99 ± 0.09	0.72	0.79	0.76	0.64	0.65	0.71 ± 0.064	0.71
0	739	0.87	0.89	0.79	0.79	1.03	0.87 ± 0.10	0.80	0.79	0.89	0.89	0.68	0.81 ± 0.085	0.81
0	848	0.73	0.87	0.78	0.71	0.86	0.79 ± 0.07	0.96	0.80	0.90	0.99	0.81	0.89 ± 0.082	0.89
0	958	0.67	0.68	0.70	0.68	0.67	0.68 ± 0.01	1.04	1.03	1.00	1.03	1.04	1.03 ± 0.018	1.03
1028	2.90	2.47	2.64	2.43	2.53	2.67	2.55 ± 0.10	0.28	0.27	0.29	0.28	0.26	0.28 ± 0.011	0.28
1028	5.56	2.47	2.51	2.49	2.44	2.42	2.47 ± 0.04	0.28	0.28	0.28	0.29	0.29	0.28 ± 0.004	0.28
1028	8.20	2.33	2.31	2.29	2.33	2.27	2.31 ± 0.03	0.30	0.30	0.31	0.30	0.31	0.30 ± 0.003	0.30
1028	10.04	2.21	2.29	2.11	2.28	2.20	2.22 ± 0.07	0.32	0.31	0.33	0.31	0.32	0.32 ± 0.010	0.32
1028	11.87	2.30	2.22	2.23	2.22	2.13	2.22 ± 0.06	0.30	0.32	0.31	0.32	0.33	0.32 ± 0.009	0.32
1028	13.70	2.32	2.19	2.27	2.14	2.13	2.21 ± 0.08	0.30	0.32	0.31	0.33	0.33	0.32 ± 0.012	0.32
1028	15.54	2.30	2.29	2.23	2.33	2.21	2.27 ± 0.05	0.30	0.31	0.31	0.30	0.32	0.31 ± 0.007	0.31
1028	17.37	2.17	2.26	2.24	2.19	2.12	2.20 ± 0.06	0.32	0.31	0.31	0.32	0.33	0.32 ± 0.008	0.32

Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
1028	21.04	2.14	2.18	2.27	2.33	2.06	2.20 ± 0.11	0.33	0.32	0.31	0.30	0.34	0.32 ± 0.015	0.32
1028	22.87	2.30	2.05	2.30	2.17	1.96	2.16 ± 0.15	0.30	0.34	0.30	0.32	0.36	0.33 ± 0.023	0.33
1028	28.37	2.13	2.17	1.91	1.94	2.13	2.06 ± 0.12	0.33	0.32	0.37	0.36	0.33	0.34 ± 0.021	0.34
1028	33.87	1.98	2.02	2.11	2.11	1.89	2.02 ± 0.09	0.35	0.35	0.33	0.33	0.37	0.35 ± 0.016	0.35
1028	37.54	1.90	2.09	2.13	1.87	2.07	2.01 ± 0.12	0.37	0.33	0.33	0.37	0.34	0.35 ± 0.021	0.35
1028	43.04	1.82	2.01	1.99	1.86	2.17	1.97 ± 0.14	0.38	0.35	0.35	0.38	0.32	0.36 ± 0.025	0.36
1028	48.54	1.93	1.99	1.99	2.07	2.09	2.01 ± 0.07	0.36	0.35	0.35	0.34	0.33	0.35 ± 0.011	0.35
1028	59.53	1.85	2.01	1.75	1.94	1.92	1.89 ± 0.10	0.38	0.35	0.40	0.36	0.36	0.37 ± 0.020	0.37
1028	68.70	1.78	2.04	1.82	1.88	2.02	1.91 ± 0.12	0.39	0.34	0.38	0.37	0.35	0.37 ± 0.022	0.37
1028	79.70	1.59	1.68	1.73	1.53	1.68	1.64 ± 0.08	0.44	0.42	0.40	0.46	0.42	0.43 ± 0.021	0.43
1028	88.87	1.78	1.80	1.89	1.93	1.63	1.81 ± 0.12	0.39	0.39	0.37	0.36	0.43	0.39 ± 0.026	0.39
1028	99.87	1.67	1.89	1.64	1.91	1.95	1.81 ± 0.15	0.42	0.37	0.43	0.37	0.36	0.39 ± 0.032	0.39
1028	132	1.51	1.47	1.41	1.47	1.41	1.45 ± 0.04	0.46	0.48	0.50	0.48	0.50	0.48 ± 0.014	0.48
1028	184	1.56	1.43	1.27	1.49	1.67	1.48 ± 0.15	0.45	0.49	0.55	0.47	0.42	0.48 ± 0.050	0.48
1028	289	1.43	1.21	1.30	1.33	1.25	1.30 ± 0.08	0.49	0.58	0.54	0.53	0.56	0.54 ± 0.034	0.54
1028	367	1.03	1.11	1.19	1.03	1.02	1.08 ± 0.07	0.68	0.63	0.59	0.68	0.69	0.65 ± 0.042	0.65
1028	445	1.13	1.01	1.03	0.99	1.11	1.05 ± 0.06	0.62	0.69	0.68	0.71	0.63	0.67 ± 0.039	0.67
1028	520	0.91	1.03	1.06	0.93	0.96	0.98 ± 0.06	0.77	0.68	0.66	0.75	0.73	0.72 ± 0.047	0.72
1028	629	0.99	0.73	0.98	0.95	0.98	0.93 ± 0.11	0.71	0.96	0.71	0.74	0.71	0.77 ± 0.108	0.77
1028	739	0.90	0.80	0.64	0.96	1.13	0.89 ± 0.18	0.78	0.88	1.09	0.73	0.62	0.82 ± 0.179	0.82
1028	848	0.46	0.50	0.50	0.54	0.55	0.51 ± 0.04	1.09	1.00	1.00	0.93	0.91	0.98 ± 0.071	0.98
1028	958	0.44	0.49	0.33	0.44	0.49	0.44 ± 0.07	1.14	1.02	1.52	1.14	1.02	1.17 ± 0.204	1.17
1028	1067	0.54	0.37	0.33	0.40	0.34	0.40 ± 0.09	0.93	1.35	1.52	1.25	1.47	1.30 ± 0.235	1.30

Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
0	2.90	0.33	0.33	0.36	0.33	0.34	0.34 ± 0.012	0.35
0	5.56	0.35	0.35	0.35	0.34	0.36	0.35 ± 0.010	0.35
0	8.20	0.40	0.39	0.37	0.38	0.36	0.38 ± 0.015	0.35
0	10.04	0.39	0.33	0.39	0.40	0.34	0.37 ± 0.033	0.35
0	11.87	0.42	0.38	0.37	0.35	0.37	0.38 ± 0.023	0.36
0	13.70	0.38	0.39	0.40	0.40	0.35	0.38 ± 0.020	0.36
0	15.54	0.40	0.40	0.41	0.38	0.40	0.40 ± 0.009	0.36
0	17.37	0.40	0.39	0.40	0.41	0.41	0.40 ± 0.008	0.36
0	21.04	0.44	0.42	0.41	0.41	0.39	0.42 ± 0.019	0.36
0	22.87	0.41	0.43	0.44	0.39	0.40	0.42 ± 0.020	0.36
0	28.37	0.45	0.43	0.43	0.41	0.45	0.44 ± 0.015	0.36
0	33.87	0.44	0.44	0.46	0.41	0.45	0.44 ± 0.018	0.37
0	37.54	0.43	0.44	0.45	0.46	0.46	0.45 ± 0.013	0.37
0	43.04	0.45	0.43	0.46	0.44	0.44	0.44 ± 0.008	0.37
0	48.54	0.47	0.47	0.43	0.43	0.43	0.44 ± 0.021	0.37
0	59.53	0.46	0.46	0.43	0.47	0.50	0.46 ± 0.028	0.38
0	68.70	0.47	0.50	0.49	0.50	0.53	0.50 ± 0.022	0.38
0	79.70	0.52	0.52	0.52	0.50	0.54	0.52 ± 0.017	0.39
0	88.87	0.52	0.52	0.54	0.52	0.50	0.52 ± 0.013	0.39
0	99.87	0.61	0.57	0.56	0.59	0.54	0.58 ± 0.026	0.40
0	132	0.66	0.68	0.65	0.65	0.59	0.65 ± 0.032	0.41
0	184	0.69	0.66	0.63	0.69	0.63	0.66 ± 0.028	0.44
0	289	0.65	0.69	0.67	0.71	0.71	0.69 ± 0.026	0.49
0	367	0.79	0.76	0.69	0.65	0.67	0.71 ± 0.061	0.53
0	445	0.79	0.73	0.75	0.78	0.73	0.76 ± 0.028	0.57
0	520	0.75	0.84	0.91	0.79	0.79	0.82 ± 0.062	0.60

Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
0	629	1.00	1.09	1.05	0.89	0.91	0.99 ± 0.088	0.66
0	739	1.11	1.09	1.23	1.23	0.94	1.12 ± 0.118	0.71
0	848	1.33	1.11	1.24	1.37	1.13	1.24 ± 0.114	0.77
0	958	1.45	1.43	1.38	1.43	1.45	1.43 ± 0.025	0.82
1028	2.90	0.39	0.37	0.40	0.38	0.36	0.38 ± 0.016	0.38
1028	5.56	0.39	0.39	0.39	0.40	0.40	0.39 ± 0.006	0.38
1028	8.20	0.42	0.42	0.42	0.42	0.43	0.42 ± 0.005	0.38
1028	10.04	0.44	0.42	0.46	0.43	0.44	0.44 ± 0.015	0.38
1028	11.87	0.42	0.44	0.43	0.44	0.46	0.44 ± 0.012	0.38
1028	13.70	0.42	0.44	0.43	0.45	0.46	0.44 ± 0.016	0.38
1028	15.54	0.42	0.42	0.43	0.42	0.44	0.43 ± 0.009	0.39
1028	17.37	0.45	0.43	0.43	0.44	0.46	0.44 ± 0.011	0.39
1028	21.04	0.45	0.44	0.43	0.42	0.47	0.44 ± 0.021	0.39
1028	22.87	0.42	0.47	0.42	0.45	0.49	0.45 ± 0.032	0.39
1028	28.37	0.46	0.45	0.51	0.50	0.46	0.47 ± 0.028	0.39
1028	33.87	0.49	0.48	0.46	0.46	0.51	0.48 ± 0.022	0.39
1028	37.54	0.51	0.46	0.46	0.52	0.47	0.48 ± 0.029	0.40
1028	43.04	0.53	0.48	0.49	0.52	0.45	0.49 ± 0.034	0.40
1028	48.54	0.50	0.49	0.49	0.47	0.46	0.48 ± 0.016	0.40
1028	59.53	0.52	0.48	0.55	0.50	0.50	0.51 ± 0.027	0.41
1028	68.70	0.54	0.48	0.53	0.52	0.48	0.51 ± 0.031	0.41
1028	79.70	0.61	0.58	0.56	0.63	0.58	0.59 ± 0.030	0.42
1028	88.87	0.54	0.54	0.51	0.50	0.59	0.54 ± 0.036	0.42
1028	99.87	0.58	0.51	0.59	0.51	0.50	0.54 ± 0.044	0.43
1028	132	0.64	0.66	0.69	0.66	0.69	0.67 ± 0.020	0.44
1028	184	0.62	0.68	0.76	0.65	0.58	0.66 ± 0.069	0.47

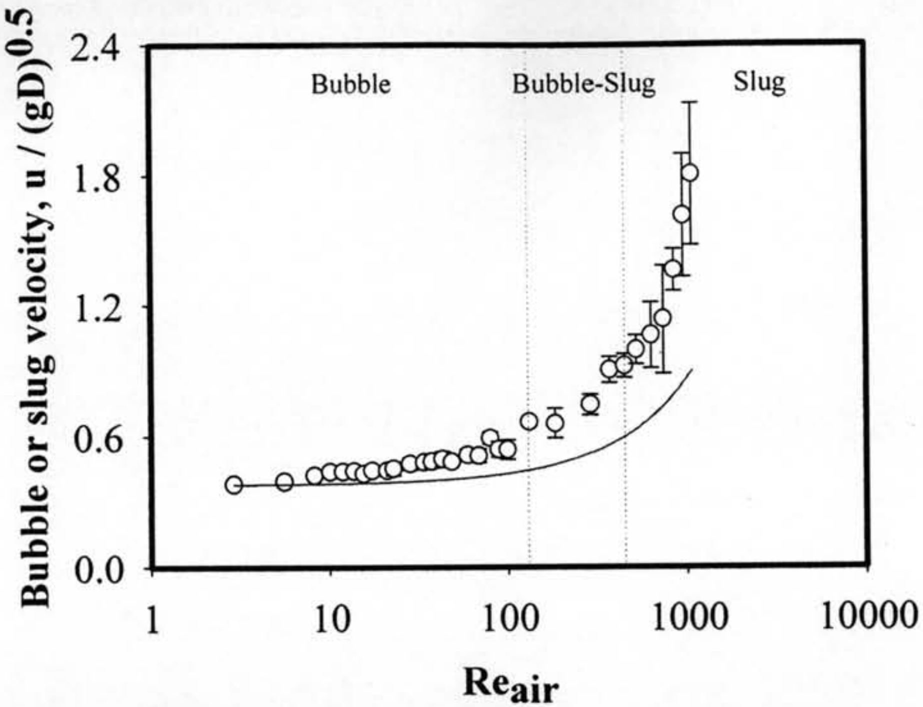
Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
1028	289	0.68	0.80	0.75	0.73	0.78	0.75 ± 0.047	0.52
1028	367	0.94	0.87	0.81	0.94	0.95	0.90 ± 0.059	0.56
1028	445	0.86	0.96	0.94	0.98	0.87	0.92 ± 0.054	0.60
1028	520	1.07	0.94	0.91	1.04	1.01	0.99 ± 0.065	0.63
1028	629	0.98	1.33	0.99	1.02	0.99	1.06 ± 0.150	0.69
1028	739	1.08	1.21	1.51	1.01	0.86	1.13 ± 0.248	0.74
1028	848	1.51	1.38	1.38	1.28	1.26	1.36 ± 0.098	0.79
1028	958	1.57	1.41	2.10	1.57	1.41	1.61 ± 0.282	0.85
1028	1067	1.28	1.87	2.10	1.73	2.04	1.80 ± 0.325	0.90



○ Bubble and slug velocity from experiment by using $Re_{water} = 0$

—— Bubble and slug velocity from Nicklin's, Wilkes's and Davidson's theory by using $Re_{water} = 0$

Figure B7 Comparison bubble or slug velocity from experiment vs. air Reynolds number of pure water at $Re_{water} = 0$ comparing with theory by using pipe diameter 53.15 mm.



○ Bubble and slug velocity from experiment by using $Re_{water} = 1028$

—— Bubble and slug velocity from Nicklin's, Wilkes's and Davidson's theory by using $Re_{water} = 1028$

Figure B8 Comparison bubble or slug velocity from experiment vs. air Reynolds number of pure water at $Re_{water} = 1028$ comparing with theory by using pipe diameter 53.15 mm.

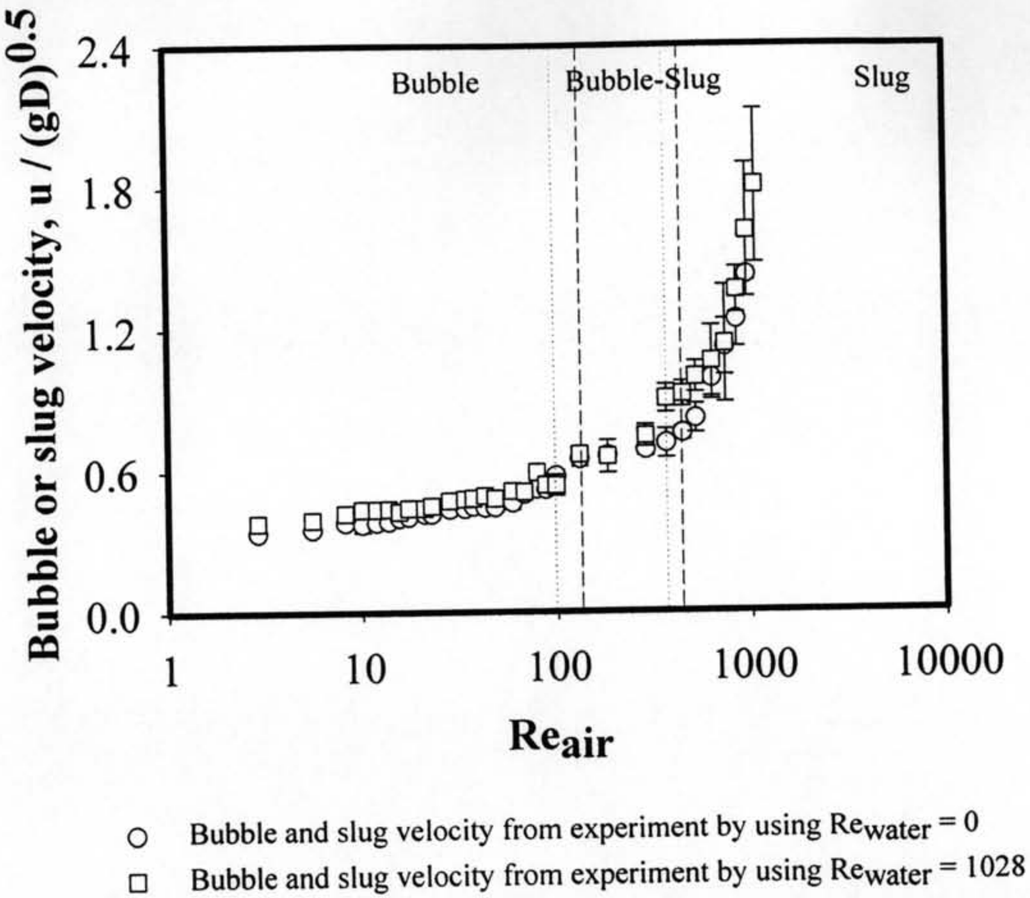


Figure B9 Bubble or slug velocity from experiment vs. air Reynolds number of pure water by using pipe diameter 53.15 mm.

Table B4 Determination of the pressure gradient for the bubble flow regime from Nicklin's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

Superficial liquid velocity, $j_{liquid} = \dfrac{Q_{liquid}}{A}$ (B3)

Superficial air velocity, $j_{air} = \dfrac{Q_{air}}{A}$ (B4)

Reynolds number of liquid, $\mathrm{Re}_{liquid} = \dfrac{\rho j_{liquid} D}{\mu_{liquid}}$ (B5)

Reynolds number of air, $\mathrm{Re}_{air} = \dfrac{\rho j_{air} D}{\mu_{air}}$ (B6)

Bubble velocity rising in stagnant liquid, $u_b = 1.00\sqrt{g R_b}$ (B7)

where R_b is equivalent radius of the bubble which defined as the radius of a sphere that has the same volume as the bubble

Void fraction, $\varepsilon = \dfrac{Q_{air}}{Q_{air} + Q_{liquid} + u_b A}$ (B8)

Pressure gradient for bubble flow regime, $\dfrac{dp}{dz} = -\rho_l g(1-\varepsilon)$ (B9)

Q_{water} (ml/min)	Sup. water velocity j_{water} (m/s)	Q_{water} (m^3/sec)	Re_{water}	Q_{air} (L/min)	Sup. Air velocity j_{air} (m/s)	Q_{air} (m^3/sec)	Re_{air}	Flow regime	U_b (m/s)	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
0	0	0	0	0.1139	0.0009	1.898E-06	2.90	bubble	0.2603	0.0033	9.7290
0	0	0	0	0.2180	0.0016	3.634E-06	5.56	bubble	0.2802	0.0058	9.7042
0	0	0	0	0.3220	0.0024	5.367E-06	8.20	bubble	0.3158	0.0076	9.6867
0	0	0	0	0.3939	0.0030	6.566E-06	10.04	bubble	0.3441	0.0085	9.6777
0	0	0	0	0.4659	0.0035	7.765E-06	11.87	bubble	0.3550	0.0098	9.6656
0	0	0	0	0.5378	0.0040	8.96E-06	13.70	bubble	0.3645	0.0110	9.6539
0	0	0	0	0.6098	0.0046	1.016E-05	15.54	bubble	0.3726	0.0121	9.6424
0	0	0	0	0.6817	0.0051	1.136E-05	17.37	bubble	0.3748	0.0135	9.6293
0	0	0	0	0.8256	0.0062	1.376E-05	21.04	bubble	0.3729	0.0164	9.6012
0	0	0	0	0.8976	0.0067	1.496E-05	22.87	bubble	0.3882	0.0171	9.5942
0	0	0	0	1.1134	0.0084	1.856E-05	28.37	bubble	0.4021	0.0204	9.5619
0	0	0	0	1.3293	0.0100	2.215E-05	33.87	bubble	0.3996	0.0244	9.5228
0	0	0	0	1.4732	0.0111	2.455E-05	37.54	bubble	0.4237	0.0255	9.5124
0	0	0	0	1.6890	0.0127	2.815E-05	43.04	bubble	0.4208	0.0293	9.4751
0	0	0	0	1.9049	0.0143	3.175E-05	48.54	bubble	0.4338	0.0320	9.4491
0	0	0	0	2.3366	0.0176	3.894E-05	59.53	bubble	0.4454	0.0379	9.3907
0	0	0	0	2.6963	0.0203	4.494E-05	68.70	bubble	0.4598	0.0422	9.3489
0	0	0	0	3.1280	0.0235	5.213E-05	79.70	bubble	0.4526	0.0494	9.2790
0	0	0	0	3.4878	0.0262	5.813E-05	88.87	bubble	0.4688	0.0529	9.2441
0	0	0	0	3.9195	0.0295	6.532E-05	99.87	bubble	0.4944	0.0562	9.2120
2193	0.0165	3.655E-05	1028	0.1139	0.0009	1.898E-06	2.90	bubble	0.2491	0.0032	9.7296
2193	0.0165	3.655E-05	1028	0.2180	0.0016	3.634E-06	5.56	bubble	0.2491	0.0061	9.7011
2193	0.0165	3.655E-05	1028	0.3220	0.0024	5.367E-06	8.20	bubble	0.3193	0.0072	9.6911

Q_{water} (ml/min)	Sup. water velocity j_{water} (m/s)	Q_{water} (m^3/sec)	Re_{water}	Q_{air} (L/min)	Sup. Air velocity j_{air} (m/s)	Q_{air} (m^3/sec)	Re_{air}	Flow regime	U_b (m/s)	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
2193	0.0165	3.655E-05	1028	0.3939	0.0030	6.566E-06	10.04	bubble	0.3351	0.0083	9.6794
2193	0.0165	3.655E-05	1028	0.4659	0.0035	7.765E-06	11.87	bubble	0.3359	0.0098	9.6649
2193	0.0165	3.655E-05	1028	0.5378	0.0040	8.964E-06	13.70	bubble	0.3375	0.0113	9.6507
2193	0.0165	3.655E-05	1028	0.6098	0.0046	1.016E-05	15.54	bubble	0.3603	0.0120	9.6436
2193	0.0165	3.655E-05	1028	0.6817	0.0051	1.136E-05	17.37	bubble	0.3552	0.0136	9.6282
2193	0.0165	3.655E-05	1028	0.8256	0.0062	1.376E-05	21.04	bubble	0.3787	0.0155	9.6100
2193	0.0165	3.655E-05	1028	0.8976	0.0067	1.496E-05	22.87	bubble	0.3743	0.0170	9.5953
2193	0.0165	3.655E-05	1028	1.1134	0.0084	1.856E-05	28.37	bubble	0.3828	0.0205	9.5606
2193	0.0165	3.655E-05	1028	1.3293	0.0100	2.215E-05	33.87	bubble	0.3938	0.0238	9.5289
2193	0.0165	3.655E-05	1028	1.4732	0.0111	2.455E-05	37.54	bubble	0.3910	0.0265	9.5028
2193	0.0165	3.655E-05	1028	1.6890	0.0127	2.815E-05	43.04	bubble	0.3957	0.0299	9.4693
2193	0.0165	3.655E-05	1028	1.9049	0.0143	3.175E-05	48.54	bubble	0.4352	0.0307	9.4611
2193	0.0165	3.655E-05	1028	2.3366	0.0176	3.894E-05	59.53	bubble	0.4488	0.0364	9.4060
2193	0.0165	3.655E-05	1028	2.6963	0.0203	4.494E-05	68.70	bubble	0.4734	0.0397	9.3732
2193	0.0165	3.655E-05	1028	3.1280	0.0235	5.213E-05	79.70	bubble	0.4911	0.0443	9.3288
2193	0.0165	3.655E-05	1028	3.4878	0.0262	5.813E-05	88.87	bubble	0.5037	0.0480	9.2927
2193	0.0165	3.655E-05	1028	3.9195	0.0295	6.532E-05	99.87	bubble	0.5056	0.0534	9.2396
2193	0.0165	3.655E-05	1028	5.1787	0.0389	8.631E-05	131.95	bubble	0.5035	0.0696	9.0812

Table B5 Determination of the pressure gradient for the slug flow regime from Nicklin's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, $\rho_{water} = 995$ kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, $\rho_{air} = 1.18$ kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

Mean liquid velocity, $$u_l = \frac{Q_{air} + Q_{liquid}}{A} \qquad \text{(B10)}$$

Reynolds number of the liquid slug, $$\mathrm{Re}_{slug} = \frac{\rho_{liquid} u_l D}{\mu_{liquid}} \qquad \text{(B11)}$$

Fanning friction factor, $$f_F = \frac{16}{\mathrm{Re}_{slug}} \quad \text{for laminar flow } (\mathrm{Re}_{slug} < 2000) \qquad \text{(B12)}$$

$$f_F = 0.079\,\mathrm{Re}_{slug}^{-1/4} \quad \text{for turbulent flow } (\mathrm{Re}_{slug} > 4000) \qquad \text{(B13)}$$

Single-phase frictional pressure gradient for liquid only, $$\left(\frac{dp}{dz}\right)_{sp} = \frac{2 f_F \rho_{liquid} u_l}{D} \qquad \text{(B14)}$$

Void fraction, $$\varepsilon = \frac{Q_{air}}{1.2\left(Q_{air} + Q_{liquid}\right) + 0.35 A\sqrt{gD}} \qquad \text{(B15)}$$

Pressure gradient for slug flow regime, $$\frac{dp}{dz} = (1-\varepsilon)\left[-\rho_{liquid} g + \left(\frac{dp}{dz}\right)_{sp}\right] \qquad \text{(B16)}$$

Q_{water} (m^3/sec)	Re_{water}	Q_{air} (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
0	0	0.00019	288.69	slug	0.0852	5311	0.0093	2.5127	0.2399	7.4209
0	0	0.00024	367.06	slug	0.1083	6752	0.0087	3.8253	0.2830	7.0018
0	0	0.00029	445.44	slug	0.1314	8194	0.0083	5.3672	0.3202	6.6396
0	0	0.00034	519.64	slug	0.1533	9559	0.0080	7.0283	0.3510	6.3392
0	0	0.00041	629.11	slug	0.1856	11573	0.0076	9.8208	0.3903	5.9569
0	0	0.00048	738.59	slug	0.2179	13587	0.0073	13.0039	0.4237	5.6325
0	0	0.00055	848.06	slug	0.2502	15601	0.0071	16.5622	0.4524	5.3539
0	0	0.00063	957.53	slug	0.2824	17615	0.0069	20.4829	0.4774	5.1120
0	0	0.00070	1067.01	slug	0.3147	19628	0.0067	24.7551	0.4993	4.9001
0	0	0.00077	1176.48	slug	0.3470	21642	0.0065	29.3694	0.5186	4.7130
0	0	0.00087	1322.45	slug	0.3901	24327	0.0063	36.0399	0.5412	4.4952
0	0	0.00095	1450.17	slug	0.4278	26677	0.0062	42.3499	0.5584	4.3291
3.655E-05	1028	0.00029	445.44	slug	0.1479	9222	0.0081	6.6001	0.3054	6.7842
3.655E-05	1028	0.00034	519.64	slug	0.1698	10587	0.0078	8.4035	0.3358	6.4886
3.655E-05	1028	0.00041	629.11	slug	0.2021	12601	0.0075	11.3975	0.3747	6.1102
3.655E-05	1028	0.00048	738.59	slug	0.2343	14615	0.0072	14.7738	0.4080	5.7869
3.655E-05	1028	0.00055	848.06	slug	0.2666	16628	0.0070	18.5186	0.4368	5.5077
3.655E-05	1028	0.00063	957.53	slug	0.2989	18642	0.0068	22.6199	0.4619	5.2642
3.655E-05	1028	0.00070	1067.01	slug	0.3312	20656	0.0066	27.0678	0.4841	5.0499
3.655E-05	1028	0.00077	1176.48	slug	0.3635	22670	0.0064	31.8535	0.5037	4.8600
3.655E-05	1028	0.00087	1322.45	slug	0.4066	25355	0.0063	38.7465	0.5267	4.6381
3.655E-05	1028	0.00095	1450.17	slug	0.4442	27705	0.0061	45.2463	0.5444	4.4682

Q_{water} (m^3/sec)	Re_{water}	Q_{air} (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
3.655E-05	1028	0.00167	2547.92	slug-churn	0.7681	47899	0.0053	117.9456	0.6400	3.5567
3.655E-05	1028	0.00333	5095.84	slug-churn	1.5196	94770	0.0045	389.3015	0.7240	2.8019
3.655E-05	1028	0.00500	7643.77	slug-churn	2.2712	141640	0.0041	786.4903	0.7571	2.5622

Table B6 Determination of the pressure gradient for the slug flow regime from Sylvester's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, $\rho_{water} = 995$ kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, $\rho_{air} = 1.18$ kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

$$\beta = L_{TB}/L_{SU} \qquad \text{(B17)}$$

where: L_{TB} is length of the Taylor bubble

L_{SU} is length of the slug unit

Friction factor associated with the Taylor bubble, $$f_{TB} = \frac{1}{\left[-2.0\log\left\{\frac{\left(1-\alpha_{TB}^{1/2}\right)}{7.4}\right\}\right]^2} \qquad \text{(B18)}$$

Reynolds number of the liquid slug, $$\mathrm{Re}_{LS} = \frac{\rho_L U_{LLS} D}{\mu_L} \qquad \text{(B19)}$$

where: velocity of the liquid in the liquid slug, $U_{LLS} = U_{SG} + U_{SL}$ (B20)

Friction factor associated with the liquid slug, $$f_{LS} = \frac{1}{\left[-2.0\log\left\{\frac{\varepsilon/D}{3.7} - \left(\frac{5.02}{\mathrm{Re}_{LS}}\right)\log\left(\frac{\varepsilon/D}{3.7} + \frac{13}{\mathrm{Re}_{LS}}\right)\right\}\right]^2} \qquad \text{(B21)}$$

where: ε is the pipe roughness

Acceleration pressure drop, $(\Delta P)_A = \rho_L(U_{LTB} + U_{TB})(1-\alpha_{TB})(U_{LTB} + U_{TB} + U_{LLS})$ (B22)

where: velocity of the liquid film around the Taylor bubble, $U_{LTB} = 9.916\left[gD\left(1-\sqrt{\alpha_{TB}}\right)\right]^{1/2}$ (B23) velocity of the Taylor bubble, $U_{TB} = 1.2(U_{SG} + U_{SL}) + 0.35\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}$ (B24)

area average void fraction of the Taylor bubble, $\alpha_{TB} = \frac{\text{Average all area at Taylor bubble region}}{\text{Average area in Taylor bubble}}$ (B25)

Hydrostatic pressure drop, $(\Delta P)_H = \rho_L(1-\alpha_{LS})gL_{LS}$ (B26)

where: void fraction of the liquid slug, $\alpha_{LS} = \frac{U_{SG}}{0.425 + 2.65(U_{SG} + U_{SL})}$ (B27)

length of the liquid slug, L_{LS}

Frictional pressure drop of slug unit, $(\Delta P)_F = \frac{L_{LS}}{2D}\left[\frac{\rho_G \beta f_{TB} U_{TB}^2}{(1-\beta)\left[1-(1-\alpha_{TB}^{1/2}\right]} + U_{LLS}^2 \rho_L (1-\alpha_{LS}) f_{LS} (1-\beta)\right]$ (B28)

Total pressure drop in the slug unit, $(\Delta P)_T = (\Delta P)_A + (\Delta P)_H + (\Delta P)_F$ (B29)

Re_{water}	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
0	288.69	slug	0.2233	0.0640	5311	0.0368	859	2520	0.5087	3379.4	3.3794	8.8376
0	367.06	slug	0.2756	0.0640	6752	0.0344	888	2623	0.7490	3512.3	3.5123	8.0267
0	445.44	slug	0.2500	0.0601	8194	0.0327	708	3114	1.2793	3824.0	3.8240	7.4613
0	519.64	slug	0.3696	0.0641	9559	0.0314	948	2288	1.0448	3236.8	3.2368	7.0992
0	629.11	slug	0.3212	0.0602	11573	0.0299	771	2908	1.9758	3680.9	3.6809	6.6887
0	738.59	slug	0.4149	0.0617	13587	0.0287	890	2521	1.9711	3413.0	3.4130	6.0505
0	848.06	slug	0.4883	0.0639	15601	0.0277	1064	2526	2.2238	3592.2	3.5922	5.4703
0	957.53	slug	0.5069	0.0639	17615	0.0269	1110	2650	2.7864	3762.7	3.7627	5.1900
1028	445.44	slug	0.2864	0.0639	9222	0.0317	931	2478	1.1918	3410.0	3.4100	8.0445
1028	519.64	slug	0.3088	0.0621	10587	0.0306	853	2207	1.3075	3062.0	3.0620	7.7192
1028	629.11	slug	0.3463	0.0640	12601	0.0292	1007	2704	2.0570	3712.4	3.7124	7.0688
1028	738.59	slug	0.3348	0.0639	14615	0.0282	1046	3170	3.1725	4218.8	4.2188	6.8414
1028	848.06	slug	0.4131	0.0640	16628	0.0273	1090	2489	2.7739	3582.1	3.5821	6.4215
1028	957.53	slug	0.4122	0.0638	18642	0.0265	1124	2717	3.7022	3845.1	3.8451	6.2352
1028	1067.01	slug	0.4903	0.0640	20656	0.0259	1179	1943	2.7772	3124.7	3.1247	6.0673

Table B7 Determination of the pressure gradient from experiment for pure water

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.053 m;

cross-sectional area of pipe, A = 0.0022 m^2; pressure taps difference = 0.4 m

Procedure to determine of pressure gradient from experiment:

1. Read the highest and lowest difference level from manometer.
2. Put the value of difference level in $-\frac{dp}{dz} = \frac{\rho_w g(100 - level_{water,L}) - (100 - level_{water,R})}{100x0.4x1000}$ (B30)

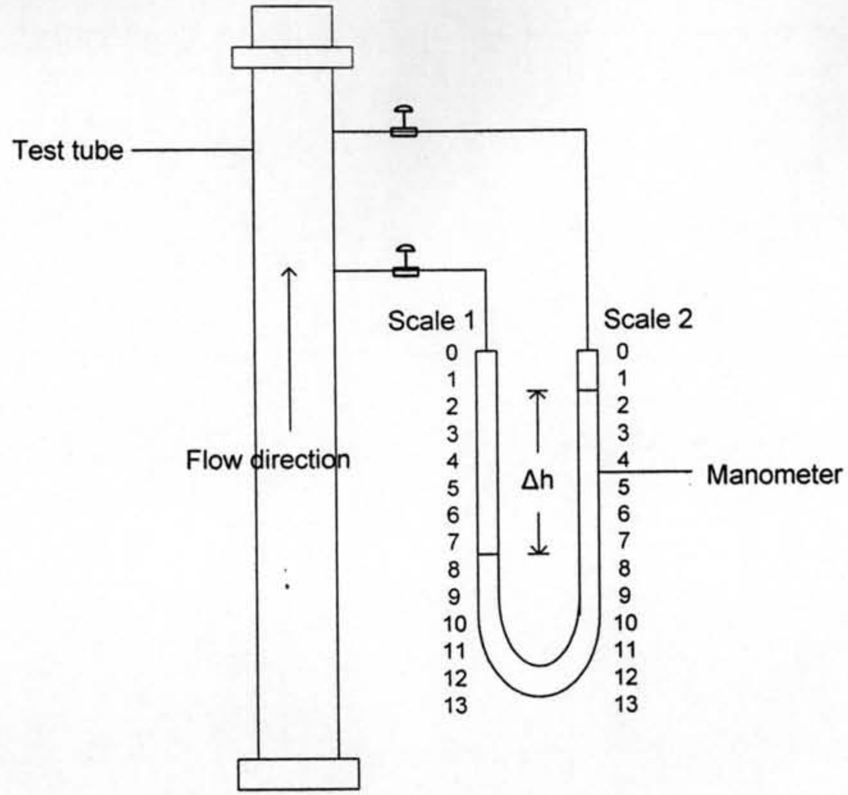


Figure B10 Appearance scale and water level in manometer.

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
0	2.90	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	5.56	Bubble	79	79	79	79	79	39.1	39.1	39.1	39.1	39.1
0	8.20	Bubble	79	79	79	79	79	39.1	39.1	39.1	39.1	39.1
0	10.04	Bubble	79	79	79	79	79	39.1	39.1	39.1	39.1	39.1
0	11.87	Bubble	79	79	79	79	79	39.1	39.1	39.1	39.1	39.1
0	13.70	Bubble	79	79	79	79	79	39.1	39.1	39.1	39.1	39.1
0	15.54	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	17.37	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	21.04	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	22.87	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	28.37	Bubble	79.2	79.2	79.2	79.2	79.2	39.3	39.3	39.3	39.3	39.3
0	33.87	Bubble	79.2	79.2	79.2	79.2	79.2	39.3	39.3	39.3	39.3	39.3
0	37.54	Bubble	79.2	79.2	79.2	79.2	79.2	39.3	39.3	39.3	39.3	39.3
0	43.04	Bubble	79.1	79.1	79.1	79.1	79.1	39.3	39.3	39.3	39.3	39.3
0	48.54	Bubble	79.1	79.1	79.1	79.1	79.1	39.4	39.4	39.4	39.4	39.4
0	59.53	Bubble	79	79	79	79	79	39.5	39.5	39.5	39.5	39.5
0	68.70	Bubble	78.8	78.8	78.8	78.8	78.8	39.6	39.7	39.6	39.6	39.6
0	79.70	Bubble	79	79	79	79	79	39.6	39.6	39.6	39.6	39.6
0	88.87	Bubble	78.6	78.6	78.6	78.6	78.6	39.9	39.9	39.9	39.9	39.9
0	100	Bubble	78.5	78.5	78.5	78.5	78.5	40	40	40	40	40
0	132	Bubble-Slug	93	93	93	93	93	58	58	58	58	58
0	184	Bubble-Slug	77	77.2	77	77	77	41	41.2	41.1	41.3	41.2
0	289	Slug	75.8	75.8	75.8	75.7	75.7	42.7	42.8	42.9	43	42.8
0	367	Slug	75	75	75	75	75	43.2	43.5	43.4	43.6	43.5
0	445	Slug	91	91.2	91.2	91	91	59.9	59.6	60	60.2	59.9

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
0	520	Slug	73	72.8	72.5	72.5	72.6	42.8	43.8	44	43.9	44.2
0	629	Slug	93.5	93.5	93.5	93.4	93.4	66	66.2	66.3	66.2	66.3
0	739	Slug	70	70	71	70.5	70.5	47	46.5	45.8	46	45.5
0	848	Slug	90.8	91	90.9	90.8	90.6	69	69	69	68.9	69
0	958	Slug	89.4	89.4	89.4	89.4	89.5	70.4	70.5	70.5	70.5	70.3
0	1067	Slug	88.6	88.6	88.6	88.5	88.5	71.4	71.3	71.3	71.4	71.3
0	1176	Slug	87.8	87.8	87.8	87.5	87.5	72	72	72	72.2	72.1
0	1322	Slug	88	87.6	87.6	87.7	88	71.8	72.2	72	72	71.8
0	1450	Slug	67.8	67.8	66	67	66.8	48.8	48.8	50.5	49	49.5
1028	2.90	Bubble	90	90	90	90	90	50.2	50.2	50.2	50.2	50.2
1028	5.56	Bubble	90	90	90	90	90	50.2	50.2	50.2	50.2	50.2
1028	8.20	Bubble	90	90	90	90	90	50.2	50.2	50.2	50.2	50.2
1028	10.04	Bubble	89.9	89.9	89.9	89.9	89.9	50.2	50.2	50.2	50.2	50.2
1028	11.87	Bubble	89.9	89.9	89.9	89.9	89.9	50.3	50.3	50.3	50.3	50.3
1028	13.70	Bubble	89.9	89.9	89.9	89.9	89.9	50.3	50.3	50.3	50.3	50.3
1028	15.54	Bubble	89.8	89.8	89.8	89.8	89.8	50.3	50.3	50.3	50.3	50.3
1028	17.37	Bubble	89.8	89.8	89.8	89.8	89.8	50.3	50.3	50.3	50.3	50.3
1028	21.04	Bubble	89.7	89.7	89.7	89.7	89.7	50.4	50.4	50.4	50.4	50.4
1028	22.87	Bubble	89.7	89.7	89.7	89.7	89.7	50.4	50.4	50.4	50.4	50.4
1028	28.37	Bubble	89.6	89.6	89.6	89.6	89.6	50.5	50.5	50.5	50.5	50.5
1028	33.87	Bubble	89.4	89.4	89.4	89.4	89.4	50.6	50.6	50.6	50.6	50.6
1028	37.54	Bubble	89.4	89.4	89.4	89.4	89.4	50.7	50.7	50.7	50.7	50.7
1028	43.04	Bubble	89.3	89.3	89.3	89.3	89.3	50.8	50.8	50.8	50.8	50.8
1028	48.54	Bubble	89.2	89.2	89.2	89.2	89.2	50.9	50.9	50.9	50.9	50.9
1028	59.53	Bubble	89	89	89	89	89	51	51	51	51	51
1028	68.70	Bubble	88.9	88.9	88.9	88.9	88.9	51.2	51.2	51.2	51.2	51.2
1028	79.70	Bubble	88.9	88.9	88.9	88.9	88.9	51.3	51.3	51.3	51.3	51.3

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
1028	88.87	Bubble	88.6	88.6	88.6	88.6	88.6	51.5	51.5	51.5	51.5	51.5
1028	100	Bubble	88.5	88.5	88.5	88.5	88.5	51.6	51.6	51.6	51.6	51.6
1028	132	Bubble	88	88	88	88	88	52.2	52.2	52.2	52.2	52.2
1028	184	Bubble-Slug	87.5	87.4	87.4	87.4	87.4	52.5	52.6	52.6	52.6	52.6
1028	289	Bubble-Slug	86.5	86.5	86.5	86.5	86.6	53.6	53.6	53.7	53.4	53.5
1028	367	Bubble-Slug	86	86	85.9	86	86	54.2	54.1	54.1	54	54.1
1028	445	Slug	85.7	85.6	85.6	85.6	85.6	54.6	54.6	54.6	54.7	54.7
1028	520	Slug	81.9	82	82	82	82	51.9	51.9	51.9	51.9	51.9
1028	629	Slug	81.2	81.2	81.1	81.1	81.1	52.6	52.6	52.7	52.6	52.6
1028	739	Slug	80.5	80.4	80.5	80.5	80.5	53.1	53.2	53.2	53.2	53.3
1028	848	Slug	79.6	79.6	79.6	79.7	79.6	54	54	54.1	54.1	54.1
1028	958	Slug	79.2	79.3	79.2	79.2	79.3	54.6	54.2	54.3	54.3	54.5
1028	1067	Slug	78.5	78.5	78.6	78.6	78.6	55	55.1	55.1	55.1	55
1028	1176	Slug	77.9	77.9	77.9	78	78	56	56	56	55.8	55.8
1028	1322	Slug	77.3	77.4	77.5	77.5	77.5	56	56.1	56.1	56.1	56.2
1028	1450	Slug	76.7	76.7	76.8	76.8	76.8	57	56.8	57	57	57
1028	2548	Slug-Churn	85.9	85.8	85.7	85.8	85.8	67.6	67.5	67.5	67.6	67.5
1028	5096	Slug-Churn	83.6	83.8	83.5	83.6	83.6	69.6	70.2	69.9	69.8	69.8
1028	7644	Slug-Churn	82.6	82.5	82.6	82.8	82.8	70.5	71.1	70.8	70.9	70.6
1028	10192	Churn	82.6	82.5	82	82.5	82	70.8	71.1	71.5	71.4	71.3
1028	12740	Churn	82	82	81.6	81.8	81.9	71.5	71.6	72	71.8	71.9
1028	15288	Churn	81.5	81.2	81	81	81	72.1	72	72	72	72.2
1028	17835	Churn	80.5	80.6	80.6	80.6	80.8	72.5	72.6	72.6	72.2	72.2
1028	20383	Churn	80.5	80.6	80.5	80.5	80.5	72.6	72.5	72.5	72.5	72.8
1028	22931	Churn	80.5	80.5	80.5	80.6	80.5	72.8	72.8	72.8	73	73

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
0	2.90	Bubble	79.2	79.2	79.2	79.2	79.2	39.3	39.3	39.3	39.3	39.3
0	5.56	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	8.20	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	10.04	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	11.87	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	13.70	Bubble	79.1	79.1	79.1	79.1	79.1	39.2	39.2	39.2	39.2	39.2
0	15.54	Bubble	79.2	79.2	79.2	79.2	79.2	39.3	39.3	39.3	39.3	39.3
0	17.37	Bubble	79.2	79.2	79.2	79.2	79.2	39.3	39.3	39.3	39.3	39.3
0	21.04	Bubble	79.2	79.2	79.2	79.2	79.2	39.3	39.3	39.3	39.3	39.3
0	22.87	Bubble	79.2	79.2	79.2	79.2	79.2	39.3	39.3	39.3	39.3	39.3
0	28.37	Bubble	79.1	79.1	79.1	79.1	79.1	39.3	39.3	39.3	39.3	39.3
0	33.87	Bubble	79.1	79.1	79.1	79.1	79.1	39.3	39.3	39.3	39.3	39.3
0	37.54	Bubble	79.1	79.1	79.1	79.1	79.1	39.3	39.3	39.3	39.3	39.3
0	43.04	Bubble	79.1	79.1	79.1	79.1	79.1	39.3	39.3	39.3	39.3	39.3
0	48.54	Bubble	79	79	79	79	79	39.5	39.5	39.5	39.5	39.5
0	59.53	Bubble	78.8	78.8	78.8	78.8	78.8	39.7	39.7	39.7	39.7	39.7
0	68.70	Bubble	78.7	78.7	78.7	78.7	78.7	39.7	39.7	39.7	39.7	39.7
0	79.70	Bubble	78.7	78.6	78.6	78.6	78.6	39.8	39.8	39.8	39.8	39.8
0	88.87	Bubble	78.1	78.1	78.1	78.1	78.1	40.5	40.5	40.5	40.5	40.5
0	100	Bubble	78	78	78	78	78	40.6	40.6	40.6	40.6	40.6
0	132	Bubble-Slug	92.7	92.7	92.7	92.7	92.7	58.3	58.3	58.3	58.3	58.3
0	184	Bubble-Slug	75.4	75.3	75.5	75.4	75.5	42.7	43	42.8	43	43
0	289	Slug	74	73.9	74	74	74	43.9	44.5	44.6	44.5	44.5
0	367	Slug	73	72.8	73	73.2	73	45.5	45.6	45.5	45.4	45.4
0	445	Slug	89	88.9	89	89	89	61.6	61.6	61.5	62	61.8
0	520	Slug	71	71	71.2	71	71.3	44.5	45	44.4	44.7	44.9

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
0	629	Slug	92.6	92.5	92.5	92.6	92.5	67.4	67.5	67.4	67.3	67.5
0	739	Slug	70.5	70	69.5	70.5	69.5	46.8	48	47.5	46.5	47
0	848	Slug	89.8	89.5	89.7	89.5	89.4	70	70	70	70	70.1
0	958	Slug	88.5	88.5	88.5	88.5	88.4	71	71	71.3	71.2	71.3
0	1067	Slug	87.4	87.3	87.2	87.3	87.3	72.4	72.3	72.4	72.3	72.4
0	1176	Slug	86.5	86.6	86.4	86.5	86.5	73	72.9	73	73	73
0	1322	Slug	86.7	86.4	86.4	86.3	86.2	73.3	73.4	73.4	73.4	73.4
0	1450	Slug	64	64.5	64.3	64	63	52.5	52.5	52.2	51.8	53
1028	2.90	Bubble	90	90	90	90	90	50.2	50.2	50.2	50.2	50.2
1028	5.56	Bubble	90	90	90	90	90	50.2	50.2	50.2	50.2	50.2
1028	8.20	Bubble	90	90	90	90	90	50.2	50.2	50.2	50.2	50.2
1028	10.04	Bubble	89.9	89.9	89.9	89.9	89.9	50.2	50.2	50.2	50.2	50.2
1028	11.87	Bubble	89.9	89.9	89.9	89.9	89.9	50.3	50.3	50.3	50.3	50.3
1028	13.70	Bubble	89.9	89.9	89.9	89.9	89.9	50.3	50.3	50.3	50.3	50.3
1028	15.54	Bubble	89.8	89.8	89.8	89.8	89.8	50.3	50.3	50.3	50.3	50.3
1028	17.37	Bubble	89.8	89.8	89.8	89.8	89.8	50.3	50.3	50.3	50.3	50.3
1028	21.04	Bubble	89.7	89.7	89.7	89.7	89.7	50.4	50.4	50.4	50.4	50.4
1028	22.87	Bubble	89.7	89.7	89.7	89.7	89.7	50.4	50.4	50.4	50.4	50.4
1028	28.37	Bubble	89.6	89.6	89.6	89.6	89.6	50.5	50.5	50.5	50.5	50.5
1028	33.87	Bubble	89.4	89.4	89.4	89.4	89.4	50.6	50.6	50.6	50.6	50.6
1028	37.54	Bubble	89.4	89.4	89.4	89.4	89.4	50.7	50.7	50.7	50.7	50.7
1028	43.04	Bubble	89.3	89.3	89.3	89.3	89.3	50.8	50.8	50.8	50.8	50.8
1028	48.54	Bubble	89.2	89.2	89.2	89.2	89.2	50.9	50.9	50.9	50.9	50.9
1028	59.53	Bubble	89	89	89	89	89	51	51	51	51	51
1028	68.70	Bubble	88.8	88.8	88.8	88.8	88.8	51.3	51.3	51.3	51.3	51.3
1028	79.70	Bubble	88.7	88.7	88.7	88.7	88.7	51.4	51.4	51.4	51.4	51.4
1028	88.87	Bubble	88.5	88.5	88.5	88.5	88.5	51.6	51.6	51.6	51.6	51.6

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
1028	100	Bubble	88.3	88.3	88.3	88.3	88.3	51.7	51.7	51.7	51.7	51.7
1028	132	Bubble	87.6	87.6	87.5	87.5	87.5	52.5	52.5	52.5	52.5	52.6
1028	184	Bubble-Slug	87	87	87	87	87	53	53.1	53.1	53.1	53.1
1028	289	Bubble-Slug	86	86	86	86	86	53.9	54	54	54	54
1028	367	Bubble-Slug	85.6	85.5	85.5	85.6	85.5	54.6	54.5	54.6	54.5	54.5
1028	445	Slug	84.9	84.9	85	84.9	85	55.3	55.5	55.4	55.4	55.4
1028	520	Slug	81.5	81.5	81.4	81.4	81.5	52.3	52.2	52.2	52.3	52.2
1028	629	Slug	80.8	80.6	80.6	80.6	80.6	52.9	53	53.1	53.1	53
1028	739	Slug	79.8	79.8	79.9	79.8	79.8	54	53.9	53.8	53.9	54
1028	848	Slug	79.2	79.3	79.1	79.2	79.2	54.6	54.5	54.7	54.4	54.6
1028	958	Slug	78.6	78.5	78.5	78.6	78.6	55	55	55	55	55.1
1028	1067	Slug	77.6	77.6	77.5	77.6	77.6	56	55.9	56	55.9	55.9
1028	1176	Slug	77.5	77.5	77.5	77.4	77.4	56.5	56	56.3	56.3	56.4
1028	1322	Slug	76.6	76.6	76.7	76.7	76.7	57.3	57.4	57.3	57.2	57.2
1028	1450	Slug	76.2	76.1	76.2	76.2	76.1	57.7	57.8	57.6	57.6	57.8
1028	2548	Slug-Churn	85.1	85.1	85.1	85.1	85	68.5	68.6	68.5	68.5	68.5
1028	5096	Slug-Churn	83	83	83	83	83.1	71.4	71	71.3	70.8	70.2
1028	7644	Slug-Churn	81.8	81.8	81.6	82	81.6	71.6	71.8	71.5	71.6	71.3
1028	10192	Churn	80.5	81	81.5	81	79	72.5	72	72.5	72	74
1028	12740	Churn	79	79.5	79	79	79.8	74	73	73.8	73.6	73
1028	15288	Churn	79	79	79	79	79	74	74.5	73.8	73.8	74
1028	17835	Churn	78	79	79.2	78	79	74.4	74	74	75	73.8
1028	20383	Churn	78.5	78	78.5	78.5	78.5	74	74.8	75.2	74.5	74.6
1028	22931	Churn	78	78.5	78	78	78	75	74.3	74.8	75.1	75.2

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
0	2.90	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	5.56	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	8.20	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	10.04	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	11.87	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	13.70	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	15.54	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	17.37	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	21.04	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	22.87	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
0	28.37	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7121	9.7121	9.7121	9.7121	9.7121	9.7243 ± 0.01
0	33.87	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7121	9.7121	9.7121	9.7121	9.7121	9.7243 ± 0.01
0	37.54	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7121	9.7121	9.7121	9.7121	9.7121	9.7243 ± 0.01
0	43.04	Bubble	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121 ± 0.00
0	48.54	Bubble	9.6877	9.6877	9.6877	9.6877	9.6877	9.6389	9.6389	9.6389	9.6389	9.6389	9.6633 ± 0.03
0	59.53	Bubble	9.6389	9.6389	9.6389	9.6389	9.6389	9.5413	9.5413	9.5413	9.5413	9.5413	9.5901 ± 0.05
0	68.70	Bubble	9.5657	9.5413	9.5657	9.5657	9.5657	9.5169	9.5169	9.5169	9.5169	9.5169	9.5389 ± 0.02
0	79.70	Bubble	9.6145	9.6145	9.6145	9.6145	9.6145	9.4925	9.4681	9.4681	9.4681	9.4681	9.5438 ± 0.07
0	88.87	Bubble	9.4437	9.4437	9.4437	9.4437	9.4437	9.1753	9.1753	9.1753	9.1753	9.1753	9.3095 ± 0.14
0	100	Bubble	9.3949	9.3949	9.3949	9.3949	9.3949	9.1265	9.1265	9.1265	9.1265	9.1265	9.2607 ± 0.14
0	132	Bubble-Slug	8.5408	8.5408	8.5408	8.5408	8.5408	8.3944	8.3944	8.3944	8.3944	8.3944	8.4676 ± 0.08
0	184	Bubble-Slug	8.7849	8.7849	8.7605	8.7116	8.7361	7.9796	7.8820	7.9796	7.9064	7.9308	8.3456 ± 0.43
0	289	Slug	8.0772	8.0528	8.0284	7.9796	8.0284	7.3451	7.1743	7.1743	7.1987	7.1987	7.6257 ± 0.43
0	367	Slug	7.7600	7.6867	7.7112	7.6623	7.6867	6.7107	6.6374	6.7107	6.7839	6.7351	7.2085 ± 0.52
0	445	Slug	7.5891	7.7112	7.6135	7.5159	7.5891	6.6863	6.6618	6.7107	6.5886	6.6374	7.1304 ± 0.50

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
0	520	Slug	7.3695	7.0767	6.9547	6.9791	6.9303	6.4666	6.3446	6.5398	6.4178	6.4422	6.7521 ± 0.35
0	629	Slug	6.7107	6.6618	6.6374	6.6374	6.6130	6.1494	6.1006	6.1250	6.1738	6.1006	6.3910 ± 0.28
0	739	Slug	5.6125	5.7346	6.1494	5.9786	6.1006	5.7834	5.3685	5.3685	5.8566	5.4905	5.7443 ± 0.28
0	848	Slug	5.3197	5.3685	5.3441	5.3441	5.2709	4.8317	4.7585	4.8073	4.7585	4.7097	5.0513 ± 0.30
0	958	Slug	4.6365	4.6120	4.6120	4.6120	4.6853	4.2704	4.2704	4.1972	4.2216	4.1728	4.4290 ± 0.22
0	1067	Slug	4.1972	4.2216	4.2216	4.1728	4.1972	3.6604	3.6604	3.6116	3.6604	3.6360	3.9239 ± 0.29
0	1176	Slug	3.8556	3.8556	3.8556	3.7336	3.7580	3.2943	3.3431	3.2699	3.2943	3.2943	3.5554 ± 0.27
0	1322	Slug	3.9532	3.7580	3.8068	3.8312	3.9532	3.2699	3.1723	3.1723	3.1479	3.1235	3.5188 ± 0.37
0	1450	Slug	4.6365	4.6365	3.7824	4.3924	4.2216	2.8063	2.9283	2.9527	2.9771	2.4402	3.5774 ± 0.84
1028	2.90	Bubble	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121 ± 0.00
1028	5.56	Bubble	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121 ± 0.00
1028	8.20	Bubble	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121	9.7121 ± 0.00
1028	10.04	Bubble	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877 ± 0.00
1028	11.87	Bubble	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633 ± 0.00
1028	13.70	Bubble	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633	9.6633 ± 0.00
1028	15.54	Bubble	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389 ± 0.00
1028	17.37	Bubble	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389 ± 0.00
1028	21.04	Bubble	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901 ± 0.00
1028	22.87	Bubble	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901	9.5901 ± 0.00
1028	28.37	Bubble	9.5413	9.5413	9.5413	9.5413	9.5413	9.5413	9.5413	9.5413	9.5413	9.5413	9.5413 ± 0.00
1028	33.87	Bubble	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681 ± 0.00
1028	37.54	Bubble	9.4437	9.4437	9.4437	9.4437	9.4437	9.4437	9.4437	9.4437	9.4437	9.4437	9.4437 ± 0.00
1028	43.04	Bubble	9.3949	9.3949	9.3949	9.3949	9.3949	9.3949	9.3949	9.3949	9.3949	9.3949	9.3949 ± 0.00
1028	48.54	Bubble	9.3461	9.3461	9.3461	9.3461	9.3461	9.3461	9.3461	9.3461	9.3461	9.3461	9.3461 ± 0.00
1028	59.53	Bubble	9.2729	9.2729	9.2729	9.2729	9.2729	9.2729	9.2729	9.2729	9.2729	9.2729	9.2729 ± 0.00
1028	68.70	Bubble	9.1997	9.1997	9.1997	9.1997	9.1997	9.1509	9.1509	9.1509	9.1509	9.1509	9.1753 ± 0.03
1028	79.70	Bubble	9.1753	9.1753	9.1753	9.1753	9.1753	9.1021	9.1021	9.1021	9.1021	9.1021	9.1387 ± 0.04

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
1028	88.87	Bubble	9.0533	9.0533	9.0533	9.0533	9.0533	9.0045	9.0045	9.0045	9.0045	9.0045	9.0289 ± 0.03
1028	100	Bubble	9.0045	9.0045	9.0045	9.0045	9.0045	8.9313	8.9313	8.9313	8.9313	8.9313	8.9679 ± 0.04
1028	132	Bubble	8.7361	8.7361	8.7361	8.7361	8.7361	8.5652	8.5652	8.5408	8.5408	8.5164	8.6409 ± 0.10
1028	184	Bubble-Slug	8.5408	8.4920	8.4920	8.4920	8.4920	8.2968	8.2724	8.2724	8.2724	8.2724	8.3895 ± 0.12
1028	289	Bubble-Slug	8.0284	8.0284	8.0040	8.0772	8.0772	7.8332	7.8088	7.8088	7.8088	7.8088	7.9283 ± 0.12
1028	367	Bubble-Slug	7.7600	7.7844	7.7600	7.8088	7.7844	7.5647	7.5647	7.5403	7.5891	7.5647	7.6721 ± 0.11
1028	445	Slug	7.5891	7.5647	7.5647	7.5403	7.5403	7.2231	7.1743	7.2231	7.1987	7.2231	7.3842 ± 0.19
1028	520	Slug	7.3207	7.3451	7.3451	7.3451	7.3451	7.1255	7.1499	7.1255	7.1011	7.1499	7.2353 ± 0.11
1028	629	Slug	6.9791	6.9791	6.9303	6.9547	6.9547	6.8083	6.7351	6.7107	6.7107	6.7351	6.8497 ± 0.12
1028	739	Slug	6.6863	6.6374	6.6618	6.6618	6.6374	6.2958	6.3202	6.3690	6.3202	6.2958	6.4886 ± 0.18
1028	848	Slug	6.2470	6.2470	6.2226	6.2470	6.2226	6.0030	6.0518	5.9542	6.0518	6.0030	6.1250 ± 0.12
1028	958	Slug	6.0030	6.1250	6.0762	6.0762	6.0518	5.7590	5.7346	5.7346	5.7590	5.7346	5.9054 ± 0.17
1028	1067	Slug	5.7346	5.7102	5.7346	5.7346	5.7590	5.2709	5.2953	5.2465	5.2953	5.2953	5.5076 ± 0.24
1028	1176	Slug	5.3441	5.3441	5.3441	5.4173	5.4173	5.1245	5.2465	5.1733	5.1489	5.1245	5.2685 ± 0.12
1028	1322	Slug	5.1977	5.1977	5.2221	5.2221	5.1977	4.7097	4.6853	4.7341	4.7585	4.7585	4.9683 ± 0.25
1028	1450	Slug	4.8073	4.8561	4.8317	4.8317	4.8317	4.5144	4.4656	4.5388	4.5388	4.4656	4.6682 ± 0.17
1028	2548	Slug-Churn	4.4656	4.4656	4.4412	4.4412	4.4656	4.0508	4.0264	4.0508	4.0508	4.0264	4.2485 ± 0.22
1028	5096	Slug-Churn	3.4163	3.3187	3.3187	3.3675	3.3675	2.8307	2.9283	2.8551	2.9771	3.1479	3.1528 ± 0.23
1028	7644	Slug-Churn	2.9527	2.7819	2.8795	2.9039	2.9771	2.4890	2.4402	2.4646	2.5378	2.5134	2.6940 ± 0.22
1028	10192	Churn	2.8795	2.7819	2.5622	2.7087	2.6111	1.9522	2.1962	2.1962	2.1962	1.2201	2.3304 ± 0.50
1028	12740	Churn	2.5622	2.5378	2.3426	2.4402	2.4402	1.2201	1.5862	1.2689	1.3177	1.6594	1.9375 ± 0.57
1028	15288	Churn	2.2938	2.2450	2.1962	2.1962	2.1474	1.2201	1.0981	1.2689	1.2689	1.2201	1.7155 ± 0.53
1028	17835	Churn	1.9522	1.9522	1.9522	2.0498	2.0986	0.8785	1.2201	1.2689	0.7321	1.2689	1.5373 ± 0.52
1028	20383	Churn	1.9278	1.9766	1.9522	1.9522	1.8790	1.0981	0.7809	0.8053	0.9761	0.9517	1.4300 ± 0.54
1028	22931	Churn	1.8790	1.8790	1.8790	1.8546	1.8302	0.7321	1.0249	0.7809	0.7077	0.6833	1.3250 ± 0.58

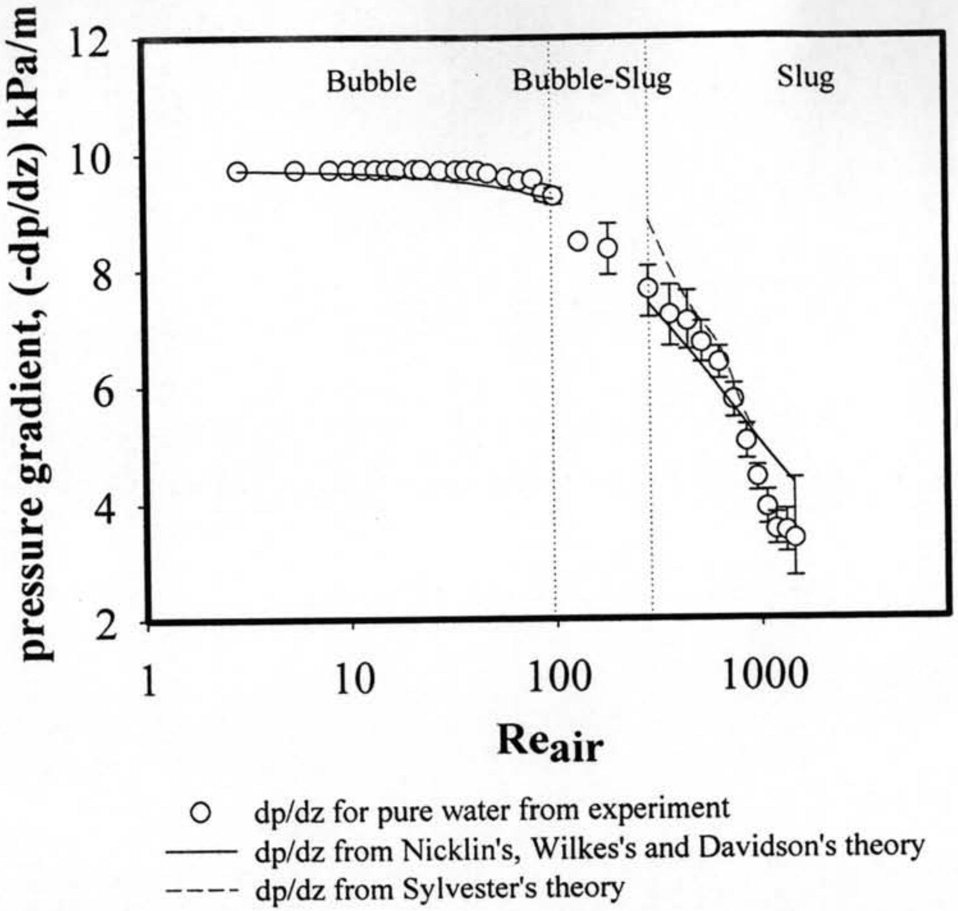


Figure B11 Comparison between Nicklin's theory, Sylvester's theory and experimental pressure gradient vs. air Reynolds number of pure water at $Re_{water} = 0$ by using pipe diameter 53.15 mm.

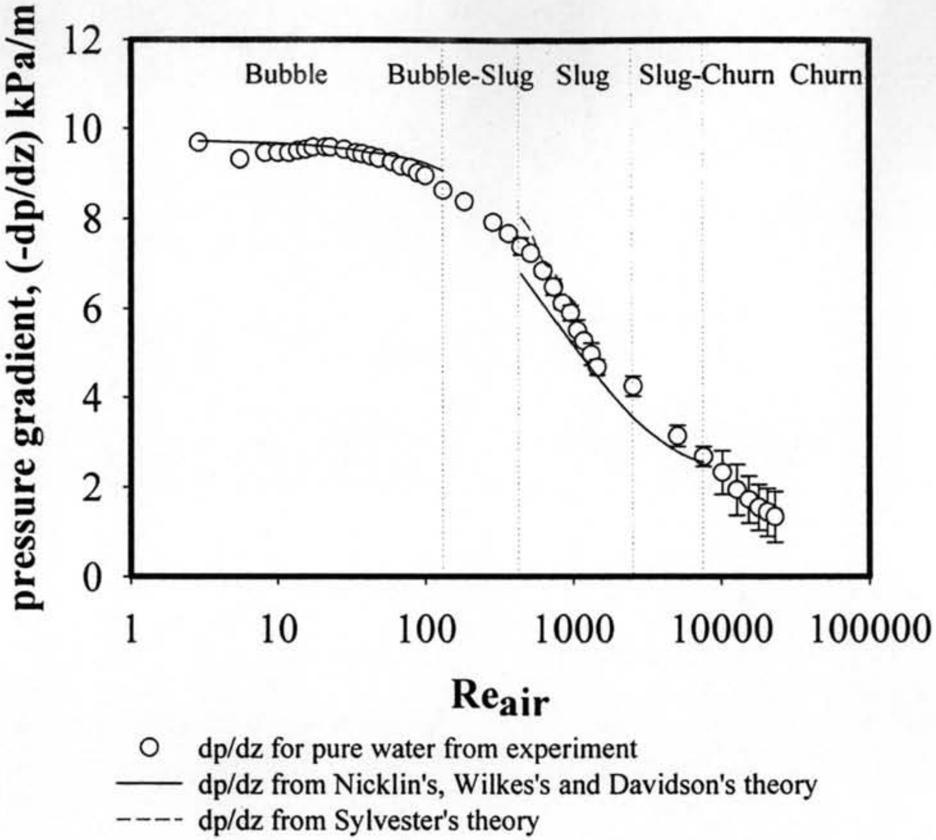


Figure B12 Comparison between Nicklin's theory, Sylvester's theory and experimental pressure gradient vs. air Reynolds number of pure water at Re_{water} = 1028 by using pipe diameter 53.15 mm.

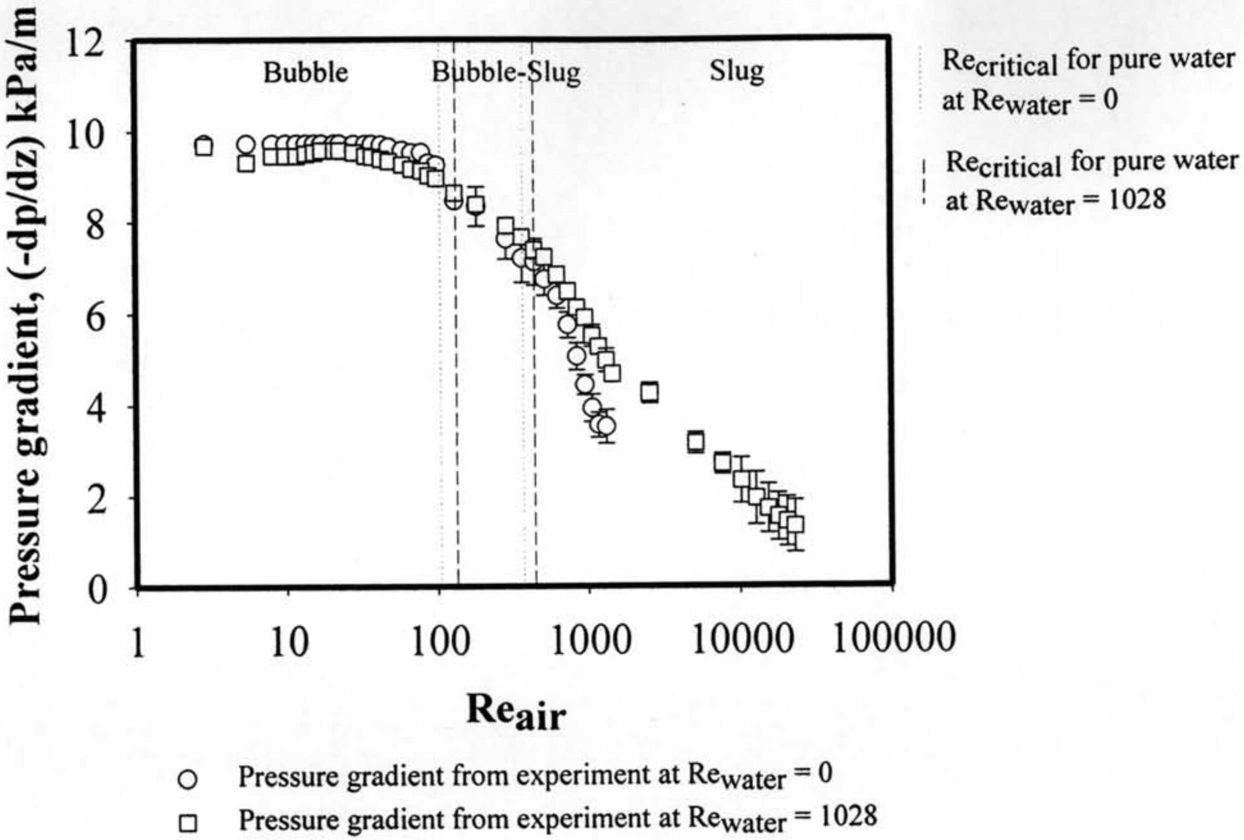


Figure B13 Comparison pressure gradient from experiment vs. air Reynolds number of pure water by using pipe diameter 53.15 mm.

Table B8 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes by using pipe diameter of 53.15 mm

Pipe diameter (mm)	Re_{water}	Re_{air}(critical) for each flow regime					
		Bubble-slug	Slug	Slug-churn	Churn	Annular	Mist
53.15	0	132	289	-	-	-	-
	1028	184	445	2548	10192	-	-

Appendix C Water-Air Flow for the Pipe diameter of 10.75 mm

Table C1 Determination of bubble size for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

Procedure to determine the bubble size:

1. Make a movie of the bubble flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the bubble size by Scion Image software program.

Equivalent diameter (D_e) of the bubble is defined as the diameter of a sphere that has the same volume as the bubble.

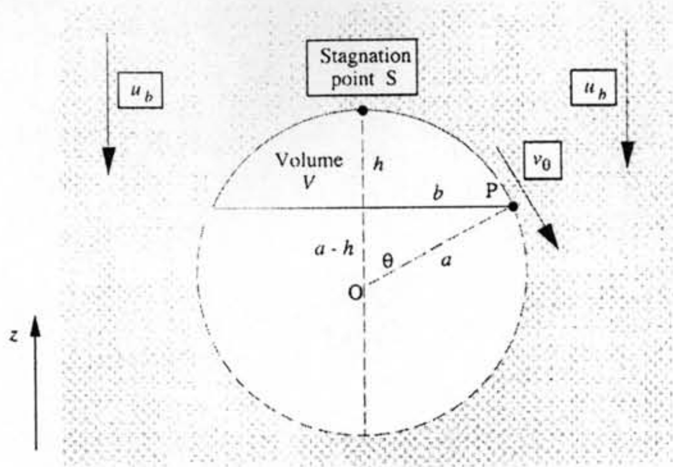


Figure C1 Flow around a spherical cap bubble (Wilkes, 1999).

$$\text{Equivalent diameter } (D_e) = \sqrt[3]{3.94h\left[\frac{h^2+b^2}{2h}\right]^2 - 1.94b^2\left[\left(\frac{h^2+b^2}{2h}\right)-h\right]} \qquad \text{(C1)}$$

Re_{water}	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble width, W_b (mm)			Average bubble width (mm)	Equivalent diameter, D_e (mm)			Average equivalent diameter, De (mm)
		1	2	3		1	2	3		1	2	3	
0	1.2	11.3	11.2	11.4	11.3 ± 0.1	8.8	8.4	9.1	8.8 ± 0.3	12.7	12.5	12.9	12.7 ± 0.2
0	3.4	11.5	11.9	11.6	11.7 ± 0.2	8.8	9.6	9.5	9.3 ± 0.5	12.9	13.5	13.2	13.2 ± 0.3
1079	1.2	12.7	12.0	12.2	12.3 ± 0.4	9.0	9.1	9.4	9.2 ± 0.2	14.1	13.4	13.7	13.7 ± 0.3
1079	3.4	12.7	13.0	13.1	12.9 ± 0.2	9.6	9.4	9.4	9.4 ± 0.1	14.2	14.4	14.5	14.4 ± 0.1
1079	5.6	12.9	12.8	12.7	12.8 ± 0.1	9.4	9.3	9.6	9.4 ± 0.1	14.4	14.2	14.2	14.3 ± 0.1
1079	10.0	13.0	12.9	13.1	13.0 ± 0.1	9.2	9.4	9.6	9.4 ± 0.2	14.4	14.3	14.6	14.4 ± 0.1
2727	1.2	7.1	7.8	7.3	7.4 ± 0.4	7.0	7.9	7.3	7.4 ± 0.4	8.5	9.4	8.7	8.9 ± 0.5
2727	3.4	7.3	8.4	8.1	7.9 ± 0.6	7.7	7.5	8.0	7.7 ± 0.3	8.9	9.8	9.7	9.4 ± 0.5
2727	5.6	8.5	8.8	9.2	8.8 ± 0.3	8.5	8.7	8.4	8.5 ± 0.1	10.2	10.5	10.7	10.5 ± 0.3
2727	10.0	9.2	8.8	9.1	9.0 ± 0.2	9.4	8.4	8.0	8.6 ± 0.7	11.1	10.4	10.5	10.7 ± 0.3
2727	14.3	12.9	12.0	12.7	12.5 ± 0.5	7.9	8.1	9.0	8.3 ± 0.6	13.9	13.1	14.1	13.7 ± 0.5
2727	18.7	12.2	12.7	12.7	12.5 ± 0.3	9.3	9.1	8.7	9.0 ± 0.3	13.7	14.1	14.0	13.9 ± 0.2
2727	23.1	14.2	12.4	13.5	13.3 ± 0.9	8.8	9.1	9.4	9.1 ± 0.3	15.4	13.8	14.9	14.7 ± 0.8

Re_{water}	Re_{air}	Bubble height / Pipe diameter			Average, R_h/D	Bubble Width / Pipe diameter			Average, W_b/D	Equivalent diameter / Pipe diameter			Average equivalent diameter, De/D
		1	2	3		1	2	3		1	2	3	
0	1.2	1.05	1.04	1.06	1.05 ± 0.01	0.82	0.78	0.85	0.82 ± 0.03	1.18	1.17	1.20	1.18 ± 0.02
0	3.4	1.07	1.11	1.08	1.08 ± 0.02	0.82	0.90	0.88	0.86 ± 0.04	1.20	1.26	1.23	1.23 ± 0.03
1079	1.2	1.18	1.11	1.14	1.14 ± 0.04	0.84	0.84	0.88	0.85 ± 0.02	1.31	1.25	1.28	1.28 ± 0.03
1079	3.4	1.18	1.21	1.22	1.20 ± 0.02	0.89	0.87	0.88	0.88 ± 0.01	1.33	1.34	1.35	1.34 ± 0.01
1079	5.6	1.20	1.19	1.18	1.19 ± 0.01	0.88	0.87	0.89	0.88 ± 0.01	1.34	1.32	1.32	1.33 ± 0.01
1079	10.0	1.21	1.20	1.22	1.21 ± 0.01	0.86	0.87	0.89	0.87 ± 0.02	1.34	1.33	1.36	1.34 ± 0.01
2727	1.2	0.66	0.73	0.68	0.69 ± 0.03	0.66	0.74	0.68	0.69 ± 0.04	0.79	0.88	0.81	0.83 ± 0.04
2727	3.4	0.68	0.79	0.76	0.74 ± 0.06	0.72	0.69	0.74	0.72 ± 0.02	0.83	0.91	0.90	0.88 ± 0.05
2727	5.6	0.79	0.82	0.85	0.82 ± 0.03	0.79	0.80	0.78	0.79 ± 0.01	0.95	0.97	1.00	0.97 ± 0.02
2727	10.0	0.85	0.82	0.85	0.84 ± 0.02	0.88	0.79	0.74	0.80 ± 0.07	1.03	0.97	0.98	0.99 ± 0.03
2727	14.3	1.20	1.11	1.18	1.16 ± 0.05	0.74	0.75	0.83	0.77 ± 0.05	1.29	1.22	1.31	1.27 ± 0.05
2727	18.7	1.13	1.18	1.18	1.17 ± 0.03	0.86	0.85	0.81	0.84 ± 0.03	1.27	1.31	1.30	1.29 ± 0.02
2727	23.1	1.32	1.15	1.25	1.24 ± 0.09	0.82	0.85	0.88	0.85 ± 0.03	1.43	1.28	1.38	1.36 ± 0.08

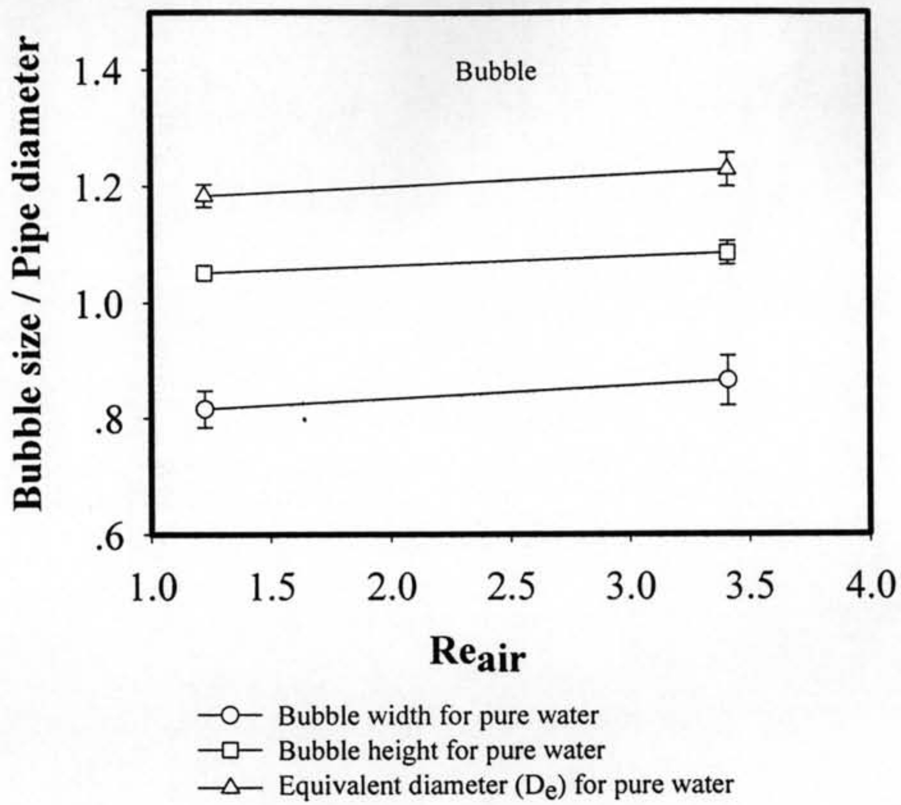


Figure C2 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of pure water at $Re_{water} = 0$ by using pipe diameter 10.75 mm.

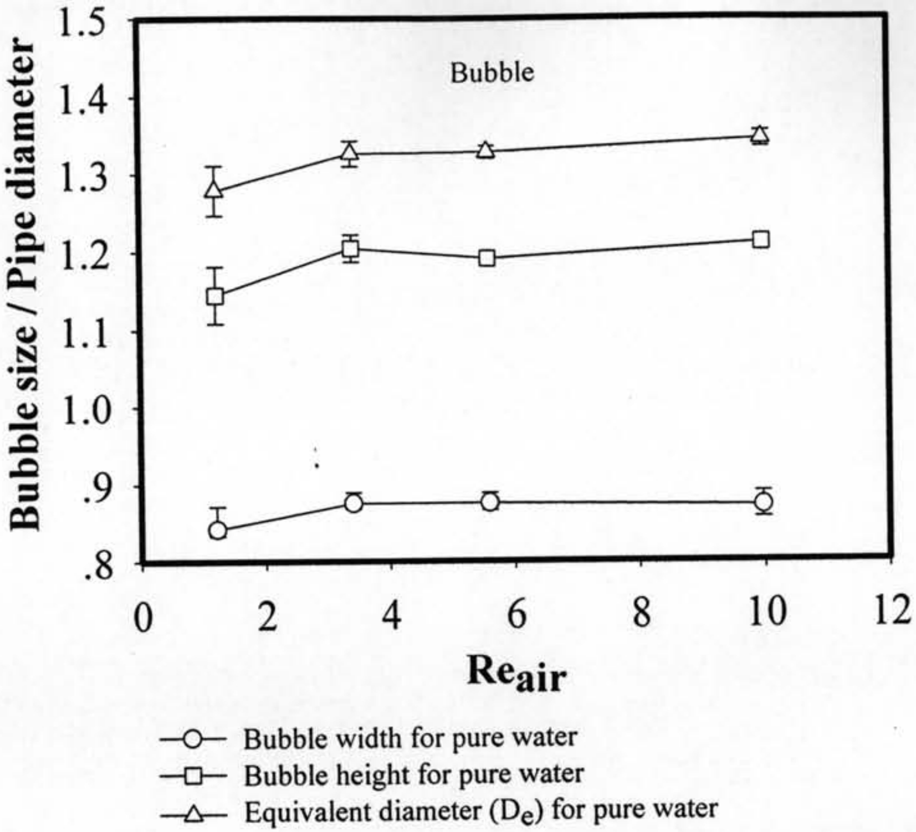


Figure C3 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of pure water at Re_{water} = 1079 by using pipe diameter 10.75 mm.

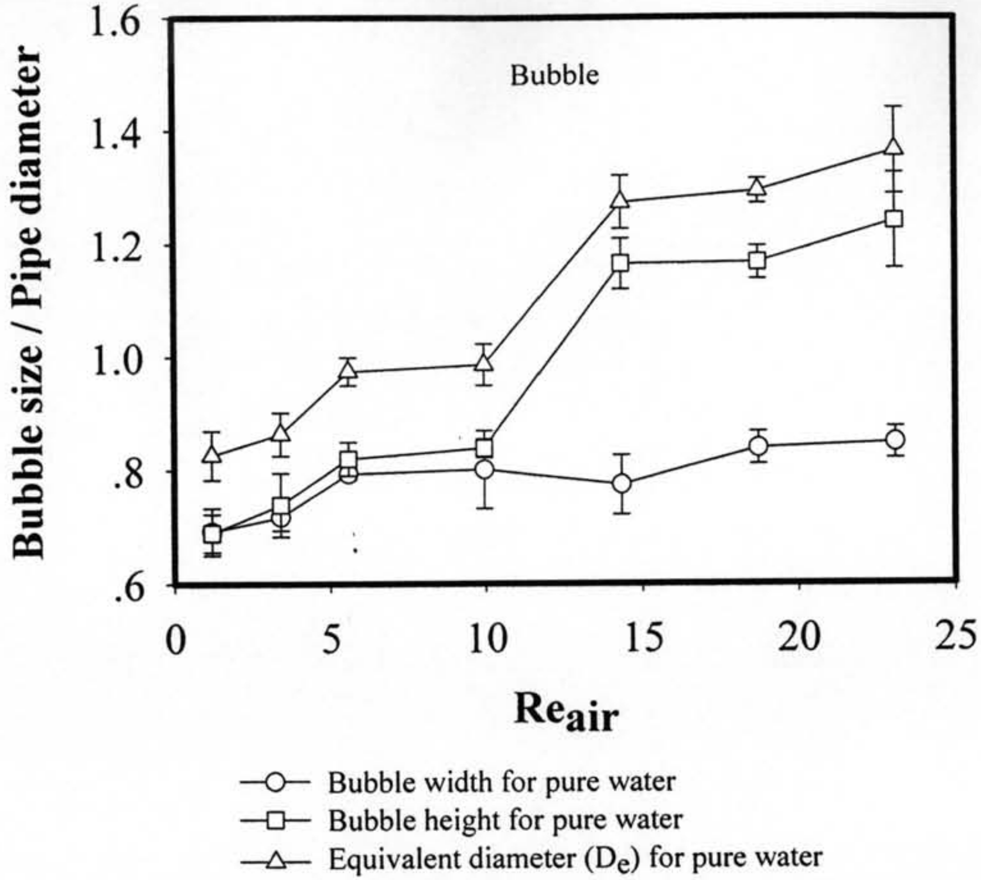


Figure C4 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of pure water at $Re_{water} = 2727$ by using pipe diameter 10.75 mm.

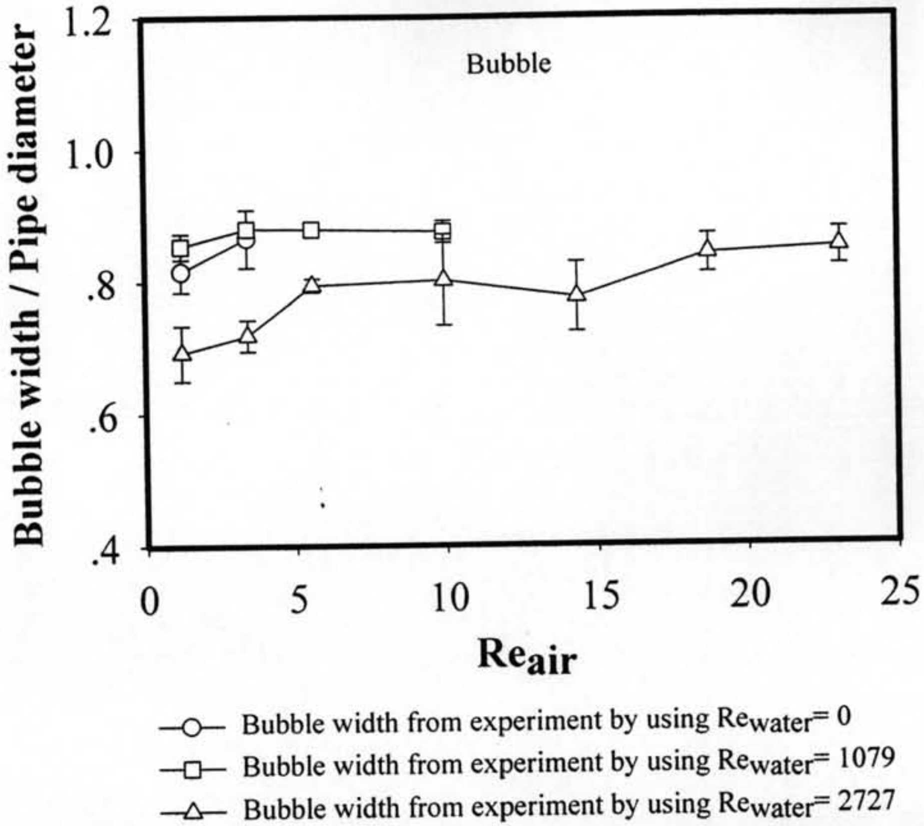


Figure C5 Bubble width from experiment vs. air Reynolds number of pure water by using pipe diameter 10.75 mm.

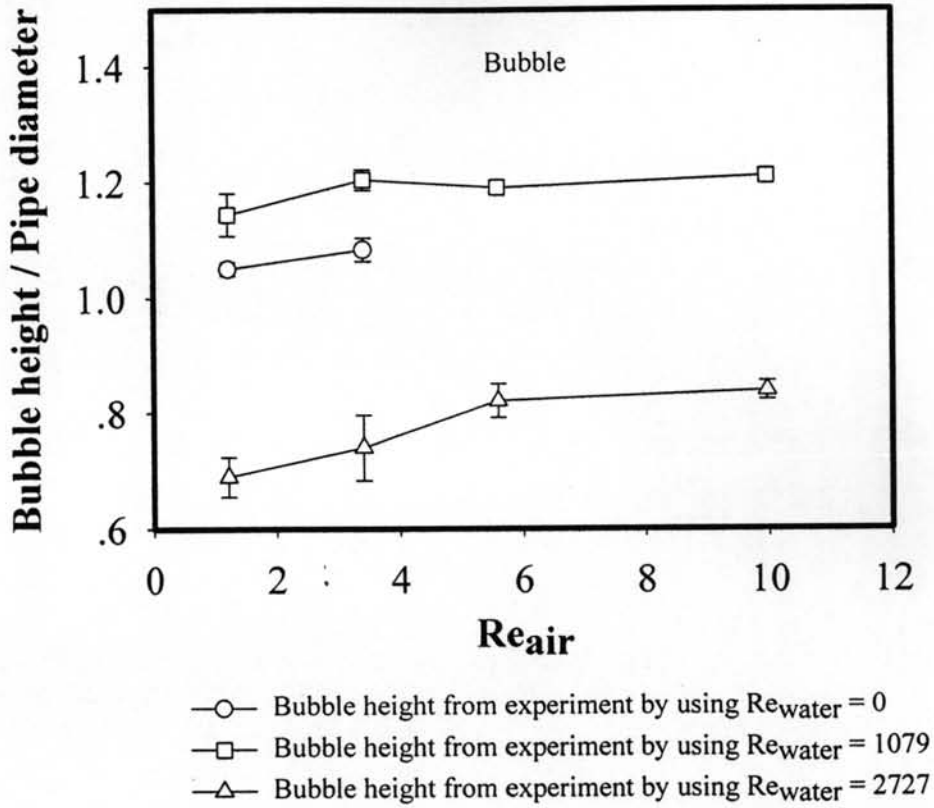


Figure C6 Bubble height from experiment vs. air Reynolds number of pure water by using pipe diameter 10.75 mm.

Table C2 Determination of slug height for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

Procedure to determine the slug height:

1. Make a movie of the slug flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the slug height by Scion Image software program.

Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
0	14.35	14.3	19.3	16.3	16.7 ± 2.5	1.3	1.8	1.5	1.6 ± 0.23
0	18.72	18.4	26.0	20.8	21.7 ± 3.9	1.7	2.4	1.9	2.0 ± 0.36
0	23.09	24.6	23.5	23.9	24.0 ± 0.6	2.3	2.2	2.2	2.2 ± 0.05
0	27.47	25.4	24.4	24.1	24.6 ± 0.7	2.4	2.3	2.2	2.3 ± 0.07
0	31.84	30.0	28.2	29.7	29.3 ± 0.9	2.8	2.6	2.8	2.7 ± 0.09
0	36.22	50.3	70.9	51.4	57.5 ± 11.6	4.7	6.6	4.8	5.3 ± 1.08
0	40.56	68.0	81.5	76.7	75.4 ± 6.9	6.3	7.6	7.1	7.0 ± 0.64
0	49.63	90.0	77.8	84.7	84.2 ± 6.1	8.4	7.2	7.9	7.8 ± 0.57
0	58.69	88.5	95.2	94.1	92.6 ± 3.6	8.2	8.9	8.8	8.6 ± 0.33
0	67.75	103.7	90.4	102.4	98.9 ± 7.3	9.6	8.4	9.5	9.2 ± 0.68
0	76.82	104.0	111.0	112.0	109.0 ± 4.4	9.7	10.3	10.4	10.1 ± 0.41
0	85.88	115.5	111.0	131.5	119.3 ± 10.8	10.7	10.3	12.2	11.1 ± 1.00
0	94.95	127.6	131.7	126.9	128.7 ± 2.6	11.9	12.3	11.8	12.0 ± 0.24
1079	23.09	16.6	17.4	15.5	16.5 ± 1.0	1.5	1.6	1.4	1.5 ± 0.09
1079	27.47	21.3	18.1	19.5	19.6 ± 1.6	2.0	1.7	1.8	1.8 ± 0.15
1079	31.84	21.1	19.3	20.7	20.4 ± 1.0	2.0	1.8	1.9	1.9 ± 0.09
1079	36.22	23.1	22.4	21.7	22.4 ± 0.7	2.1	2.1	2.0	2.1 ± 0.06
1079	40.56	22.8	25.9	25.0	24.6 ± 1.6	2.1	2.4	2.3	2.3 ± 0.15
1079	49.63	27.7	25.8	26.1	26.5 ± 1.0	2.6	2.4	2.4	2.5 ± 0.10
1079	58.69	29.3	31.0	29.7	30.0 ± 0.9	2.7	2.9	2.8	2.8 ± 0.08
1079	67.75	34.9	35.2	33.3	34.5 ± 1.0	3.2	3.3	3.1	3.2 ± 0.10
1079	76.82	31.2	34.6	36.5	34.1 ± 2.7	2.9	3.2	3.4	3.2 ± 0.25
1079	85.88	40.3	41.1	40.7	40.7 ± 0.4	3.7	3.8	3.8	3.8 ± 0.04
1079	94.95	77.1	77.9	83.3	79.4 ± 3.4	7.2	7.2	7.8	7.4 ± 0.32
1079	104	78.8	83.2	87.2	83.1 ± 4.2	7.3	7.7	8.1	7.7 ± 0.39
1079	122	89.4	96.4	85.4	90.4 ± 5.5	8.3	9.0	7.9	8.4 ± 0.52

Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
2727	36.22	16.8	17.0	17.8	17.2 ± 0.6	1.6	1.6	1.7	1.6 ± 0.05
2727	40.56	18.6	18.6	17.8	18.3 ± 0.5	1.7	1.7	1.7	1.7 ± 0.04
2727	49.63	22.5	23.4	21.0	22.3 ± 1.2	2.1	2.2	2.0	2.1 ± 0.11
2727	58.69	22.8	23.4	22.8	23.0 ± 0.4	2.1	2.2	2.1	2.1 ± 0.03
2727	67.75	20.0	25.6	26.4	24.0 ± 3.5	1.9	2.4	2.5	2.2 ± 0.32
2727	76.82	25.7	28.3	26.9	27.0 ± 1.3	2.4	2.6	2.5	2.5 ± 0.12
2727	85.88	26.6	24.3	28.7	26.5 ± 2.2	2.5	2.3	2.7	2.5 ± 0.20
2727	94.95	31.1	29.6	32.1	31.0 ± 1.3	2.9	2.8	3.0	2.9 ± 0.12
2727	104	35.3	32.5	30.3	32.7 ± 2.5	3.3	3.0	2.8	3.0 ± 0.23
2727	122	45.5	51.6	53.6	50.2 ± 4.2	4.2	4.8	5.0	4.7 ± 0.39
2727	140	49.9	41.5	55.7	49.0 ± 7.2	4.6	3.9	5.2	4.6 ± 0.67
2727	158	61.5	61.5	57.5	60.2 ± 2.3	5.7	5.7	5.3	5.6 ± 0.22
2727	177	63.6	73.9	88.5	75.4 ± 12.5	5.9	6.9	8.2	7.0 ± 1.16
2727	231	112.2	96.6	105.6	104.8 ± 7.8	10.4	9.0	9.8	9.7 ± 0.73
2727	294	105.0	106.5	125.3	112.3 ± 11.3	9.8	9.9	11.7	10.4 ± 1.05
2727	367	138.7	140.7	132.0	137.1 ± 4.5	12.9	13.1	12.3	12.8 ± 0.42
2727	523	265.3	241.3	216.0	240.9 ± 24.7	24.7	22.4	20.1	22.4 ± 2.29

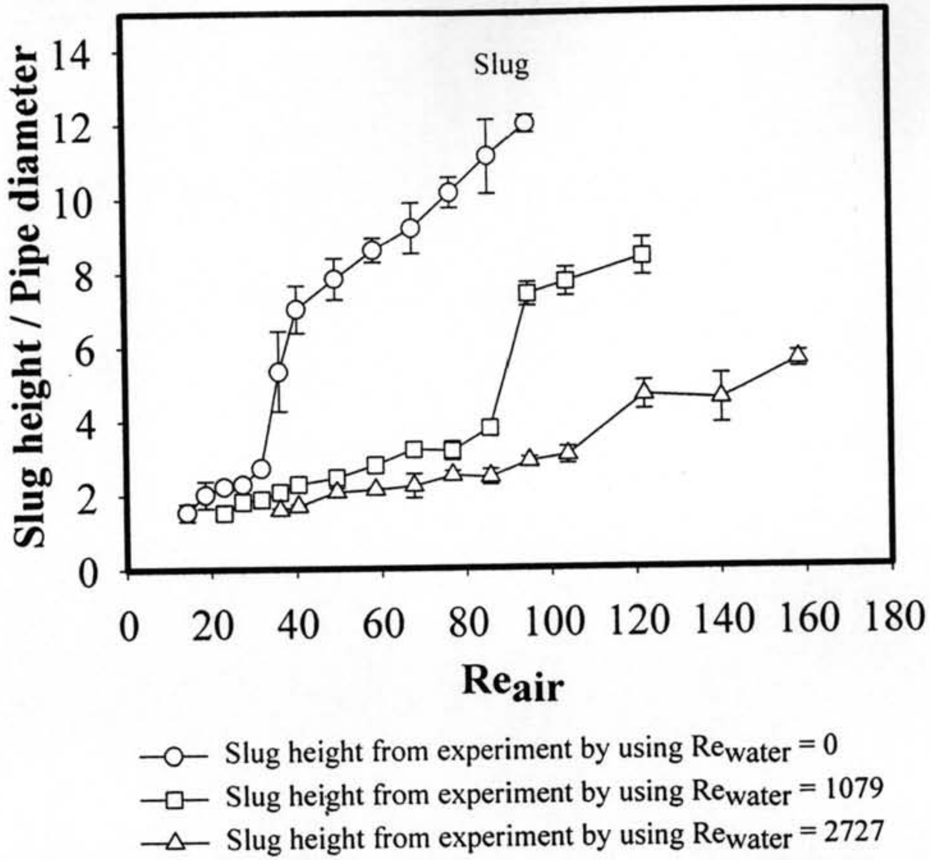


Figure C7 Slug height from experiment vs. air Reynolds number of pure water by using pipe diameter 10.75 mm.

Table C3 Determination of bubble and slug velocity for pure water from Nicklin's theory and experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

Bubble velocity from theory, $$u_s = 1.2(\frac{Q_{qir} + Q_{liquid}}{A}) + 0.35\sqrt{gD} \qquad \text{(C2)}$$

Determination of bubble velocity from experiment by timing the bubble at known distance (0.7m)

Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
0	1.22	7.75	7.62	7.66	7.75	7.69	7.69 ± 0.06	0.09	0.09	0.09	0.09	0.09	0.09 ± 0.001	0.12
0	3.41	7.19	7.18	7.16	7.28	7.32	7.23 ± 0.07	0.10	0.10	0.10	0.10	0.10	0.10 ± 0.001	0.12
0	5.60	7.13	6.79	6.87	7.32	7.06	7.03 ± 0.21	0.10	0.10	0.10	0.10	0.10	0.10 ± 0.003	0.12
0	9.97	6.60	6.65	6.75	6.72	6.69	6.68 ± 0.06	0.11	0.11	0.10	0.10	0.10	0.10 ± 0.001	0.13
0	14.35	6.59	6.72	6.50	6.56	6.60	6.59 ± 0.08	0.11	0.10	0.11	0.11	0.11	0.11 ± 0.001	0.14
0	18.72	6.12	6.10	5.90	6.06	6.10	6.06 ± 0.09	0.11	0.11	0.12	0.12	0.11	0.12 ± 0.002	0.15
0	23.09	5.71	5.69	5.72	5.72	5.72	5.71 ± 0.01	0.12	0.12	0.12	0.12	0.12	0.12 ± 0.000	0.15
0	27.47	5.34	5.34	5.47	5.47	5.40	5.40 ± 0.07	0.13	0.13	0.13	0.13	0.13	0.13 ± 0.002	0.16
0	31.84	5.25	5.28	5.25	5.25	5.28	5.26 ± 0.02	0.13	0.13	0.13	0.13	0.13	0.13 ± 0.000	0.17
0	36.22	4.78	4.69	4.63	4.78	4.75	4.73 ± 0.07	0.15	0.15	0.15	0.15	0.15	0.15 ± 0.002	0.18
0	40.56	4.41	4.37	4.32	4.44	4.40	4.39 ± 0.05	0.16	0.16	0.16	0.16	0.16	0.16 ± 0.002	0.18

Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
0	49.63	3.97	3.91	3.91	3.97	3.97	3.95 ± 0.03	0.18	0.18	0.18	0.18	0.18	0.18 ± 0.001	0.20
0	58.69	3.65	3.56	3.76	3.62	3.68	3.65 ± 0.07	0.19	0.20	0.19	0.19	0.19	0.19 ± 0.004	0.22
0	67.75	3.53	3.59	3.50	3.53	3.59	3.55 ± 0.04	0.20	0.19	0.20	0.20	0.19	0.20 ± 0.002	0.23
0	76.82	3.35	3.34	3.31	3.28	3.35	3.33 ± 0.03	0.21	0.21	0.21	0.21	0.21	0.21 ± 0.002	0.25
0	85.88	3.03	3.06	3.03	3.13	3.00	3.05 ± 0.05	0.23	0.23	0.23	0.22	0.23	0.23 ± 0.004	0.26
0	94.95	2.90	2.87	2.91	2.90	3.03	2.92 ± 0.06	0.24	0.24	0.24	0.24	0.23	0.24 ± 0.005	0.28
1079	1.22	3.62	3.59	3.75	3.72	3.62	3.66 ± 0.07	0.19	0.19	0.19	0.19	0.19	0.19 ± 0.004	0.22
1079	3.41	3.59	3.61	3.69	3.52	3.60	3.60 ± 0.06	0.19	0.19	0.19	0.20	0.19	0.19 ± 0.003	0.22
1079	5.60	3.59	3.60	3.57	3.53	3.54	3.57 ± 0.03	0.19	0.19	0.20	0.20	0.20	0.20 ± 0.002	0.23
1079	10	3.53	3.56	3.47	3.47	3.44	3.49 ± 0.05	0.20	0.20	0.20	0.20	0.20	0.20 ± 0.003	0.23
1079	14	3.53	3.50	3.47	3.50	3.46	3.49 ± 0.03	0.20	0.20	0.20	0.20	0.20	0.20 ± 0.002	0.24
1079	19	3.43	3.41	3.44	3.43	3.44	3.43 ± 0.01	0.20	0.21	0.20	0.20	0.20	0.20 ± 0.001	0.25
1079	23	3.38	3.38	3.34	3.28	3.34	3.34 ± 0.04	0.21	0.21	0.21	0.21	0.21	0.21 ± 0.003	0.26
1079	27	3.15	3.19	3.19	3.19	3.06	3.16 ± 0.06	0.22	0.22	0.22	0.22	0.23	0.22 ± 0.004	0.26
1079	32	3.04	3.09	3.03	3.06	3.07	3.06 ± 0.02	0.23	0.23	0.23	0.23	0.23	0.23 ± 0.002	0.27
1079	36	2.94	2.91	2.97	3.00	2.88	2.94 ± 0.05	0.24	0.24	0.24	0.23	0.24	0.24 ± 0.004	0.28
1079	41	2.72	2.78	2.72	2.84	2.75	2.76 ± 0.05	0.26	0.25	0.26	0.25	0.25	0.25 ± 0.005	0.29
1079	50	2.65	2.66	2.69	2.62	2.69	2.66 ± 0.03	0.26	0.26	0.26	0.27	0.26	0.26 ± 0.003	0.30
1079	59	2.47	2.50	2.47	2.43	2.47	2.47 ± 0.02	0.28	0.28	0.28	0.29	0.28	0.28 ± 0.003	0.32
1079	67.75	2.34	2.35	2.32	2.38	2.40	2.36 ± 0.03	0.30	0.30	0.30	0.29	0.29	0.30 ± 0.004	0.33
1079	76.82	2.34	2.31	2.40	2.34	2.37	2.35 ± 0.03	0.30	0.30	0.29	0.30	0.30	0.30 ± 0.004	0.35
1079	85.88	2.22	2.28	2.19	2.18	2.28	2.23 ± 0.05	0.32	0.31	0.32	0.32	0.31	0.31 ± 0.007	0.37
1079	94.95	2.12	2.10	2.13	2.06	2.10	2.10 ± 0.03	0.33	0.33	0.33	0.34	0.33	0.33 ± 0.004	0.38
1079	104	2.00	2.03	2.00	2.00	2.04	2.01 ± 0.02	0.35	0.34	0.35	0.35	0.34	0.35 ± 0.003	0.40
1079	122	1.87	1.81	1.84	1.90	1.90	1.86 ± 0.04	0.37	0.39	0.38	0.37	0.37	0.38 ± 0.008	0.43
2727	1.22	2.25	2.22	2.16	2.16	2.25	2.21 ± 0.05	0.31	0.32	0.32	0.32	0.31	0.32 ± 0.007	0.38

Re_{water}	Re_{air}	Time of bubble travel (sec)/0.7m					Average (sec/0.7 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
2727	3.41	2.13	2.09	2.09	2.13	2.06	2.10 ± 0.03	0.33	0.33	0.33	0.33	0.34	0.33 ± 0.005	0.38
2727	5.60	2.09	2.00	1.97	2.06	2.09	2.04 ± 0.05	0.33	0.35	0.36	0.34	0.33	0.34 ± 0.009	0.38
2727	9.97	2.00	2.00	1.96	1.94	1.97	1.97 ± 0.03	0.35	0.35	0.36	0.36	0.36	0.35 ± 0.005	0.39
2727	14.35	1.97	2.03	2.00	1.95	1.97	1.98 ± 0.03	0.36	0.34	0.35	0.36	0.36	0.35 ± 0.006	0.40
2727	19	2.00	1.96	1.98	1.94	1.94	1.96 ± 0.03	0.35	0.36	0.35	0.36	0.36	0.36 ± 0.005	0.41
2727	23	1.94	1.97	2.00	1.97	2.00	1.98 ± 0.03	0.36	0.36	0.35	0.36	0.35	0.35 ± 0.005	0.41
2727	27	1.97	1.90	2.00	2.00	1.94	1.96 ± 0.04	0.36	0.37	0.35	0.35	0.36	0.36 ± 0.008	0.42
2727	32	1.87	1.87	1.88	1.88	1.84	1.87 ± 0.02	0.37	0.37	0.37	0.37	0.38	0.37 ± 0.003	0.43
2727	36.22	1.81	1.81	1.84	1.85	1.81	1.82 ± 0.02	0.39	0.39	0.38	0.38	0.39	0.38 ± 0.004	0.44
2727	40.56	1.69	1.69	1.75	1.78	1.72	1.73 ± 0.04	0.41	0.41	0.40	0.39	0.41	0.41 ± 0.009	0.44
2727	49.63	1.68	1.75	1.75	1.69	1.72	1.72 ± 0.03	0.42	0.40	0.40	0.41	0.41	0.41 ± 0.008	0.46
2727	58.69	1.72	1.72	1.78	1.72	1.68	1.72 ± 0.04	0.41	0.41	0.39	0.41	0.42	0.41 ± 0.008	0.48
2727	67.75	1.63	1.69	1.63	1.69	1.65	1.66 ± 0.03	0.43	0.41	0.43	0.41	0.42	0.42 ± 0.008	0.49
2727	77	1.56	1.59	1.53	1.56	1.63	1.57 ± 0.04	0.45	0.44	0.46	0.45	0.43	0.44 ± 0.011	0.51
2727	86	1.53	1.53	1.59	1.56	1.56	1.55 ± 0.03	0.46	0.46	0.44	0.45	0.45	0.45 ± 0.007	0.52
2727	95	1.47	1.47	1.54	1.46	1.47	1.48 ± 0.03	0.48	0.48	0.45	0.48	0.48	0.47 ± 0.010	0.54
2727	104	1.44	1.50	1.44	1.47	1.44	1.46 ± 0.03	0.49	0.47	0.49	0.48	0.49	0.48 ± 0.009	0.56
2727	122	1.41	1.41	1.40	1.41	1.40	1.41 ± 0.01	0.50	0.50	0.50	0.50	0.50	0.50 ± 0.002	0.59
2727	140	1.38	1.37	1.40	1.36	1.37	1.38 ± 0.02	0.51	0.51	0.50	0.51	0.51	0.51 ± 0.006	0.62
2727	158	1.25	1.25	1.23	1.28	1.25	1.25 ± 0.02	0.56	0.56	0.57	0.55	0.56	0.56 ± 0.008	0.65
2727	177	1.15	1.12	1.13	1.16	1.14	1.14 ± 0.02	0.61	0.63	0.62	0.60	0.61	0.61 ± 0.009	0.68
2727	231	1.00	1.06	1.03	1.00	0.91	1.00 ± 0.06	0.70	0.66	0.68	0.70	0.77	0.70 ± 0.041	0.78
2727	294	0.94	0.94	0.91	0.90	0.89	0.92 ± 0.02	0.74	0.74	0.77	0.78	0.79	0.76 ± 0.019	0.89
2727	367	0.78	0.72	0.69	0.68	0.75	0.72 ± 0.04	0.90	0.97	1.01	1.03	0.93	0.97 ± 0.055	1.02
2727	523	0.53	0.56	0.52	0.52	0.53	0.53 ± 0.02	1.32	1.25	1.35	1.35	1.32	1.32 ± 0.039	1.29

Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
0	1.22	0.28	0.28	0.28	0.28	0.28	0.28 ± 0.002	0.36
0	3.41	0.30	0.30	0.30	0.30	0.29	0.30 ± 0.003	0.37
0	5.60	0.30	0.32	0.31	0.29	0.31	0.31 ± 0.009	0.38
0	9.97	0.33	0.32	0.32	0.32	0.32	0.32 ± 0.003	0.40
0	14.35	0.33	0.32	0.33	0.33	0.33	0.33 ± 0.004	0.43
0	18.72	0.35	0.35	0.37	0.36	0.35	0.36 ± 0.005	0.45
0	23.09	0.38	0.38	0.38	0.38	0.38	0.38 ± 0.001	0.47
0	27.47	0.40	0.40	0.39	0.39	0.40	0.40 ± 0.005	0.50
0	31.84	0.41	0.41	0.41	0.41	0.41	0.41 ± 0.001	0.52
0	36.22	0.45	0.46	0.47	0.45	0.45	0.46 ± 0.006	0.55
0	40.56	0.49	0.49	0.50	0.49	0.49	0.49 ± 0.005	0.57
0	49.63	0.54	0.55	0.55	0.54	0.54	0.55 ± 0.005	0.62
0	58.69	0.59	0.61	0.57	0.60	0.59	0.59 ± 0.012	0.67
0	67.75	0.61	0.60	0.62	0.61	0.60	0.61 ± 0.007	0.72
0	76.82	0.64	0.65	0.65	0.66	0.64	0.65 ± 0.006	0.76
0	85.88	0.71	0.70	0.71	0.69	0.72	0.71 ± 0.011	0.81
0	94.95	0.74	0.75	0.74	0.74	0.71	0.74 ± 0.015	0.86
1079	1.22	0.60	0.60	0.57	0.58	0.60	0.59 ± 0.011	0.67
1079	3.41	0.60	0.60	0.58	0.61	0.60	0.60 ± 0.010	0.68
1079	5.60	0.60	0.60	0.60	0.61	0.61	0.60 ± 0.005	0.70
1079	10	0.61	0.61	0.62	0.62	0.63	0.62 ± 0.009	0.72
1079	14	0.61	0.62	0.62	0.62	0.62	0.62 ± 0.005	0.74
1079	19	0.63	0.63	0.63	0.63	0.63	0.63 ± 0.002	0.77
1079	23	0.64	0.64	0.65	0.66	0.65	0.64 ± 0.008	0.79
1079	27	0.68	0.68	0.68	0.68	0.70	0.68 ± 0.012	0.81
1079	32	0.71	0.70	0.71	0.70	0.70	0.70 ± 0.005	0.84

Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
1079	36	0.73	0.74	0.73	0.72	0.75	0.73 ± 0.012	0.86
1079	41	0.79	0.78	0.79	0.76	0.78	0.78 ± 0.014	0.88
1079	50	0.81	0.81	0.80	0.82	0.80	0.81 ± 0.009	0.93
1079	59	0.87	0.86	0.87	0.89	0.87	0.87 ± 0.009	0.98
1079	67.75	0.92	0.92	0.93	0.91	0.90	0.91 ± 0.012	1.03
1079	76.82	0.92	0.93	0.90	0.92	0.91	0.92 ± 0.013	1.08
1079	85.88	0.97	0.95	0.98	0.99	0.95	0.97 ± 0.021	1.13
1079	94.95	1.02	1.03	1.01	1.05	1.03	1.03 ± 0.013	1.18
1079	104	1.08	1.06	1.08	1.08	1.06	1.07 ± 0.010	1.23
1079	122	1.15	1.19	1.17	1.13	1.13	1.16 ± 0.024	1.32
2727	1.22	0.96	0.97	1.00	1.00	0.96	0.98 ± 0.020	1.16
2727	3.41	1.01	1.03	1.03	1.01	1.05	1.03 ± 0.015	1.17
2727	5.60	1.03	1.08	1.09	1.05	1.03	1.06 ± 0.028	1.18
2727	9.97	1.08	1.08	1.10	1.11	1.09	1.09 ± 0.014	1.20
2727	14.35	1.09	1.06	1.08	1.11	1.09	1.09 ± 0.017	1.23
2727	19	1.08	1.10	1.09	1.11	1.11	1.10 ± 0.015	1.25
2727	23	1.11	1.09	1.08	1.09	1.08	1.09 ± 0.014	1.27
2727	27	1.09	1.13	1.08	1.08	1.11	1.10 ± 0.024	1.30
2727	32	1.15	1.15	1.15	1.15	1.17	1.15 ± 0.010	1.32
2727	36.22	1.19	1.19	1.17	1.17	1.19	1.18 ± 0.013	1.34
2727	40.56	1.28	1.28	1.23	1.21	1.25	1.25 ± 0.028	1.37
2727	49.63	1.28	1.23	1.23	1.28	1.25	1.26 ± 0.024	1.42
2727	58.69	1.25	1.25	1.21	1.25	1.28	1.25 ± 0.026	1.47
2727	67.75	1.32	1.28	1.32	1.28	1.31	1.30 ± 0.024	1.51
2727	77	1.38	1.36	1.41	1.38	1.32	1.37 ± 0.033	1.56
2727	86	1.41	1.41	1.36	1.38	1.38	1.39 ± 0.022	1.61

Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
2727	95	1.47	1.47	1.40	1.48	1.47	1.46 ± 0.031	1.66
2727	104	1.50	1.44	1.50	1.47	1.50	1.48 ± 0.027	1.71
2727	122	1.53	1.53	1.54	1.53	1.54	1.53 ± 0.006	1.81
2727	140	1.56	1.57	1.54	1.58	1.57	1.57 ± 0.017	1.90
2727	158	1.72	1.72	1.75	1.68	1.72	1.72 ± 0.024	2.00
2727	177	1.87	1.92	1.91	1.86	1.89	1.89 ± 0.026	2.10
2727	231	2.16	2.03	2.09	2.16	2.37	2.16 ± 0.127	2.39
2727	294	2.29	2.29	2.37	2.40	2.42	2.35 ± 0.059	2.74
2727	367	2.76	2.99	3.12	3.17	2.87	2.99 ± 0.170	3.13
2727	523	4.07	3.85	4.15	4.15	4.07	4.05 ± 0.121	3.97

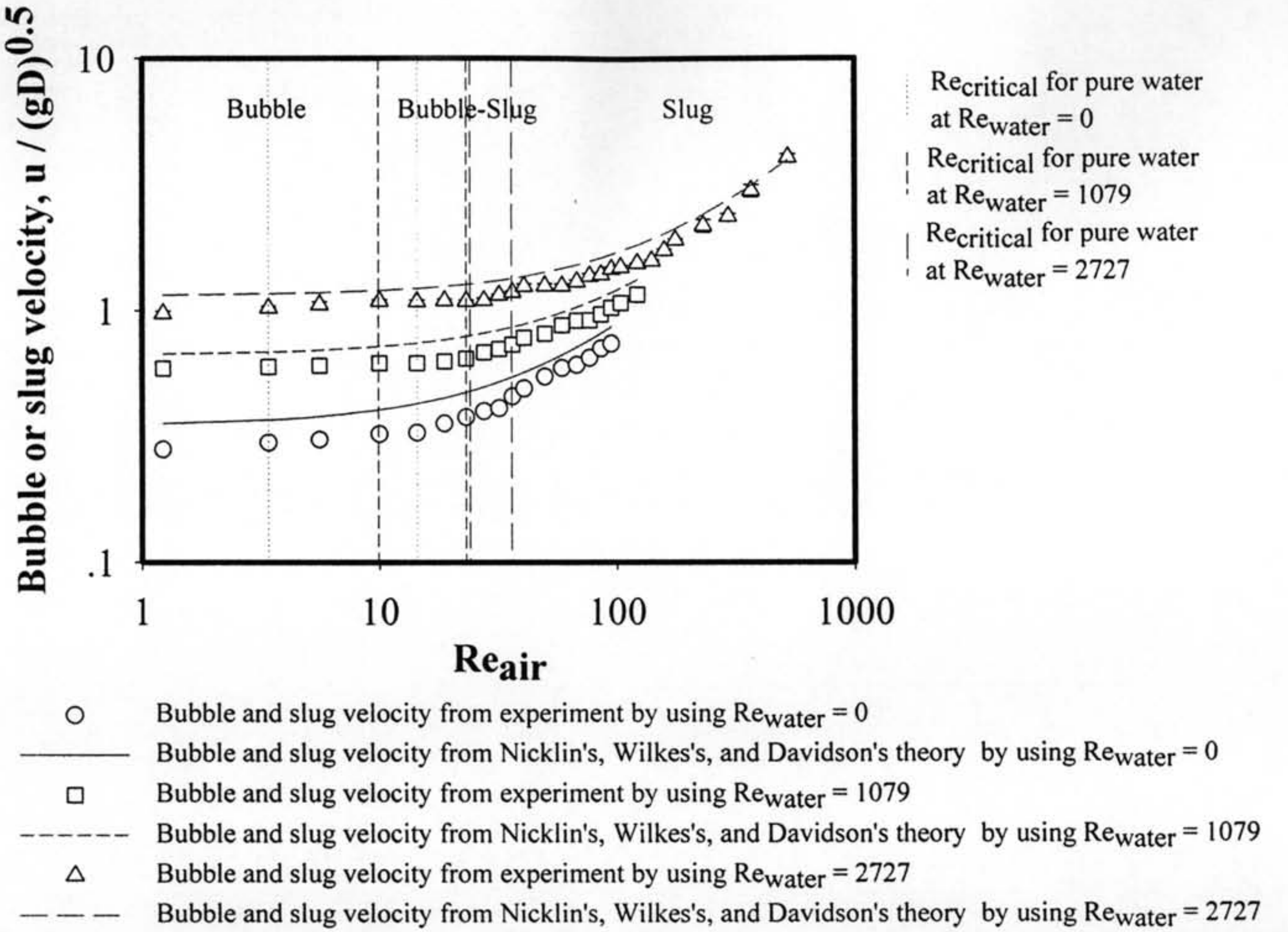


Figure C8 Comparison bubble and slug velocity from experiment vs. air Reynolds number of pure water comparing with Nicklin's theory by using pipe diameter 10.75 mm.

Table C4 Determination of the pressure gradient for the bubble flow regime from Nicklin's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

Superficial liquid velocity, $j_{liquid} = \dfrac{Q_{liquid}}{A}$ (C3)

Superficial air velocity, $j_{air} = \dfrac{Q_{air}}{A}$ (C4)

Reynolds number of liquid, $\mathrm{Re}_{liquid} = \dfrac{\rho\, j_{liquid} D}{\mu_{liquid}}$ (C5)

Reynolds number of air, $\mathrm{Re}_{air} = \dfrac{\rho\, j_{air} D}{\mu_{air}}$ (C6)

Bubble velocity rising in stagnant liquid, $u_b = 1.00\sqrt{g\, R_b}$ (C7)

where R_b is equivalent radius of the bubble which defined as the radius of a sphere that has the same volume as the bubble

Void fraction, $\varepsilon = \dfrac{Q_{air}}{Q_{air} + Q_{liquid} + u_b A}$ (C8)

Pressure gradient for bubble flow regime, $\dfrac{dp}{dz} = -\rho_l g(1-\varepsilon)$ (C9)

Q_{water} (ml/min)	Sup. water velocity j_{water} (m/s)	Q_{water} (m^3/sec)	Re_{water}	Q_{air} (L/min)	Sup. Air velocity j_{air} (m/s)	Q_{air} (m^3/sec)	Re_{air}	Flow regime	U_b (m/s)	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
0	0	0	0	0.0097	0.0018	1.61883E-07	1.22	bubble	0.2498	0.0071	9.6917
0	0	0	0	0.0271	0.0050	4.51225E-07	3.41	bubble	0.2545	0.0192	9.5738
466	0.0856	7.762E-06	1079	0.0097	0.0018	1.61883E-07	1.22	bubble	0.2596	0.0051	9.7108
466	0.0856	7.762E-06	1079	0.0271	0.0050	4.51225E-07	3.41	bubble	0.2658	0.0140	9.6247
466	0.0856	7.762E-06	1079	0.0444	0.0082	7.40567E-07	5.60	bubble	0.2645	0.0228	9.5385
466	0.0856	7.762E-06	1079	0.0792	0.0145	1.32E-06	9.97	bubble	0.2662	0.0397	9.3734
1177	0.2162	1.961E-05	2727	0.0097	0.0018	1.61883E-07	1.22	bubble	0.2491	0.0038	9.7237
1177	0.2162	1.961E-05	2727	0.0271	0.0050	4.51225E-07	3.41	bubble	0.2491	0.0106	9.6577
1177	0.2162	1.961E-05	2727	0.0444	0.0082	7.40567E-07	5.60	bubble	0.2491	0.0172	9.5927
1177	0.2162	1.961E-05	2727	0.0792	0.0145	1.31925E-06	9.97	bubble	0.2491	0.0303	9.4651
1177	0.2162	1.961E-05	2727	0.1139	0.0209	1.89793E-06	14.35	bubble	0.2592	0.0422	9.3495
1177	0.2162	1.961E-05	2727	0.1486	0.0273	2.47662E-06	18.72	bubble	0.2613	0.0541	9.2331
1177	0.2162	1.961E-05	2727	0.1833	0.0337	3.0553E-06	23.09	bubble	0.2682	0.0650	9.1265

Table C5 Determination of the pressure gradient for the slug flow regime from Nicklin's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

Mean liquid velocity, $u_l = \dfrac{Q_{air} + Q_{liquid}}{A}$ (C10)

Reynolds number of the liquid slug, $\mathrm{Re}_{slug} = \dfrac{\rho_{liquid} u_l D}{\mu_{liquid}}$ (C11)

Fanning friction factor, $f_F = \dfrac{16}{\mathrm{Re}_{slug}}$ for laminar flow ($\mathrm{Re}_{slug} < 2000$) (C12)

$f_F = 0.079\,\mathrm{Re}_{slug}^{-1/4}$ for turbulent flow ($\mathrm{Re}_{slug} > 4000$) (C13)

Single-phase frictional pressure gradient for liquid only, $\left(\dfrac{dp}{dz}\right)_{sp} = \dfrac{2 f_F \rho_{liquid} u_l}{D}$ (C14)

Void fraction, $\varepsilon = \dfrac{Q_{air}}{1.2\left(Q_{air} + Q_{liquid}\right) + 0.35 A\sqrt{gD}}$ (C15)

Pressure gradient for slug flow regime, $\dfrac{dp}{dz} = (1-\varepsilon)\left[-\rho_{liquid} g + \left(\dfrac{dp}{dz}\right)_{sp}\right]$ (C16)

Q_{water} (m^3/sec)	Re_{water}	Q_{air} (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
0	0	1.898E-06	14.35	slug	0.0209	264	0.0606	4.9127	0.1508	8.2935
0	0	2.477E-06	18.72	slug	0.0273	344	0.0465	6.4106	0.1865	7.9462
0	0	3.055E-06	23.09	slug	0.0337	425	0.0377	7.9085	0.2186	7.6335
0	0	3.634E-06	27.47	slug	0.0401	505	0.0317	9.4064	0.2477	7.3504
0	0	4.213E-06	31.84	slug	0.0464	586	0.0273	10.9043	0.2742	7.0929
0	0	4.791E-06	36.22	slug	0.0528	666	0.0240	12.4022	0.2983	6.8576
0	0	5.367E-06	40.56	slug	0.0592	746	0.0214	13.8910	0.3204	6.6432
0	0	6.566E-06	49.63	slug	0.0724	913	0.0175	16.9950	0.3610	6.2485
0	0	7.765E-06	58.69	slug	0.0856	1080	0.0148	20.0990	0.3956	5.9118
0	0	8.964E-06	67.75	slug	0.0988	1246	0.0128	23.2030	0.4255	5.6211
0	0	1.016E-05	76.82	slug	0.1120	1413	0.0113	26.3070	0.4516	5.3677
0	0	1.136E-05	85.88	slug	0.1253	1580	0.0101	29.4110	0.4745	5.1448
0	0	1.256E-05	94.95	slug	0.1385	1747	0.0092	32.5150	0.4948	4.9472
7.762E-06	1079	3.055E-06	23.09	slug	0.1192	1504	0.0106	28.0014	0.1312	8.5049
7.762E-06	1079	3.634E-06	27.47	slug	0.1256	1585	0.0101	29.4993	0.1515	8.3072
7.762E-06	1079	4.213E-06	31.84	slug	0.1320	1665	0.0096	30.9972	0.1707	8.1206
7.762E-06	1079	4.791E-06	36.22	slug	0.1384	1746	0.0092	32.4951	0.1888	7.9443
7.762E-06	1079	5.367E-06	40.56	slug	0.1447	1825	0.0088	33.9838	0.2059	7.7783
7.762E-06	1079	6.566E-06	49.63	slug	0.1579	1992	0.0080	37.0878	0.2387	7.4591
7.762E-06	1079	7.765E-06	58.69	slug	0.1712	2159	0.0074	40.1918	0.2683	7.1717
7.762E-06	1079	8.964E-06	67.75	slug	0.1844	2326	0.0069	43.2958	0.2950	6.9116
7.762E-06	1079	1.016E-05	76.82	slug	0.1976	2492	0.0064	46.3998	0.3194	6.6751
7.762E-06	1079	1.136E-05	85.88	slug	0.2108	2659	0.0060	49.5038	0.3416	6.4590
7.762E-06	1079	1.256E-05	94.95	slug	0.2240	2826	0.0057	52.6078	0.3620	6.2610
7.762E-06	1079	1.376E-05	104	slug	0.2373	2993	0.0053	55.7118	0.3808	6.0787
7.762E-06	1079	1.616E-05	122	slug	0.2637	3326	0.0104	133.9027	0.4142	5.7968

Q_{water} (m^3/sec)	Re_{water}	Q_{air} (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
7.762E-06	1079	1.856E-05	140	slug-churn	0.2901	3660	0.0102	158.2724	0.4430	5.5255
7.762E-06	1079	2.096E-05	158	slug-churn	0.3166	3993	0.0099	184.3674	0.4680	5.2904
7.762E-06	1079	2.335E-05	177	slug-churn	0.3430	4327	0.0097	212.1504	0.4901	5.0852
7.762E-06	1079	3.055E-05	231	slug-churn	0.4223	5327	0.0092	305.3067	0.5428	4.6027
7.762E-06	1079	3.894E-05	294	slug-churn	0.5149	6494	0.0088	431.8244	0.5869	4.2110
7.762E-06	1079	4.854E-05	367	slug-churn	0.6206	7828	0.0084	598.8069	0.6233	3.9025
1.961E-05	2727	4.791E-06	36.22	slug	0.2690	3393	0.0104	138.6849	0.1210	8.7018
1.961E-05	2727	5.367E-06	40.56	slug	0.2754	3473	0.0103	144.4548	0.1332	8.5860
1.961E-05	2727	6.566E-06	49.63	slug	0.2886	3640	0.0102	156.8073	0.1573	8.3572
1.961E-05	2727	7.765E-06	58.69	slug	0.3018	3807	0.0101	169.5917	0.1799	8.1442
1.961E-05	2727	8.964E-06	67.75	slug	0.3150	3974	0.0100	182.8030	0.2010	7.9454
1.961E-05	2727	1.016E-05	76.82	slug	0.3283	4140	0.0098	196.4368	0.2207	7.7595
1.961E-05	2727	1.136E-05	85.88	slug	0.3415	4307	0.0098	210.4888	0.2393	7.5854
1.961E-05	2727	1.256E-05	94.95	slug	0.3547	4474	0.0097	224.9547	0.2568	7.4219
1.961E-05	2727	1.376E-05	104	slug	0.3679	4641	0.0096	239.8308	0.2732	7.2682
1.961E-05	2727	1.616E-05	122	slug	0.3943	4974	0.0094	270.7985	0.3035	6.9869
1.961E-05	2727	1.856E-05	140	slug	0.4208	5308	0.0093	303.3639	0.3307	6.7362
1.961E-05	2727	2.096E-05	158	slug	0.4472	5641	0.0091	337.5012	0.3552	6.5114
1.961E-05	2727	2.335E-05	177	slug	0.4737	5974	0.0090	373.1867	0.3774	6.3090
1.961E-05	2727	3.055E-05	231	slug-churn	0.5530	6975	0.0086	489.3186	0.4333	5.8091
1.961E-05	2727	3.894E-05	294	slug-churn	0.6455	8142	0.0083	641.4818	0.4833	5.3751
1.961E-05	2727	4.854E-05	367	slug-churn	0.7513	9476	0.0080	836.5443	0.5270	5.0122
1.961E-05	2727	6.922E-05	523	slug-churn	0.9793	12352	0.0075	1330.3278	0.5921	4.5244
1.961E-05	2727	0.0001034	782	slug-churn	1.3560	17104	0.0069	2351.4487	0.6547	4.1821

Table C6 Determination of the pressure gradient for the slug flow regime from Sylvester's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

$$\beta = L_{TB}/L_{SU} \quad \text{(C17)}$$

where: L_{TB} is length of the Taylor bubble

L_{SU} is length of the slug unit

Friction factor associated with the Taylor bubble, $$f_{TB} = \frac{1}{\left[-2.0\log\left\{\frac{\left(1-\alpha_{TB}^{1/2}\right)}{7.4}\right\}\right]^2} \quad \text{(C18)}$$

Reynolds number of the liquid slug, $$\mathrm{Re}_{LS} = \frac{\rho_L U_{LLS} D}{\mu_L} \quad \text{(C19)}$$

where: velocity of the liquid in the liquid slug, $U_{LLS} = U_{SG} + U_{SL}$ (C20)

Friction factor associated with the liquid slug, $$f_{LS} = \frac{1}{\left[-2.0\log\left\{\frac{\varepsilon/D}{3.7} - \left(\frac{5.02}{\mathrm{Re}_{LS}}\right)\log\left(\frac{\varepsilon/D}{3.7} + \frac{13}{\mathrm{Re}_{LS}}\right)\right\}\right]^2} \quad \text{(C21)}$$

where: ε is the pipe roughness

Acceleration pressure drop, $(\Delta P)_A = \rho_L(U_{LTB} + U_{TB})(1-\alpha_{TB})(U_{LTB} + U_{TB} + U_{LLS})$ (C22)

where: velocity of the liquid film around the Taylor bubble, $U_{LTB} = 9.916\left[gD\left(1-\sqrt{\alpha_{TB}}\right)\right]^{1/2}$ (C23) velocity of the Taylor bubble, $U_{TB} = 1.2(U_{SG} + U_{SL}) + 0.35\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}$ (C24)

area average void fraction of the Taylor bubble, $\alpha_{TB} = \frac{\text{Average all area at Taylor bubble region}}{\text{Average area in Taylor bubble}}$ (C25)

Hydrostatic pressure drop, $(\Delta P)_H = \rho_L(1-\alpha_{LS})gL_{LS}$ (C26)

where: void fraction of the liquid slug, $\alpha_{LS} = \frac{U_{SG}}{0.425 + 2.65(U_{SG} + U_{SL})}$ (C27)

length of the liquid slug, L_{LS}

Frictional pressure drop of slug unit, $(\Delta P)_F = \frac{L_{LS}}{2D}\left[\frac{\rho_G \beta f_{TB} U_{TB}^2}{(1-\beta)[1-(1-\alpha_{TB}^{1/2}]} + U_{LLS}^2 \rho_L (1-\alpha_{LS}) f_{LS} (1-\beta)\right]$ (C28)

Total pressure drop in the slug unit, $(\Delta P)_T = (\Delta P)_A + (\Delta P)_H + (\Delta P)_F$ (C29)

Re_{water}	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
0	14.35	slug	0.2608	0.0567	264	0.0971	98	441	0.0668	539.1	0.5391	8.4380
0	18.72	slug	0.3019	0.0577	344	0.0883	108	464	0.1025	572.1	0.5721	7.9461
0	23.09	slug	0.3617	0.0575	425	0.0819	110	386	0.1104	495.5	0.4955	7.4765
0	27.47	slug	0.3433	0.0505	505	0.0770	63	425	0.1655	488.7	0.4887	6.8111
0	31.84	slug	0.5021	0.0565	586	0.0732	106	260	0.0995	365.3	0.3653	6.2601
0	36.22	slug	0.5324	0.0619	666	0.0700	159	447	0.2000	605.7	0.6057	5.6081
0	40.56	slug	0.5143	0.0619	746	0.0673	162	624	0.3480	786.6	0.7866	5.3674
0	49.63	slug	0.6463	0.0636	913	0.0629	188	397	0.2322	585.2	0.5852	4.4924
0	58.69	slug	0.6488	0.0615	1080	0.0595	171	425	0.3244	596.7	0.5967	4.1809
0	67.75	slug	0.6751	0.0619	1246	0.0568	183	398	0.3592	581.0	0.5810	3.9677
0	76.82	slug	0.6619	0.0614	1413	0.0546	183	459	0.5281	643.0	0.6430	3.9050
0	85.88	slug	0.6832	0.0624	1580	0.0527	203	451	0.5900	654.1	0.6541	3.7450
0	94.95	slug	0.7053	0.0619	1747	0.0510	204	433	0.6291	637.6	0.6376	3.4932
1079	23.09	slug	0.2579	0.0544	1504	0.0535	115	442	1.1859	557.9	0.5579	8.7301
1079	27.47	slug	0.3529	0.0540	1585	0.0526	114	333	0.8526	447.4	0.4474	8.0384
1079	31.84	slug	0.4125	0.0538	1665	0.0518	115	266	0.6740	381.5	0.3815	7.7244
1079	36.22	slug	0.4099	0.0543	1746	0.0510	121	293	0.8078	415.5	0.4155	7.6128
1079	40.56	slug	0.4199	0.0537	1825	0.0503	118	307	0.8969	426.5	0.4265	7.2860
1079	49.63	slug	0.4150	0.0536	1992	0.0490	122	334	1.1384	456.9	0.4569	7.1482
1079	58.69	slug	0.4591	0.0531	2159	0.0478	122	311	1.1274	434.9	0.4349	6.6552
1079	67.75	slug	0.5355	0.0536	2326	0.0467	132	260	0.9224	393.3	0.3933	6.1112
1079	76.82	slug	0.4926	0.0539	2492	0.0458	140	302	1.3127	443.5	0.4435	6.4057
1079	85.88	slug	0.5608	0.0518	2659	0.0449	124	271	1.1429	396.3	0.3963	5.4656
1079	94.95	slug	0.6651	0.0640	2826	0.0441	288	337	1.2291	626.7	0.6267	5.2467
1079	104.01	slug	0.5785	0.0620	2993	0.0433	265	506	2.5140	773.4	0.7734	5.3856
1079	122.14	slug	0.6080	0.0617	3326	0.0420	278	479	2.6589	759.1	0.7591	5.1064

Re_{water}	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
2727	36.22	slug	0.2890	0.0530	3393	0.0418	159	394	4.0261	557.6	0.5576	9.3632
2727	40.56	slug	0.3189	0.0541	3473	0.0415	175	363	3.6955	541.0	0.5410	9.4099
2727	49.63	slug	0.2937	0.0541	3640	0.0409	180	491	5.6187	676.9	0.6769	8.9264
2727	58.69	slug	0.4418	0.0537	3807	0.0404	181	264	2.5825	447.3	0.4473	8.6011
2727	67.75	slug	0.4065	0.0526	3974	0.0399	173	315	3.5268	491.6	0.4916	8.3337
2727	76.82	slug	0.4730	0.0535	4140	0.0394	191	268	2.8659	462.0	0.4620	8.1029
2727	85.88	slug	0.4565	0.0523	4307	0.0390	181	279	3.2928	463.5	0.4635	7.9786
2727	94.95	slug	0.4915	0.0533	4474	0.0386	200	281	3.3147	484.5	0.4845	7.6938
2727	104	slug	0.4721	0.0535	4641	0.0382	209	318	4.1474	531.0	0.5310	7.6653
2727	122	slug	0.4697	0.0536	4974	0.0374	224	487	7.1774	717.5	0.7175	6.7077
2727	140	slug	0.5429	0.0539	5308	0.0368	241	349	4.9888	595.6	0.5956	6.5960
2727	158	slug	0.5754	0.0543	5641	0.0362	262	371	5.4841	638.8	0.6388	6.1085
2727	177	slug	0.5617	0.0537	5974	0.0356	266	486	8.1713	760.2	0.7602	5.6674

Table C7 Determination of the pressure gradient for the annular and mist flow regime from Wallis's theory (Pure water)

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} PA.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

Fanning friction factor, $f_F = \dfrac{16}{\text{Re}}$ for laminar flow (Re < 2000) (C30)

$f_F = 0.079\,\text{Re}^{-1/4}$ for turbulent flow (Re > 4000) (C31)

Pressure gradient for air, $\left(\dfrac{dp}{dz}\right)_{air} = \dfrac{2 f_F \rho_{air} j_{air}}{D}$ (C32)

Pressure gradient for liquid, $\left(\dfrac{dp}{dz}\right)_{liquid} = \dfrac{2 f_F \rho_{liquid} j_{liquid}}{D}$ (C33)

Martinelli parameter, X

from $\left(1+X^{2/3.61}\right)^{3.61}\left(\dfrac{dp}{dz}\right)_{air} - \rho_{air} g = \dfrac{\left(1+X^{2/3.61}\right)^{3.61}}{X^2}\left(\dfrac{dp}{dz}\right)_{liquid} - [\dfrac{1}{(1+0.0904X^{0.548})^{2.82}}\rho_{air} + (1-\dfrac{1}{(1+0.0904X^{0.548})^{2.82}})\rho_{liquid}]g$ (C34)

Void fraction, $\varepsilon = \dfrac{1}{\left(1+0.0904\,X^{0.548}\right)^{2.82}}$ (C35)

Gas two-phase flow multiplier, $\phi_g = \left(1+X^{2/3.61}\right)^{3.61/2}$ (C36)

Pressure gradient for two-phase flow, $\left(\frac{dp}{dz}\right) = \phi_g^2 \left(\frac{dp}{dz}\right)_{air} - \rho_{air} g$ (C37)

Q_{water} (ml/min)	Re_{water}	Q_{air} (L/min)	Re_{air}	Flow regime	f_F of air	f_F of water	$(-dp/dz)_{air}$ (Pa/m)	$(-dp/dz)_{water}$ (Pa/m)	Martinelli parameter (X)	Void fraction (ε)	Φ_g^2	Pressure gradient $(-dp/dz)_{tp}$ (kPa/m)
466	1079	36	4554	Annular	0.0096	0.0148	93	20.0928	2.5776	0.6712	35.5834	3.3252
466	1079	44	5546	Annular	0.0092	0.0148	131	20.0928	1.6967	0.7250	21.5320	2.8427
466	1079	100	12597	Annular	0.0075	0.0148	553	20.0928	0.2663	0.8862	4.1219	2.2892
466	1079	200	25195	mist	0.0063	0.0148	1859	20.0928	0.1128	0.9268	2.5672	4.7830
466	1079	300	37792	mist	0.0057	0.0148	3779	20.0928	0.0756	0.9406	2.1691	8.2081
1177	2727	100	12597	Annular	0.0075	0.0059	553	50.7718	0.4076	0.8592	5.5578	3.0827
1177	2727	200	25195	Mist	0.0063	0.0059	1859	50.7718	0.1793	0.9069	3.2483	6.0488

Table C8 Determination of the pressure gradient from experiment for pure water

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.011 m;

cross-sectional area of pipe, A = 0.00009 m^2; pressure taps difference = 0.4 m

Procedure to determine of pressure gradient from experiment:

1. Read the highest and lowest difference level from manometer.
2. Put the value of difference level in $-\frac{dp}{dz} = \frac{\rho_w g(100 - level_{water,L}) - (100 - level_{water,R})}{100x0.4x1000}$ (C38)

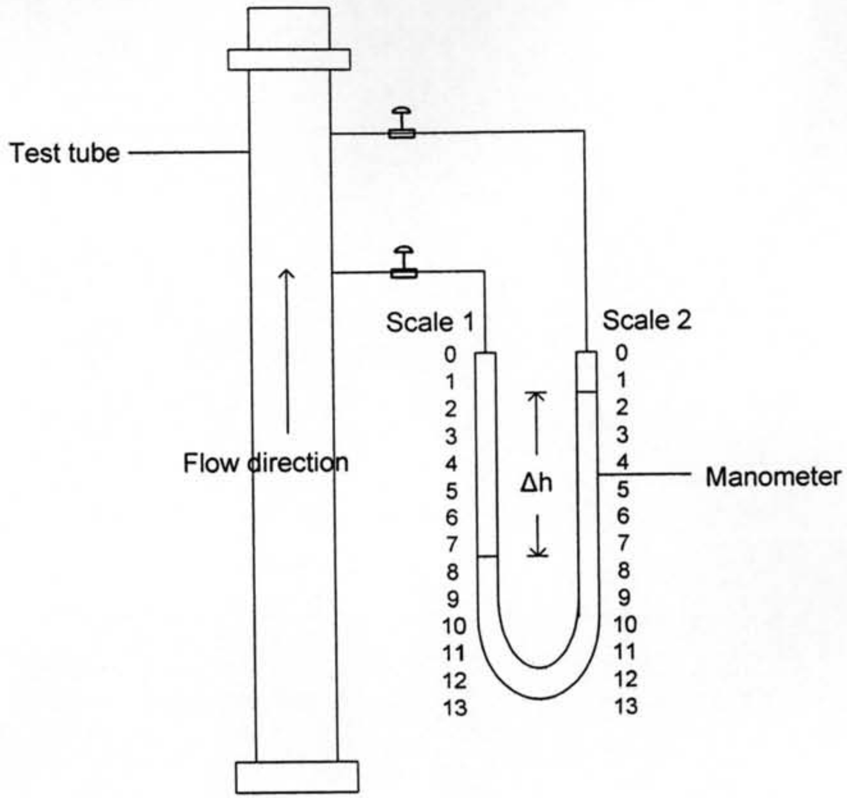


Figure C9 Appearance scale and water level in manometer.

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
0	3.41	Bubble	78.4	78.4	78.4	78.4	78.4	40.9	40.9	40.9	40.9	40.9
0	5.60	Bubble-Slug	98.7	98.7	98.7	98.7	98.7	61.5	61.5	61.5	61.5	61.5
0	9.97	Bubble-Slug	98	98	98	98	98	63.3	63.3	63.3	63.3	63.3
0	14.35	Slug	97.2	97.2	97.2	97.2	97.2	64.5	64.5	64.5	64.5	64.5
0	18.72	Slug	96.3	96.3	96.3	96.3	96.3	65.5	65.5	65.5	65.5	65.5
0	23.09	Slug	95.5	95.5	95.5	95.5	95.5	66.4	66.4	66.4	66.4	66.4
0	27.47	Slug	94.4	94.4	94.4	94.4	94.4	67.5	67.5	67.5	67.5	67.5
0	31.84	Slug	93.6	93.6	93.6	93.6	93.6	68.1	68.1	68.1	68.1	68.1
0	36.22	Slug	92.6	92.6	92.6	92.6	92.6	69.1	69.1	69.1	69.1	69.1
0	40.56	Slug	91.7	91.6	91.5	91.6	91.6	70	70.1	70.1	70	70.1
0	49.63	Slug	91.1	91	91	91	91	70.7	70.8	70.8	70.8	70.8
0	58.69	Slug	90.5	90.5	90.5	90.5	90.5	71.5	71.5	71.5	71.5	71.5
0	67.75	Slug	89.7	89.6	89.6	89.6	89.6	72.1	72	72.1	72.1	72.2
0	76.82	Slug	89.3	89.2	89.2	89.2	89.2	72.6	72.6	72.6	72.6	72.6
0	85.88	Slug	88.7	88.7	88.7	88.7	88.7	73.2	73.2	73.2	73.2	73.2
0	94.95	Slug	88.4	88.3	88.3	88.4	88.3	73.6	73.4	73.5	73.6	73.6
1079	3.41	Bubble	79.8	79.8	79.8	79.8	79.8	40.1	40.1	40.1	40.1	40.1
1079	5.60	Bubble	80.4	80.4	80.4	80.4	80.4	40.9	40.9	40.9	40.9	40.9
1079	9.97	Bubble	80.1	80.1	80.1	80.1	80.1	41.3	41.3	41.3	41.3	41.3
1079	14.35	Bubble-Slug	79.1	79.1	79.1	79.1	79.1	42.2	42.2	42.2	42.2	42.2
1079	18.72	Bubble-Slug	78.3	78.3	78.3	78.3	78.3	43	43	43	43	43
1079	23.09	Slug	77.8	77.8	77.8	77.8	77.8	43.5	43.5	43.5	43.5	43.5
1079	27.47	Slug	77.3	77.3	77.3	77.3	77.3	44	44	44	44	44
1079	31.84	Slug	76.5	76.5	76.5	76.5	76.5	44.8	44.8	44.8	44.8	44.8
1079	36.22	Slug	75.7	75.7	75.7	75.7	75.7	45.6	45.6	45.6	45.6	45.6
1079	40.56	Slug	75.1	75.1	75.1	75.1	75.1	46.2	46.2	46.2	46.2	46.2

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
1079	49.63	Slug	74.3	74.3	74.3	74.3	74.3	47	47	47	47	47
1079	58.69	Slug	73.9	73.9	73.9	73.9	73.9	47.5	47.5	47.5	47.5	47.5
1079	67.75	Slug	73.5	73.5	73.5	73.5	73.5	47.9	47.9	47.9	47.9	47.9
1079	76.82	Slug	72.8	72.8	72.8	72.8	72.8	48.5	48.5	48.5	48.5	48.5
1079	85.88	Slug	72.3	72.3	72.3	72.3	72.3	49.1	49.1	49.1	49.1	49.1
1079	94.95	Slug	72.1	72.1	72.1	72.1	72.1	49.3	49.3	49.3	49.3	49.3
1079	104	Slug	71.6	71.6	71.6	71.6	71.6	49.6	49.6	49.6	49.6	49.6
1079	122	Slug	70.7	70.7	70.7	70.7	70.7	50.6	50.5	50.6	50.6	50.6
1079	140	Slug-Churn	70.2	70.2	70.3	70.3	70.3	51.2	51.3	51.2	51.2	51.2
1079	158	Slug-Churn	69.7	69.7	69.8	69.8	69.7	51.8	51.8	51.7	51.6	51.7
1079	177	Slug-Churn	69.3	69.4	69.4	69.4	69.4	52.1	52.1	52.1	52.1	52.2
1079	231	Slug-Churn	68	68	68	68	68	53.4	53.4	53.4	53.4	53.4
1079	294	Slug-Churn	67.4	67.5	67.4	67.5	67.5	54.1	54.2	54.2	54	54
1079	367	Slug-Churn	66.8	66.8	66.7	66.7	66.7	54.9	55	54.8	54.9	54.7
1079	523	Churn	65.7	65.5	65.5	65.5	65.5	56.3	56	56	56	56
1079	782	Churn	65.4	65.3	65.2	65.2	65	56.2	56.3	56	56.2	56.2
1079	1427	Churn	66	66	66	66	66	55.6	55.7	55.6	55.7	55.6
1079	2461	Churn	66	66	65.9	66	66	55.5	55.6	55.6	55.6	55.6
1079	3471	Churn	65.7	65.7	65.7	65.7	65.7	55.9	55.8	55.8	56	55.9
1079	4554	Annular	65.7	65.7	65.7	65.7	65.7	56	56	56	56	56
1079	5546	Annular	65.6	65.6	65.6	65.6	65.6	56	56	56	56	56
1079	12597	Annular	64	64	64	64	64	51.4	51.4	51.4	51.4	51.4
1079	25195	Mist	76.1	76.1	76.1	76.1	76.1	39.1	39.1	39.1	39.1	39.1
2727	3.41	Bubble	79.9	79.9	79.9	79.9	79.9	40	40	40	40	40
2727	5.60	Bubble	80.3	80.3	80.3	80.3	80.3	40.4	40.4	40.4	40.4	40.4
2727	9.97	Bubble	80.4	80.4	80.4	80.4	80.4	40.6	40.6	40.6	40.6	40.6

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2727	14.35	Bubble	80.4	80.4	80.4	80.4	80.4	40.7	40.7	40.7	40.7	40.7
2727	18.72	Bubble	79.8	79.8	79.8	79.8	79.8	41.5	41.5	41.5	41.5	41.5
2727	23.09	Bubble	79.3	79.3	79.3	79.3	79.3	41.9	41.9	41.9	41.9	41.9
2727	27.47	Bubble-Slug	78.8	78.8	78.8	78.8	78.8	42.3	42.3	42.3	42.3	42.3
2727	31.84	Bubble-Slug	78.2	78.2	78.2	78.2	78.2	42.9	42.9	42.9	42.9	42.9
2727	36.22	Slug	77.9	77.9	77.9	77.9	77.9	43.3	43.3	43.3	43.3	43.3
2727	40.56	Slug	77.3	77.3	77.3	77.3	77.3	44	44	44	44	44
2727	49.63	Slug	76.7	76.7	76.7	76.7	76.7	44.5	44.5	44.5	44.5	44.5
2727	58.69	Slug	76.3	76.3	76.3	76.3	76.3	45	45	45	45	45
2727	67.75	Slug	75.8	75.8	75.8	75.8	75.8	45.4	45.4	45.4	45.4	45.4
2727	76.82	Slug	75.5	75.5	75.5	75.5	75.5	45.9	45.9	45.9	45.9	45.9
2727	85.88	Slug	75	75	75	75	75	46.2	46.2	46.2	46.2	46.2
2727	94.95	Slug	74.6	74.6	74.6	74.6	74.6	46.6	46.6	46.6	46.6	46.6
2727	104	Slug	74.4	74.4	74.4	74.4	74.4	47	47	47	47	47
2727	122	Slug	73.7	73.7	73.7	73.7	73.7	47.5	47.5	47.5	47.5	47.5
2727	140	Slug	73.3	73.3	73.3	73.3	73.3	48	48	48	48	48
2727	158	Slug	72.5	72.5	72.5	72.5	72.5	48.7	48.7	48.7	48.7	48.7
2727	177	Slug	72.1	72.1	72.1	72.1	72.1	49	49	49	49	49
2727	231	Slug-Churn	71.1	71.1	71.1	71.1	71.1	50.3	50.3	50.3	50.3	50.3
2727	294	Slug-Churn	70.3	70.3	70.3	70.3	70.3	51.3	51.3	51.3	51.3	51.3
2727	367	Slug-Churn	69.3	69.3	69.3	69.3	69.3	52	52.1	52	52.1	52
2727	523	Slug-Churn	68.3	68.4	68.3	68.3	68.3	53.5	53.5	53.5	53.5	53.5
2727	782	Slug-Churn	67.3	67.5	67.5	67.5	67.5	54	54	54	54	54
2727	1427	Churn	68	67.8	67.8	68	67.8	53.6	53.7	53.5	53.5	53.7
2727	2461	Churn	69.3	69	69	69.2	69	52	52.3	52.2	52.5	52.4
2727	3471	Churn	68.8	69	68.8	68.8	68.9	52.5	52.7	52.5	52.5	52.6
2727	4554	Churn	69	69	69	69	69	52.2	52.3	52.2	52.2	52.3

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2727	5546	Churn	70.4	70.3	70.4	70.4	70.5	51	51	51	51	51
2727	12597	Annular	59.6	59.6	59.6	59.6	59.6	34.7	34.7	34.7	34.7	34.7
2727	25195	Mist	70.2	70.2	70.2	70.2	70.2	32	32	32	32	32

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
0	3.41	Bubble	78.4	78.4	78.4	78.4	78.4	40.9	40.9	40.9	40.9	40.9
0	5.60	Bubble-Slug	98.7	98.7	98.7	98.7	98.7	61.5	61.5	61.5	61.5	61.5
0	9.97	Bubble-Slug	98	98	98	98	98	63.3	63.3	63.3	63.3	63.3
0	14.35	Slug	97.2	97.2	97.2	97.2	97.2	64.5	64.5	64.5	64.5	64.5
0	18.72	Slug	96.2	96.2	96.2	96.2	96.2	65.6	65.6	65.6	65.6	65.6
0	23.09	Slug	95.4	95.4	95.4	95.4	95.4	66.5	66.5	66.5	66.5	66.5
0	27.47	Slug	94.2	94.2	94.2	94.2	94.2	67.6	67.6	67.6	67.6	67.6
0	31.84	Slug	93.4	93.4	93.4	93.4	93.4	68.3	68.3	68.3	68.3	68.3
0	36.22	Slug	92.5	92.5	92.5	92.5	92.5	69.3	69.3	69.3	69.3	69.3
0	40.56	Slug	91.5	91.5	91.5	91.5	91.5	70.4	70.4	70.4	70.4	70.4
0	49.63	Slug	90.6	90.7	90.7	90.7	90.6	70.9	71	71.1	71.2	71
0	58.69	Slug	90	90	90	90	90	71.8	71.7	71.7	71.7	71.7
0	67.75	Slug	89.4	89.4	89.5	89.5	89.5	72.3	72.4	72.4	72.4	72.4
0	76.82	Slug	89	89	89	89	89	73	72.8	72.8	72.8	72.8
0	85.88	Slug	88.4	88.4	88.5	88.5	88.4	73.5	73.5	73.6	73.5	73.6

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
0	94.95	Slug	88	88	88	88	88	73.7	73.7	73.8	73.8	73.8
1079	3.41	Bubble	79.8	79.8	79.8	79.8	79.8	40.1	40.1	40.1	40.1	40.1
1079	5.60	Bubble	80.4	80.4	80.4	80.4	80.4	40.9	40.9	40.9	40.9	40.9
1079	9.97	Bubble	80.1	80.1	80.1	80.1	80.1	41.3	41.3	41.3	41.3	41.3
1079	14.35	Bubble-Slug	79.1	79.1	79.1	79.1	79.1	42.2	42.2	42.2	42.2	42.2
1079	18.72	Bubble-Slug	78.3	78.3	78.3	78.3	78.3	43	43	43	43	43
1079	23.09	Slug	77.7	77.7	77.7	77.7	77.7	43.6	43.6	43.6	43.6	43.6
1079	27.47	Slug	77.2	77.2	77.2	77.2	77.2	44.1	44.1	44.1	44.1	44.1
1079	31.84	Slug	76.5	76.5	76.5	76.5	76.5	44.8	44.8	44.8	44.8	44.8
1079	36.22	Slug	75.6	75.6	75.6	75.6	75.6	45.7	45.7	45.7	45.7	45.7
1079	40.56	Slug	75	75	75	75	75	46.3	46.3	46.3	46.3	46.3
1079	49.63	Slug	74.3	74.3	74.3	74.3	74.3	47	47	47	47	47
1079	58.69	Slug	73.8	73.8	73.8	73.8	73.8	47.5	47.5	47.5	47.5	47.5
1079	67.75	Slug	73.4	73.4	73.4	73.4	73.4	48	48	48	48	48
1079	76.82	Slug	72.7	72.7	72.7	72.7	72.7	48.7	48.7	48.7	48.7	48.7
1079	85.88	Slug	72.2	72.2	72.2	72.2	72.2	49.2	49.2	49.2	49.2	49.2
1079	94.95	Slug	72	72	72	72	72	49.4	49.4	49.4	49.4	49.4
1079	104	Slug	71.4	71.4	71.4	71.4	71.4	50	50	50	50	50
1079	122	Slug	70.4	70.4	70.4	70.5	70.5	50.9	51	50.9	50.9	51
1079	140	Slug-Churn	69.8	69.7	69.8	69.8	69.8	51.6	51.7	51.6	51.7	51.7
1079	158	Slug-Churn	69.2	69.2	69.1	69.1	69.1	52.3	52.3	52.5	52.4	52.5
1079	177	Slug-Churn	68.5	68.5	68.6	68.6	68.6	52.8	52.8	52.7	52.7	52.7
1079	231	Slug-Churn	67.5	67.5	67.5	67.5	67.5	54	54	54	54	54
1079	294	Slug-Churn	66.6	66.6	66.5	66.4	66.5	55	54.9	55	55.1	55
1079	367	Slug-Churn	65.3	65.5	65.4	65.5	65.3	56	56	56	56.2	56
1079	523	Churn	64.5	64.5	64.6	64.3	64.5	57	57	57	57.2	57.2

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
1079	782	Churn	63.5	63.2	63.2	63	63	57.8	58	58	58.2	58
1079	1427	Churn	63.5	63.7	63.7	63.7	63.7	57.8	57.8	57.7	57.9	57.6
1079	2461	Churn	65	65	65	65	65	56.5	56.4	56.5	56.4	56.4
1079	3471	Churn	65.2	65	65.1	65.1	65.1	56.1	56.3	56.3	56.3	56.3
1079	4554	Annular	65.3	65.3	65.3	65.3	65.3	56.5	56.4	56.4	56.5	56.5
1079	5546	Annular	65.5	65.5	65.5	65.5	65.5	56.1	56.1	56.1	56.1	56.1
1079	12597	Annular	64	64	64	64	64	51.4	51.4	51.4	51.4	51.4
1079	25195	Mist	75.9	75.9	75.9	75.9	75.9	39.3	39.3	39.3	39.3	39.3
2727	3.41	Bubble	79.9	79.9	79.9	79.9	79.9	40	40	40	40	40
2727	5.60	Bubble	80.3	80.3	80.3	80.3	80.3	40.4	40.4	40.4	40.4	40.4
2727	9.97	Bubble	80.4	80.4	80.4	80.4	80.4	40.7	40.7	40.7	40.7	40.7
2727	14.35	Bubble	80.3	80.3	80.3	80.3	80.3	40.8	40.8	40.8	40.8	40.8
2727	18.72	Bubble	79.6	79.6	79.6	79.6	79.6	41.6	41.6	41.6	41.6	41.6
2727	23.09	Bubble	79.2	79.2	79.2	79.2	79.2	42	42	42	42	42
2727	27.47	Bubble-Slug	78.8	78.7	78.7	78.6	78.6	42.4	42.5	42.5	42.6	42.6
2727	31.84	Bubble-Slug	78.1	78.1	78.1	78.1	78.1	43	43	43	43	43
2727	36.22	Slug	77.8	77.8	77.8	77.8	77.8	43.4	43.4	43.4	43.4	43.4
2727	40.56	Slug	77.2	77.2	77.2	77.2	77.2	44.1	44.1	44.1	44.1	44.1
2727	49.63	Slug	76.7	76.7	76.7	76.7	76.7	44.5	44.5	44.5	44.5	44.5
2727	58.69	Slug	76.2	76.2	76.2	76.2	76.2	45.1	45.1	45.1	45.1	45.1
2727	67.75	Slug	75.7	75.7	75.7	75.7	75.7	45.5	45.5	45.5	45.5	45.5
2727	76.82	Slug	75.4	75.4	75.4	75.4	75.4	46	46	46	46	46
2727	85.88	Slug	74.9	74.9	74.9	74.9	74.9	46.3	46.3	46.3	46.3	46.3
2727	94.95	Slug	74.5	74.5	74.5	74.5	74.5	46.7	46.7	46.7	46.7	46.7
2727	104	Slug	74.4	74.4	74.4	74.4	74.4	47	47	47	47	47
2727	122	Slug	73.6	73.6	73.6	73.6	73.6	47.6	47.6	47.6	47.6	47.6

Re_{water}	Re_{air}	Flow regime	Appearance water levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2727	140	Slug	73.2	73.2	73.2	73.2	73.2	48.1	48.1	48.1	48.1	48.1
2727	158	Slug	72.5	72.5	72.5	72.5	72.5	48.8	48.8	48.8	48.8	48.8
2727	177	Slug	72	72	72	72	72	49.2	49.2	49.2	49.1	49.1
2727	231	Slug-Churn	70.8	70.8	70.8	70.8	70.8	50.5	50.5	50.5	50.5	50.5
2727	294	Slug-Churn	70.1	70.1	70.1	70.1	70.1	51.4	51.4	51.4	51.4	51.4
2727	367	Slug-Churn	68.9	68.9	68.9	68.9	68.9	52.5	52.6	52.5	52.5	52.5
2727	523	Slug-Churn	67.5	67.6	67.5	67.5	67.5	54	54	53.9	54	54
2727	782	Slug-Churn	66.3	66.3	66.3	66.2	66.3	55.5	55.5	55.4	55.4	55.5
2727	1427	Churn	65.5	65.5	65.5	65.6	65.6	55.8	55.7	55.6	55.7	55.8
2727	2461	Churn	67.2	67.3	67.2	67.2	67.2	54	54.1	54.1	54.2	54
2727	3471	Churn	67.8	67.5	67.6	67.6	67.5	53.5	53.6	53.6	53.6	53.6
2727	4554	Churn	68.5	68.6	68.6	68.5	68.5	53	53	52.9	53	53
2727	5546	Churn	70	70.1	70.1	70.1	70	51.4	51.4	51.5	51.4	51.5
2727	12597	Annular	59.6	59.6	59.6	59.6	59.6	34.7	34.7	34.7	34.7	34.7
2727	25195	Mist	70	70	70	70	70	32	32	32	32	32

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
0	3.41	Bubble	9.1509	9.1509	9.1509	9.1509	9.1509	9.1509	9.1509	9.1509	9.1509	9.1509	9.1509 ± 0.00
0	5.60	Bubble-Slug	9.0777	9.0777	9.0777	9.0777	9.0777	9.0777	9.0777	9.0777	9.0777	9.0777	9.0777 ± 0.00
0	9.97	Bubble-Slug	8.4676	8.4676	8.4676	8.4676	8.4676	8.4676	8.4676	8.4676	8.4676	8.4676	8.4676 ± 0.00
0	14.35	Slug	7.9796	7.9796	7.9796	7.9796	7.9796	7.9796	7.9796	7.9796	7.9796	7.9796	7.9796 ± 0.00
0	18.72	Slug	7.5159	7.5159	7.5159	7.5159	7.5159	7.4671	7.4671	7.4671	7.4671	7.4671	7.4915 ± 0.03
0	23.09	Slug	7.1011	7.1011	7.1011	7.1011	7.1011	7.0523	7.0523	7.0523	7.0523	7.0523	7.0767 ± 0.03
0	27.47	Slug	6.5642	6.5642	6.5642	6.5642	6.5642	6.4910	6.4910	6.4910	6.4910	6.4910	6.5276 ± 0.04
0	31.84	Slug	6.2226	6.2226	6.2226	6.2226	6.2226	6.1250	6.1250	6.1250	6.1250	6.1250	6.1738 ± 0.05
0	36.22	Slug	5.7346	5.7346	5.7346	5.7346	5.7346	5.6614	5.6614	5.6614	5.6614	5.6614	5.6980 ± 0.04
0	40.56	Slug	5.2953	5.2465	5.2221	5.2709	5.2465	5.1489	5.1489	5.1489	5.1489	5.1489	5.2026 ± 0.06
0	49.63	Slug	4.9781	4.9293	4.9293	4.9293	4.9293	4.8073	4.8073	4.7829	4.7585	4.7829	4.8634 ± 0.08
0	58.69	Slug	4.6365	4.6365	4.6365	4.6365	4.6365	4.4412	4.4656	4.4656	4.4656	4.4656	4.5486 ± 0.09
0	67.75	Slug	4.2948	4.2948	4.2704	4.2704	4.2460	4.1728	4.1484	4.1728	4.1728	4.1728	4.2216 ± 0.06
0	76.82	Slug	4.0752	4.0508	4.0508	4.0508	4.0508	3.9044	3.9532	3.9532	3.9532	3.9532	3.9995 ± 0.06
0	85.88	Slug	3.7824	3.7824	3.7824	3.7824	3.7824	3.6360	3.6360	3.6360	3.6604	3.6116	3.7092 ± 0.08
0	94.95	Slug	3.6116	3.6360	3.6116	3.6116	3.5871	3.4895	3.4895	3.4651	3.4651	3.4651	3.5432 ± 0.07
1079	3.41	Bubble	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877	9.6877 ± 0.00
1079	5.60	Bubble	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389	9.6389 ± 0.00
1079	9.97	Bubble	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681	9.4681 ± 0.00
1079	14.35	Bubble-Slug	9.0045	9.0045	9.0045	9.0045	9.0045	9.0045	9.0045	9.0045	9.0045	9.0045	9.0045 ± 0.00
1079	18.72	Bubble-Slug	8.6140	8.6140	8.6140	8.6140	8.6140	8.6140	8.6140	8.6140	8.6140	8.6140	8.6140 ± 0.00
1079	23.09	Slug	8.3700	8.3700	8.3700	8.3700	8.3700	8.3212	8.3212	8.3212	8.3212	8.3212	8.3456 ± 0.03
1079	27.47	Slug	8.1260	8.1260	8.1260	8.1260	8.1260	8.0772	8.0772	8.0772	8.0772	8.0772	8.1016 ± 0.03
1079	31.84	Slug	7.7356	7.7356	7.7356	7.7356	7.7356	7.7356	7.7356	7.7356	7.7356	7.7356	7.7356 ± 0.00
1079	36.22	Slug	7.3451	7.3451	7.3451	7.3451	7.3451	7.2963	7.2963	7.2963	7.2963	7.2963	7.3207 ± 0.03
1079	40.56	Slug	7.0523	7.0523	7.0523	7.0523	7.0523	7.0035	7.0035	7.0035	7.0035	7.0035	7.0279 ± 0.03

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
1079	49.63	Slug	6.6618	6.6618	6.6618	6.6618	6.6618	6.6618	6.6618	6.6618	6.6618	6.6618	6.6618 ± 0.00
1079	58.69	Slug	6.4422	6.4422	6.4422	6.4422	6.4422	6.4178	6.4178	6.4178	6.4178	6.4178	6.4300 ± 0.01
1079	67.75	Slug	6.2470	6.2470	6.2470	6.2470	6.2470	6.1982	6.1982	6.1982	6.1982	6.1982	6.2226 ± 0.03
1079	76.82	Slug	5.9298	5.9298	5.9298	5.9298	5.9298	5.8566	5.8566	5.8566	5.8566	5.8566	5.8932 ± 0.04
1079	85.88	Slug	5.6614	5.6614	5.6614	5.6614	5.6614	5.6125	5.6125	5.6125	5.6125	5.6125	5.6369 ± 0.03
1079	94.95	Slug	5.5637	5.5637	5.5637	5.5637	5.5637	5.5149	5.5149	5.5149	5.5149	5.5149	5.5393 ± 0.03
1079	104	Slug	5.3685	5.3685	5.3685	5.3685	5.3685	5.2221	5.2221	5.2221	5.2221	5.2221	5.2953 ± 0.08
1079	122	Slug	4.9049	4.9293	4.9049	4.9049	4.9049	4.7585	4.7341	4.7585	4.7829	4.7585	4.8341 ± 0.08
1079	140	Slug-Churn	4.6365	4.6120	4.6609	4.6609	4.6609	4.4412	4.3924	4.4412	4.4168	4.4168	4.5340 ± 0.12
1079	158	Slug-Churn	4.3680	4.3680	4.4168	4.4412	4.3924	4.1240	4.1240	4.0508	4.0752	4.0508	4.2411 ± 0.17
1079	177	Slug-Churn	4.1972	4.2216	4.2216	4.2216	4.1972	3.8312	3.8312	3.8800	3.8800	3.8800	4.0362 ± 0.19
1079	231	Slug-Churn	3.5627	3.5627	3.5627	3.5627	3.5627	3.2943	3.2943	3.2943	3.2943	3.2943	3.4285 ± 0.14
1079	294	Slug-Churn	3.2455	3.2455	3.2211	3.2943	3.2943	2.8307	2.8551	2.8063	2.7575	2.8063	3.0357 ± 0.24
1079	367	Slug-Churn	2.9039	2.8795	2.9039	2.8795	2.9283	2.2694	2.3182	2.2938	2.2694	2.2694	2.5915 ± 0.32
1079	523	Churn	2.2938	2.3182	2.3182	2.3182	2.3182	1.8302	1.8302	1.8546	1.7326	1.7814	2.0596 ± 0.27
1079	782	Churn	2.2450	2.1962	2.2450	2.1962	2.1474	1.3909	1.2689	1.2689	1.1713	1.2201	1.7350 ± 0.50
1079	1427	Churn	2.5378	2.5134	2.5378	2.5134	2.5378	1.3909	1.4397	1.4641	1.4153	1.4885	1.9839 ± 0.57
1079	2461	Churn	2.5622	2.5378	2.5134	2.5378	2.5378	2.0742	2.0986	2.0742	2.0986	2.0986	2.3133 ± 0.24
1079	3471	Churn	2.3914	2.4158	2.4158	2.3670	2.3914	2.2206	2.1230	2.1474	2.1474	2.1474	2.2767 ± 0.13
1079	4554	Annular	2.3670	2.3670	2.3670	2.3670	2.3670	2.1474	2.1718	2.1718	2.1474	2.1474	2.2621 ± 0.11
1079	5546	Annular	2.3426	2.3426	2.3426	2.3426	2.3426	2.2938	2.2938	2.2938	2.2938	2.2938	2.3182 ± 0.03
1079	12597	Annular	3.0747	3.0747	3.0747	3.0747	3.0747	3.0747	3.0747	3.0747	3.0747	3.0747	3.0747 ± 0.00
1079	25195	Mist	9.0289	9.0289	9.0289	9.0289	9.0289	8.9313	8.9313	8.9313	8.9313	8.9313	8.9801 ± 0.05
2727	3.41	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
2727	5.60	Bubble	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365	9.7365 ± 0.00
2727	9.97	Bubble	9.7121	9.7121	9.7121	9.7121	9.7121	9.6877	9.6877	9.6877	9.6877	9.6877	9.6999 ± 0.01
2727	14.35	Bubble	9.6877	9.6877	9.6877	9.6877	9.6877	9.6389	9.6389	9.6389	9.6389	9.6389	9.6633 ± 0.03

Re_{water}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2727	18.72	Bubble	9.3461	9.3461	9.3461	9.3461	9.3461	9.2729	9.2729	9.2729	9.2729	9.2729	9.3095 ± 0.04
2727	23.09	Bubble	9.1265	9.1265	9.1265	9.1265	9.1265	9.0777	9.0777	9.0777	9.0777	9.0777	9.1021 ± 0.03
2727	27.47	Bubble-Slug	8.9069	8.9069	8.9069	8.9069	8.9069	8.8825	8.8337	8.8337	8.7849	8.7849	8.8654 ± 0.05
2727	31.84	Bubble-Slug	8.6140	8.6140	8.6140	8.6140	8.6140	8.5652	8.5652	8.5652	8.5652	8.5652	8.5896 ± 0.03
2727	36.22	Slug	8.4432	8.4432	8.4432	8.4432	8.4432	8.3944	8.3944	8.3944	8.3944	8.3944	8.4188 ± 0.03
2727	40.56	Slug	8.1260	8.1260	8.1260	8.1260	8.1260	8.0772	8.0772	8.0772	8.0772	8.0772	8.1016 ± 0.03
2727	49.63	Slug	7.8576	7.8576	7.8576	7.8576	7.8576	7.8576	7.8576	7.8576	7.8576	7.8576	7.8576 ± 0.00
2727	58.69	Slug	7.6379	7.6379	7.6379	7.6379	7.6379	7.5891	7.5891	7.5891	7.5891	7.5891	7.6135 ± 0.03
2727	67.75	Slug	7.4183	7.4183	7.4183	7.4183	7.4183	7.3695	7.3695	7.3695	7.3695	7.3695	7.3939 ± 0.03
2727	76.82	Slug	7.2231	7.2231	7.2231	7.2231	7.2231	7.1743	7.1743	7.1743	7.1743	7.1743	7.1987 ± 0.03
2727	85.88	Slug	7.0279	7.0279	7.0279	7.0279	7.0279	6.9791	6.9791	6.9791	6.9791	6.9791	7.0035 ± 0.03
2727	94.95	Slug	6.8327	6.8327	6.8327	6.8327	6.8327	6.7839	6.7839	6.7839	6.7839	6.7839	6.8083 ± 0.03
2727	104	Slug	6.6863	6.6863	6.6863	6.6863	6.6863	6.6863	6.6863	6.6863	6.6863	6.6863	6.6863 ± 0.00
2727	122	Slug	6.3934	6.3934	6.3934	6.3934	6.3934	6.3446	6.3446	6.3446	6.3446	6.3446	6.3690 ± 0.03
2727	140	Slug	6.1738	6.1738	6.1738	6.1738	6.1738	6.1250	6.1250	6.1250	6.1250	6.1250	6.1494 ± 0.03
2727	158	Slug	5.8078	5.8078	5.8078	5.8078	5.8078	5.7834	5.7834	5.7834	5.7834	5.7834	5.7956 ± 0.01
2727	177	Slug	5.6369	5.6369	5.6369	5.6369	5.6369	5.5637	5.5637	5.5637	5.5881	5.5881	5.6052 ± 0.03
2727	231	Slug-Churn	5.0757	5.0757	5.0757	5.0757	5.0757	4.9537	4.9537	4.9537	4.9537	4.9537	5.0147 ± 0.06
2727	294	Slug-Churn	4.6365	4.6365	4.6365	4.6365	4.6365	4.5632	4.5632	4.5632	4.5632	4.5632	4.5998 ± 0.04
2727	367	Slug-Churn	4.2216	4.1972	4.2216	4.1972	4.2216	4.0020	3.9776	4.0020	4.0020	4.0020	4.1045 ± 0.11
2727	523	Slug-Churn	3.6116	3.6360	3.6116	3.6116	3.6116	3.2943	3.3187	3.3187	3.2943	3.2943	3.4603 ± 0.17
2727	782	Slug-Churn	3.2455	3.2943	3.2943	3.2943	3.2943	2.6355	2.6355	2.6599	2.6355	2.6355	2.9624 ± 0.34
2727	1427	Churn	3.5139	3.4407	3.4895	3.5383	3.4407	2.3670	2.3914	2.4158	2.4158	2.3914	2.9405 ± 0.57
2727	2461	Churn	4.2216	4.0752	4.0996	4.0752	4.0508	3.2211	3.2211	3.1967	3.1723	3.2211	3.6555 ± 0.48
2727	3471	Churn	3.9776	3.9776	3.9776	3.9776	3.9776	3.4895	3.3919	3.4163	3.4163	3.3919	3.6994 ± 0.29
2727	4554	Churn	4.0996	4.0752	4.0996	4.0996	4.0752	3.7824	3.8068	3.8312	3.7824	3.7824	3.9434 ± 0.16
2727	5546	Churn	4.7341	4.7097	4.7341	4.7341	4.7585	4.5388	4.5632	4.5388	4.5632	4.5144	4.6389 ± 0.10
2727	12597	Annular	6.0762	6.0762	6.0762	6.0762	6.0762	6.0762	6.0762	6.0762	6.0762	6.0762	6.0762 ± 0.00
2727	25195	Mist	9.3217	9.3217	9.3217	9.3217	9.3217	9.2729	9.2729	9.2729	9.2729	9.2729	9.2973 ± 0.03

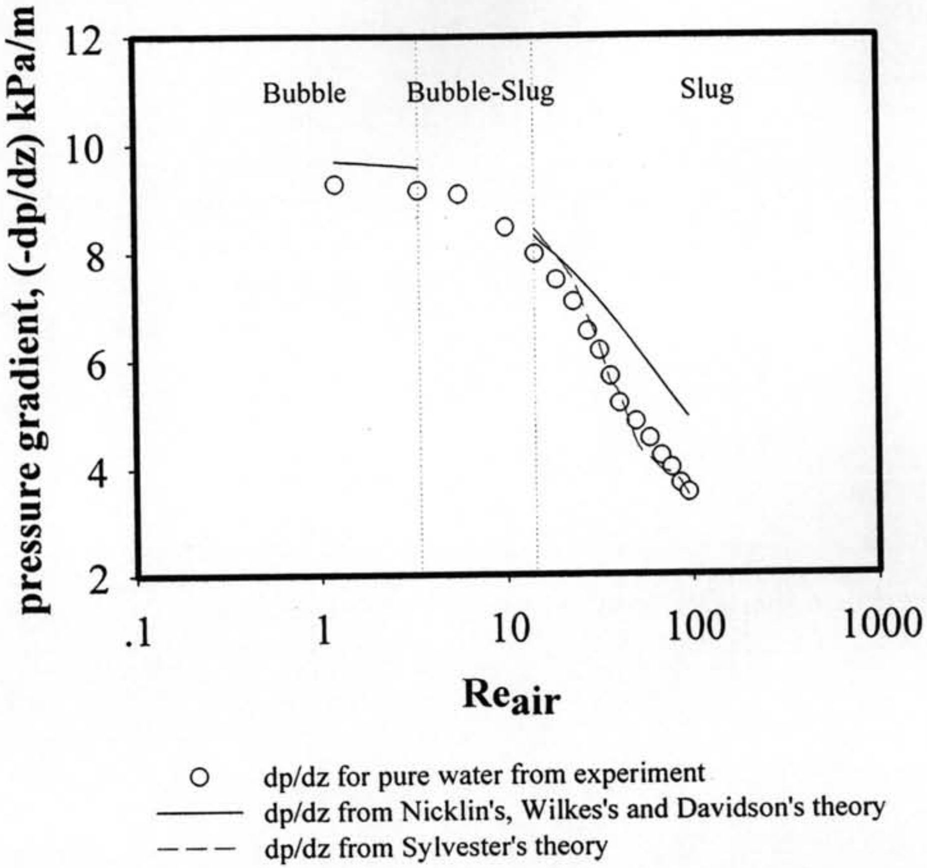


Figure C10 Comparison between Nicklin's theory, Sylvester's theory and experimental pressure gradient vs. air Reynolds number of pure water at $Re_{water} = 0$ by using pipe diameter 10.75 mm.

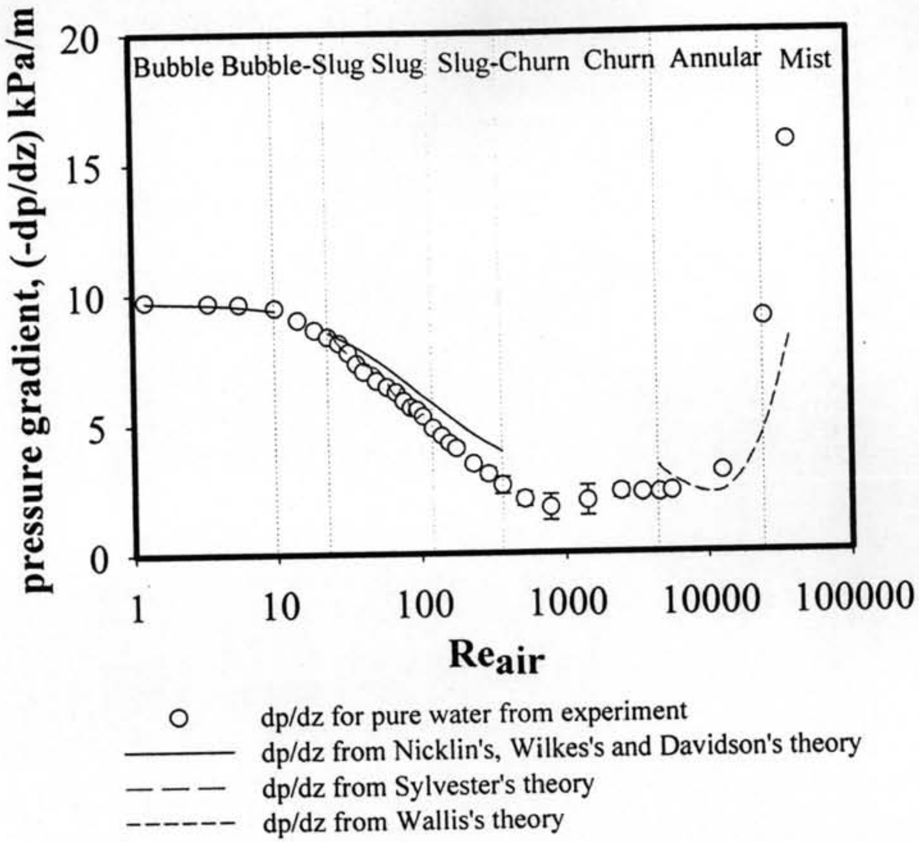


Figure C11 Comparison between Nicklin's theory, Sylvester's theory, Wallis's theory and experimental pressure gradient vs. air Reynolds number of pure water at Re_{water} = 1079 by using pipe diameter 10.75 mm.

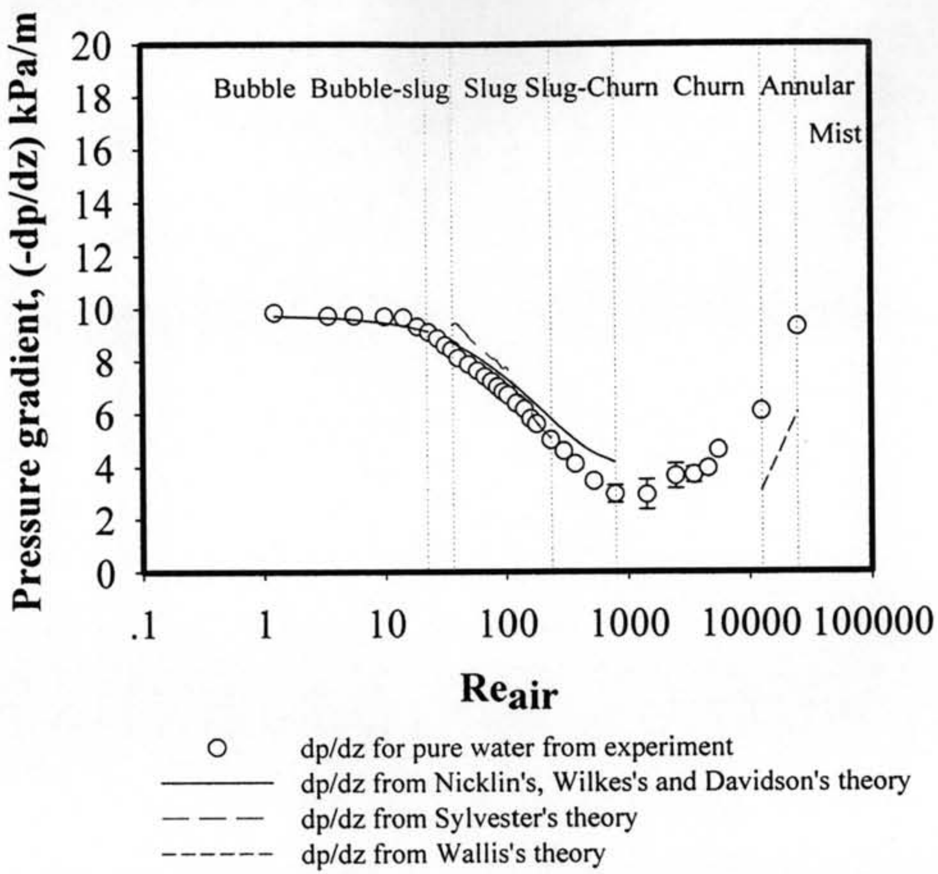


Figure C12 Comparison between Nicklin's theory, Sylvester's theory, Wallis's theory and experimental pressure gradient vs. air Reynolds number of pure water at $Re_{water} = 2727$ by using pipe diameter 10.75 mm.

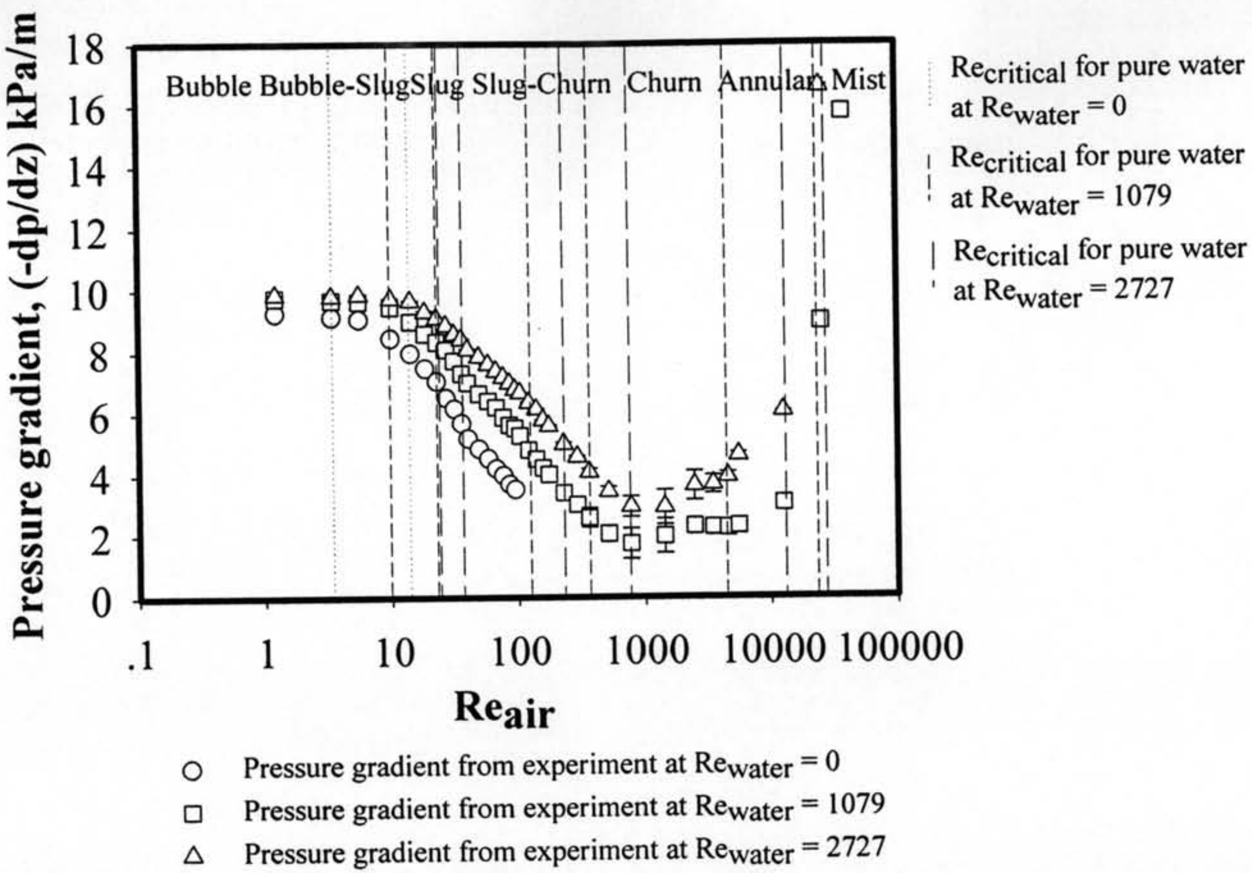


Figure C13 Comparison pressure gradient from experiment vs. air Reynolds number of pure water by using pipe diameter 10.75 mm.

Table C9 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes by using pipe diameter of 10.75 mm

Pipe diameter (mm)	Re_{water}	Re_{air}(critical) for each flow regime					
		Bubble-slug	Slug	Slug-churn	Churn	Annular	Mist
10.75	0	5.6	14.35	-	-	-	-
	1079	14.35	23.09	140	523	4554	25195
	2727	27.47	36.22	231	1427	12597	25195

Appendix D Comparison the Experimental Data Between Pipe Diameter of 10.75 mm, 19 mm and 53.15 mm

Table D1 Comparison of bubble width for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

temperature, T = 31 °C (± 1 °C)

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble width, W_b (mm)			Average bubble width, (mm)	Bubble width / Pipe diameter			Average bubble width / Pipe diameter
			1	2	3		1	2	3	
10.75	0	1.2	8.8	8.4	9.1	8.8 ± 0.3	0.82	0.78	0.85	0.82 ± 0.03
10.75	0	3.4	8.8	9.6	9.5	9.3 ± 0.5	0.82	0.90	0.88	0.86 ± 0.04
19	0	3.17	13.6	14.9	14.4	14.3 ± 0.7	0.72	0.78	0.76	0.75 ± 0.03
19	0	4.40	14.7	14.4	13.8	14.3 ± 0.5	0.77	0.76	0.72	0.75 ± 0.02
19	0	5.64	14.7	14.0	14.0	14.2 ± 0.4	0.77	0.74	0.74	0.75 ± 0.02
19	0	6.88	14.3	14.7	15.0	14.7 ± 0.4	0.75	0.77	0.79	0.77 ± 0.02
19	0	8.12	15.0	15.5	15.2	15.2 ± 0.3	0.79	0.82	0.80	0.80 ± 0.01
53.15	0	2.9	14.0	15.4	14.4	14.6 ± 0.7	0.26	0.29	0.27	0.27 ± 0.01
53.15	0	5.6	18.6	17.4	16.6	17.5 ± 1.0	0.35	0.33	0.31	0.33 ± 0.02
53.15	0	8.2	25.7	28.3	23.1	25.7 ± 2.6	0.48	0.53	0.43	0.48 ± 0.05
53.15	0	10.0	25.6	33.3	32.6	30.5 ± 4.3	0.48	0.63	0.61	0.57 ± 0.08
53.15	0	11.9	33.2	27.3	31.5	30.7 ± 3.1	0.63	0.51	0.59	0.58 ± 0.06
53.15	0	13.7	28.9	33.0	28.1	30.0 ± 2.6	0.54	0.62	0.53	0.56 ± 0.05
53.15	0	15.5	28.9	31.9	31.0	30.6 ± 1.5	0.54	0.60	0.58	0.58 ± 0.03
53.15	0	17.4	30.5	30.2	31.6	30.8 ± 0.7	0.57	0.57	0.59	0.58 ± 0.01
53.15	0	21.0	28.9	38.3	29.3	32.2 ± 5.3	0.54	0.72	0.55	0.61 ± 0.10
53.15	0	22.9	26.4	32.3	35.5	31.4 ± 4.6	0.50	0.61	0.67	0.59 ± 0.09
53.15	0	28.4	35.9	31.3	29.7	32.3 ± 3.2	0.67	0.59	0.56	0.61 ± 0.06
53.15	0	33.9	28.1	33.0	35.7	32.3 ± 3.9	0.53	0.62	0.67	0.61 ± 0.07
53.15	0	37.5	34.8	34.9	33.6	34.4 ± 0.7	0.65	0.66	0.63	0.65 ± 0.01
53.15	0	43.0	35.4	31.6	32.3	33.1 ± 2.0	0.67	0.59	0.61	0.62 ± 0.04
53.15	0	48.5	34.6	37.4	35.7	35.9 ± 1.4	0.65	0.70	0.67	0.68 ± 0.03
53.15	0	59.5	35.9	35.1	37.3	36.1 ± 1.1	0.68	0.66	0.70	0.68 ± 0.02
53.15	0	68.7	37.0	44.1	45.0	42.0 ± 4.4	0.70	0.83	0.85	0.79 ± 0.08
53.15	0	79.7	41.1	45.1	43.9	43.4 ± 2.1	0.77	0.85	0.83	0.82 ± 0.04
53.15	0	88.9	42.7	43.5	41.7	42.6 ± 0.9	0.80	0.82	0.79	0.80 ± 0.02
53.15	0	99.9	47.0	44.4	41.8	44.4 ± 2.6	0.89	0.84	0.79	0.84 ± 0.05
10.75	1079	1.2	9.0	9.1	9.4	9.2 ± 0.2	0.84	0.84	0.88	0.85 ± 0.02

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble width, W_b (mm)			Average bubble width, (mm)	Bubble Width / Pipe diameter			Average bubble width / Pipe diameter
			1	2	3		1	2	3	
10.75	1079	3.4	9.6	9.4	9.4	9.4 ± 0.1	0.89	0.87	0.88	0.88 ± 0.01
10.75	1079	5.6	9.4	9.3	9.6	9.4 ± 0.1	0.88	0.87	0.89	0.88 ± 0.01
10.75	1079	10.0	9.2	9.4	9.6	9.4 ± 0.2	0.86	0.87	0.89	0.87 ± 0.02
19	1010	3.17	15.4	15.0	14.5	15.0 ± 0.5	0.81	0.79	0.76	0.79 ± 0.02
19	1010	5.64	14.3	14.3	14.1	14.2 ± 0.1	0.75	0.75	0.74	0.75 ± 0.01
19	1010	8.12	14.6	14.6	14.8	14.7 ± 0.1	0.77	0.77	0.78	0.77 ± 0.01
19	1010	10.59	15.2	13.8	15.3	14.8 ± 0.8	0.80	0.73	0.80	0.78 ± 0.04
19	1010	13.07	14.5	15.6	15.0	15.0 ± 0.6	0.76	0.82	0.79	0.79 ± 0.03
53.15	1028	2.9	7.4	8.1	8.6	8.0 ± 0.6	0.14	0.15	0.16	0.15 ± 0.01
53.15	1028	5.6	7.2	6.4	9.2	7.6 ± 1.4	0.14	0.12	0.17	0.14 ± 0.03
53.15	1028	8.2	15.5	20.1	19.3	18.3 ± 2.5	0.29	0.38	0.36	0.34 ± 0.05
53.15	1028	10.0	23.4	17.4	23.7	21.5 ± 3.6	0.44	0.33	0.45	0.40 ± 0.07
53.15	1028	11.9	23.3	26.7	16.7	22.2 ± 5.1	0.44	0.50	0.31	0.42 ± 0.10
53.15	1028	13.7	25.9	19.9	27.3	24.4 ± 3.9	0.49	0.37	0.51	0.46 ± 0.07
53.15	1028	15.5	23.4	22.6	24.4	23.5 ± 0.9	0.44	0.43	0.46	0.44 ± 0.02
53.15	1028	17.4	27.6	26.5	24.1	26.1 ± 1.8	0.52	0.50	0.45	0.49 ± 0.03
53.15	1028	21.0	30.4	28.1	22.7	27.1 ± 4.0	0.57	0.53	0.43	0.51 ± 0.07
53.15	1028	22.9	23.5	27.1	29.4	26.7 ± 3.0	0.44	0.51	0.55	0.50 ± 0.06
53.15	1028	28.4	31.1	29.9	28.8	30.0 ± 1.1	0.58	0.56	0.54	0.56 ± 0.02
53.15	1028	33.9	29.8	34.6	31.4	31.9 ± 2.4	0.56	0.65	0.59	0.60 ± 0.05
53.15	1028	37.5	34.7	27.2	33.0	31.6 ± 3.9	0.65	0.51	0.62	0.59 ± 0.07
53.15	1028	43.0	33.0	32.2	30.0	31.7 ± 1.6	0.62	0.61	0.56	0.60 ± 0.03
53.15	1028	48.5	37.5	34.6	33.0	35.0 ± 2.2	0.70	0.65	0.62	0.66 ± 0.04
53.15	1028	59.5	36.2	36.2	36.4	36.2 ± 0.1	0.68	0.68	0.68	0.68 ± 0.00
53.15	1028	68.7	39.1	40.3	36.1	38.5 ± 2.2	0.74	0.76	0.68	0.72 ± 0.04
53.15	1028	79.7	33.3	36.7	41.2	37.1 ± 3.9	0.63	0.69	0.78	0.70 ± 0.07
53.15	1028	88.9	39.8	41.1	37.8	39.6 ± 1.7	0.75	0.77	0.71	0.74 ± 0.03
53.15	1028	99.9	38.1	43.6	38.8	40.2 ± 3.0	0.72	0.82	0.73	0.76 ± 0.06

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble width, W_b (mm)			Average bubble width, (mm)	Bubble Width / Pipe diameter			Average bubble width / Pipe diameter
			1	2	3		1	2	3	
53.15	1028	132	36.6	35.6	45.8	39.3 ± 5.6	0.69	0.67	0.86	0.74 ± 0.11
10.75	2727	1.2	7.0	7.9	7.3	7.4 ± 0.4	0.66	0.74	0.68	0.69 ± 0.04
10.75	2727	3.4	7.7	7.5	8.0	7.7 ± 0.3	0.72	0.69	0.74	0.72 ± 0.02
10.75	2727	5.6	8.5	8.7	8.4	8.5 ± 0.1	0.79	0.80	0.78	0.79 ± 0.01
10.75	2727	10.0	9.4	8.4	8.0	8.6 ± 0.7	0.88	0.79	0.74	0.80 ± 0.07
10.75	2727	14.3	7.9	8.1	9.0	8.3 ± 0.6	0.74	0.75	0.83	0.77 ± 0.05
10.75	2727	18.7	9.3	9.1	8.7	9.0 ± 0.3	0.86	0.85	0.81	0.84 ± 0.03
10.75	2727	23.1	8.8	9.1	9.4	9.1 ± 0.3	0.82	0.85	0.88	0.85 ± 0.03
19	2740	3.17	13.8	12.8	12.6	13.1 ± 0.6	0.73	0.68	0.66	0.69 ± 0.03
19	2740	5.64	14.8	14.9	13.7	14.5 ± 0.7	0.78	0.79	0.72	0.76 ± 0.04
19	2740	8.12	14.8	14.5	14.7	14.6 ± 0.2	0.78	0.76	0.77	0.77 ± 0.01
19	2740	10.59	13.7	13.7	14.1	13.8 ± 0.2	0.72	0.72	0.74	0.73 ± 0.01
19	2740	13.07	14.1	14.5	14.5	14.3 ± 0.2	0.74	0.76	0.76	0.75 ± 0.01
19	2740	15.54	15.0	14.8	15.7	15.2 ± 0.5	0.79	0.78	0.82	0.80 ± 0.02
19	2740	18.02	16.3	15.1	15.0	15.5 ± 0.7	0.86	0.79	0.79	0.82 ± 0.04
19	2740	20.49	15.0	13.8	15.2	14.6 ± 0.7	0.79	0.73	0.80	0.77 ± 0.04
19	2740	22.95	15.3	14.8	15.2	15.1 ± 0.3	0.81	0.78	0.80	0.79 ± 0.01
19	2740	28.08	15.4	15.1	15.3	15.2 ± 0.2	0.81	0.79	0.80	0.80 ± 0.01
19	2740	33.21	15.6	15.0	15.1	15.2 ± 0.3	0.82	0.79	0.79	0.80 ± 0.02

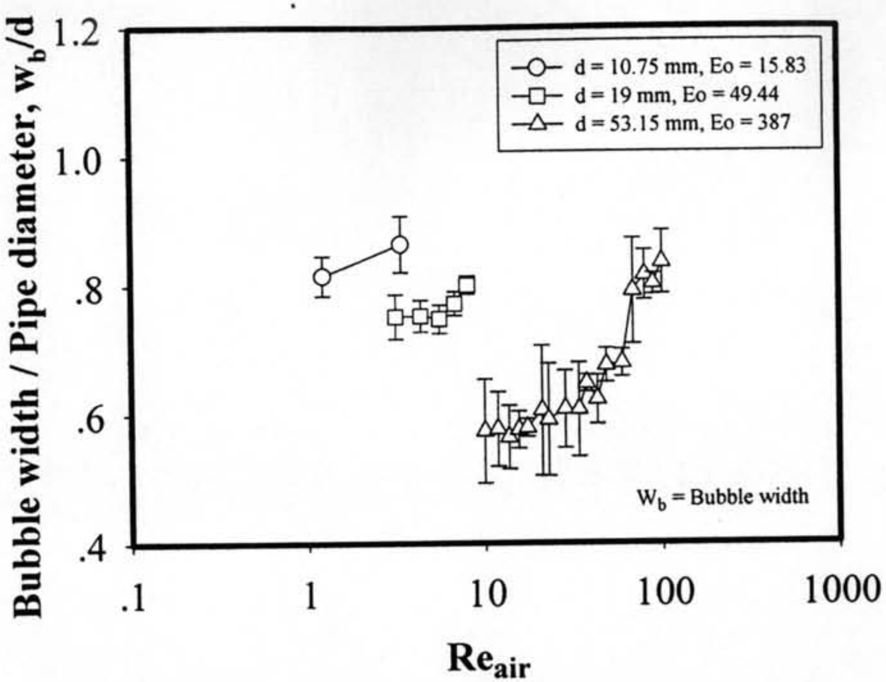


Figure D1 Comparison bubble width from experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at $Re_{water} = 0$.

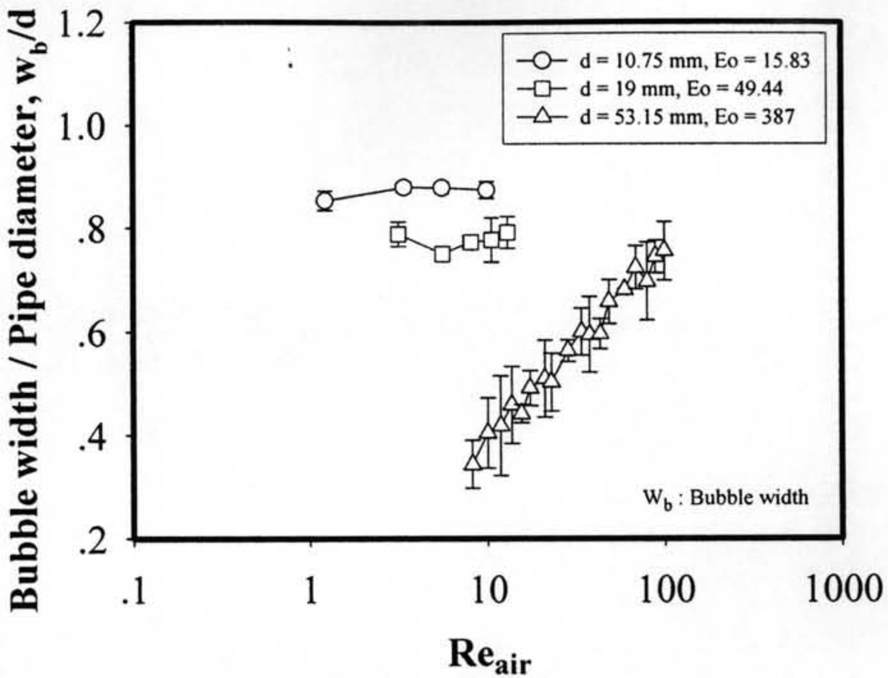


Figure D2 Comparison bubble width from experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at Re_{water} = 1079, 1010 and 1028.

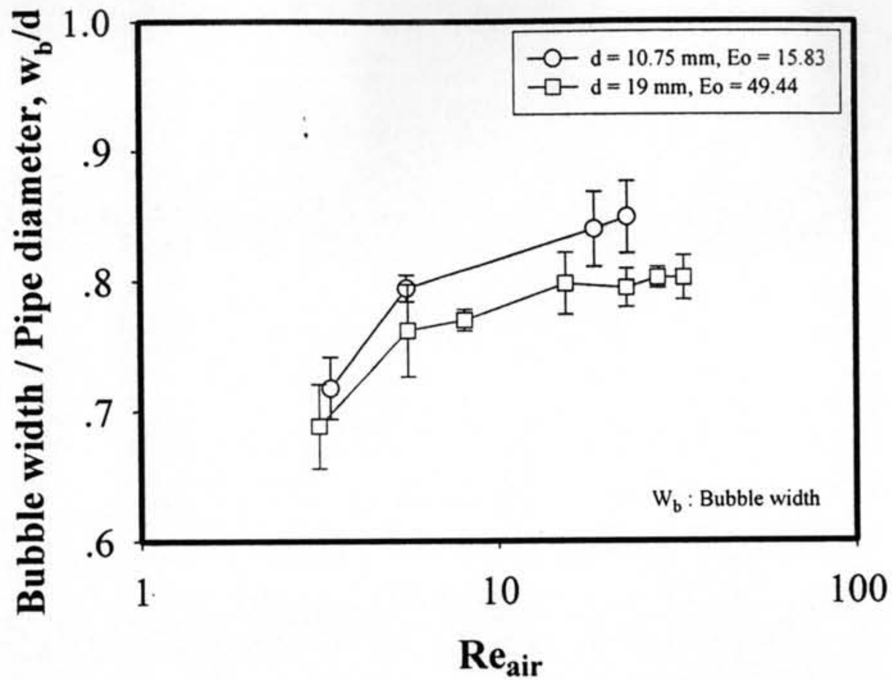


Figure D3 Comparison bubble width from experiment between pipe diameter 10.75 mm and 19 mm vs. air Reynolds number of pure water at Re_{water} = 2727 and 2740.

Table D2 Comparison of bubble height for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

temperature, T = 31 °C (± 1 °C)

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble height / Pipe diameter			Average, R_h/D
			1	2	3		1	2	3	
10.75	0	1.2	11.3	11.2	11.4	11.3 ± 0.1	1.05	1.04	1.06	1.05 ± 0.01
10.75	0	3.4	11.5	11.9	11.6	11.7 ± 0.2	1.07	1.11	1.08	1.08 ± 0.02
19	0	3.17	12.5	12.2	12.9	12.5 ± 0.3	0.66	0.64	0.68	0.66 ± 0.02
19	0	4.40	13.3	13.5	13.3	13.4 ± 0.1	0.70	0.71	0.70	0.70 ± 0.01
19	0	5.64	15.6	15.3	15.0	15.3 ± 0.3	0.82	0.81	0.79	0.81 ± 0.02
19	0	6.88	16.2	16.4	16.3	16.3 ± 0.1	0.85	0.86	0.86	0.86 ± 0.01
19	0	8.12	17.4	18.2	17.4	17.6 ± 0.5	0.91	0.96	0.91	0.93 ± 0.03
53.15	0	2.9	8.6	10.2	11.7	10.2 ± 1.5	0.16	0.19	0.22	0.19 ± 0.03
53.15	0	5.6	11.2	10.8	12.4	11.5 ± 0.8	0.21	0.20	0.23	0.22 ± 0.02
53.15	0	8.2	12.4	14.0	12.2	12.9 ± 1.0	0.23	0.26	0.23	0.24 ± 0.02
53.15	0	10.0	13.5	16.8	15.7	15.3 ± 1.7	0.25	0.32	0.30	0.29 ± 0.03
53.15	0	11.9	16.8	16.8	17.9	17.2 ± 0.6	0.32	0.32	0.34	0.32 ± 0.01
53.15	0	13.7	18.3	16.7	22.7	19.3 ± 3.1	0.34	0.31	0.43	0.36 ± 0.06
53.15	0	15.5	19.7	21.7	20.2	20.5 ± 1.0	0.37	0.41	0.38	0.39 ± 0.02
53.15	0	17.4	21.0	20.2	21.4	20.9 ± 0.6	0.39	0.38	0.40	0.39 ± 0.01
53.15	0	21.0	20.7	19.4	19.3	19.8 ± 0.8	0.39	0.37	0.36	0.37 ± 0.01
53.15	0	22.9	23.1	25.1	21.1	23.1 ± 2.0	0.43	0.47	0.40	0.43 ± 0.04
53.15	0	28.4	28.2	20.2	27.9	25.4 ± 4.5	0.53	0.38	0.52	0.48 ± 0.08
53.15	0	33.9	25.8	25.2	23.8	24.9 ± 1.0	0.49	0.47	0.45	0.47 ± 0.02
53.15	0	37.5	27.8	28.9	30.0	28.9 ± 1.1	0.52	0.54	0.56	0.54 ± 0.02
53.15	0	43.0	26.2	30.0	30.4	28.9 ± 2.3	0.49	0.56	0.57	0.54 ± 0.04
53.15	0	48.5	31.1	31.5	28.5	30.4 ± 1.6	0.59	0.59	0.54	0.57 ± 0.03
53.15	0	59.5	36.1	33.6	28.5	32.8 ± 3.9	0.68	0.63	0.54	0.62 ± 0.07
53.15	0	68.7	32.7	33.5	33.9	33.4 ± 0.6	0.62	0.63	0.64	0.63 ± 0.01
53.15	0	79.7	33.2	26.4	33.7	31.1 ± 4.1	0.63	0.50	0.63	0.59 ± 0.08
53.15	0	88.9	35.4	34.8	35.4	35.2 ± 0.3	0.67	0.66	0.67	0.66 ± 0.01
53.15	0	99.9	39.6	41.4	40.2	40.4 ± 0.9	0.75	0.78	0.76	0.76 ± 0.02
10.75	1079	1.2	12.7	12.0	12.2	12.3 ± 0.4	1.18	1.11	1.14	1.14 ± 0.04

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble height / Pipe diameter			Average, R_h/D
			1	2	3		1	2	3	
10.75	1079	3.4	12.7	13.0	13.1	12.9 ± 0.2	1.18	1.21	1.22	1.20 ± 0.02
10.75	1079	5.6	12.9	12.8	12.7	12.8 ± 0.1	1.20	1.19	1.18	1.19 ± 0.01
10.75	1079	10.0	13.0	12.9	13.1	13.0 ± 0.1	1.21	1.20	1.22	1.21 ± 0.01
19	1010	3.17	15.9	17.1	15.6	16.2 ± 0.8	0.84	0.90	0.82	0.85 ± 0.04
19	1010	5.64	16.6	18.5	18.3	17.8 ± 1.1	0.87	0.98	0.96	0.94 ± 0.06
19	1010	8.12	23.3	20.7	22.4	22.1 ± 1.3	1.23	1.09	1.18	1.17 ± 0.07
19	1010	10.59	24.0	23.2	23.2	23.5 ± 0.5	1.26	1.22	1.22	1.24 ± 0.02
19	1010	13.07	23.6	25.2	23.9	24.2 ± 0.8	1.24	1.32	1.26	1.28 ± 0.04
53.15	1028	2.9	7.8	6.9	8.0	7.5 ± 0.6	0.15	0.13	0.15	0.14 ± 0.01
53.15	1028	5.6	8.9	9.0	10.8	9.5 ± 1.1	0.17	0.17	0.20	0.18 ± 0.02
53.15	1028	8.2	17.5	15.5	17.8	16.9 ± 1.3	0.33	0.29	0.34	0.32 ± 0.02
53.15	1028	10.0	16.0	19.4	18.8	18.0 ± 1.8	0.30	0.36	0.35	0.34 ± 0.03
53.15	1028	11.9	20.0	19.5	14.2	17.9 ± 3.2	0.38	0.37	0.27	0.34 ± 0.06
53.15	1028	13.7	19.0	16.1	16.4	17.2 ± 1.6	0.36	0.30	0.31	0.32 ± 0.03
53.15	1028	15.5	21.8	20.3	22.4	21.5 ± 1.1	0.41	0.38	0.42	0.40 ± 0.02
53.15	1028	17.4	17.8	20.8	19.7	19.5 ± 1.5	0.34	0.39	0.37	0.37 ± 0.03
53.15	1028	21.0	23.2	22.4	24.1	23.2 ± 0.8	0.44	0.42	0.45	0.44 ± 0.02
53.15	1028	22.9	21.0	23.2	23.7	22.6 ± 1.4	0.40	0.44	0.45	0.43 ± 0.03
53.15	1028	28.4	24.6	21.1	22.6	22.8 ± 1.7	0.46	0.40	0.42	0.43 ± 0.03
53.15	1028	33.9	26.3	21.4	24.2	23.9 ± 2.5	0.49	0.40	0.46	0.45 ± 0.05
53.15	1028	37.5	21.9	23.2	25.6	23.6 ± 1.8	0.41	0.44	0.48	0.44 ± 0.03
53.15	1028	43.0	23.9	25.8	23.6	24.5 ± 1.2	0.45	0.49	0.44	0.46 ± 0.02
53.15	1028	48.5	30.8	30.4	32.0	31.1 ± 0.8	0.58	0.57	0.60	0.58 ± 0.02
53.15	1028	59.5	32.5	32.9	35.0	33.5 ± 1.3	0.61	0.62	0.66	0.63 ± 0.03
53.15	1028	68.7	37.5	39.5	37.0	38.0 ± 1.3	0.71	0.74	0.70	0.71 ± 0.02
53.15	1028	79.7	42.3	42.3	43.0	42.5 ± 0.4	0.80	0.79	0.81	0.80 ± 0.01
53.15	1028	88.9	44.5	43.6	45.5	44.5 ± 0.9	0.84	0.82	0.86	0.84 ± 0.02
53.15	1028	99.9	46.8	42.2	45.2	44.7 ± 2.3	0.88	0.79	0.85	0.84 ± 0.04

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble height / Pipe diameter			Average, R_h/D
			1	2	3		1	2	3	
53.15	1028	132	43.7	44.2	45.8	44.6 ± 1.1	0.82	0.83	0.86	0.84 ± 0.02
10.75	2727	1.2	7.1	7.8	7.3	7.4 ± 0.4	0.66	0.73	0.68	0.69 ± 0.03
10.75	2727	3.4	7.3	8.4	8.1	7.9 ± 0.6	0.68	0.79	0.76	0.74 ± 0.06
10.75	2727	5.6	8.5	8.8	9.2	8.8 ± 0.3	0.79	0.82	0.85	0.82 ± 0.03
10.75	2727	10.0	9.2	8.8	9.1	9.0 ± 0.2	0.85	0.82	0.85	0.84 ± 0.02
10.75	2727	14.3	12.9	12.0	12.7	12.5 ± 0.5	1.20	1.11	1.18	1.16 ± 0.05
10.75	2727	18.7	12.2	12.7	12.7	12.5 ± 0.3	1.13	1.18	1.18	1.17 ± 0.03
10.75	2727	23.1	14.2	12.4	13.5	13.3 ± 0.9	1.32	1.15	1.25	1.24 ± 0.09
19	2740	3.17	10.9	9.5	9.7	10.0 ± 0.7	0.57	0.50	0.51	0.53 ± 0.04
19	2740	5.64	11.3	11.1	10.7	11.0 ± 0.3	0.59	0.58	0.57	0.58 ± 0.01
19	2740	8.12	11.4	11.8	11.5	11.6 ± 0.2	0.60	0.62	0.61	0.61 ± 0.01
19	2740	10.59	13.9	13.9	12.8	13.5 ± 0.6	0.73	0.73	0.67	0.71 ± 0.03
19	2740	13.07	16.4	16.1	17.5	16.7 ± 0.7	0.86	0.85	0.92	0.88 ± 0.04
19	2740	15.54	18.3	17.3	18.2	17.9 ± 0.5	0.96	0.91	0.96	0.94 ± 0.03
19	2740	18.02	19.7	18.2	17.7	18.5 ± 1.0	1.04	0.96	0.93	0.98 ± 0.05
19	2740	20.49	20.4	19.3	20.6	20.1 ± 0.7	1.07	1.02	1.08	1.06 ± 0.04
19	2740	22.95	22.2	22.2	22.3	22.2 ± 0.1	1.17	1.17	1.17	1.17 ± 0.00
19	2740	28.08	20.4	19.3	20.6	20.1 ± 0.7	1.07	1.02	1.08	1.06 ± 0.04
19	2740	33.21	22.2	22.2	22.3	22.2 ± 0.1	1.17	1.17	1.17	1.17 ± 0.00

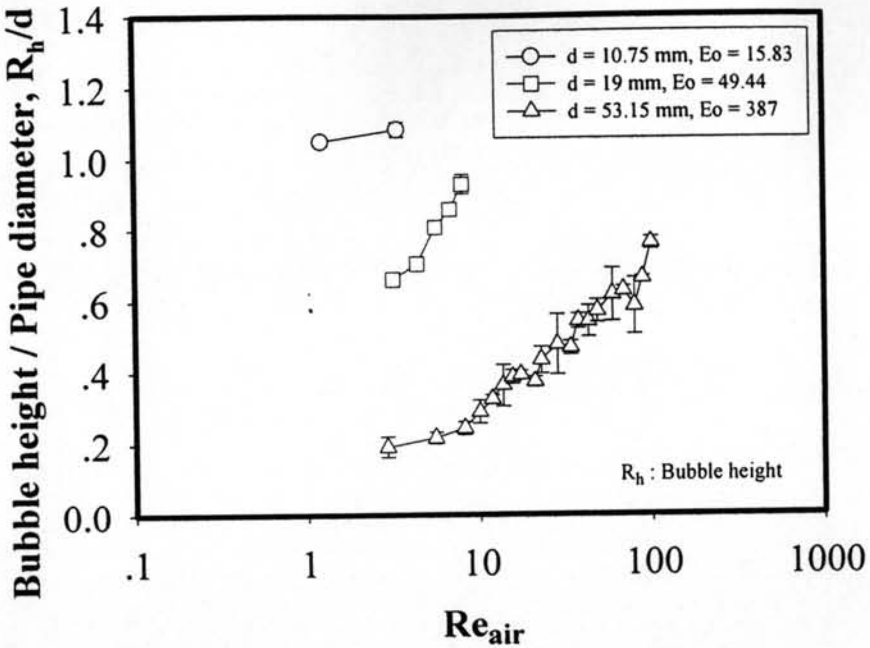


Figure D4 Comparison bubble height from experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at $Re_{water} = 0$.

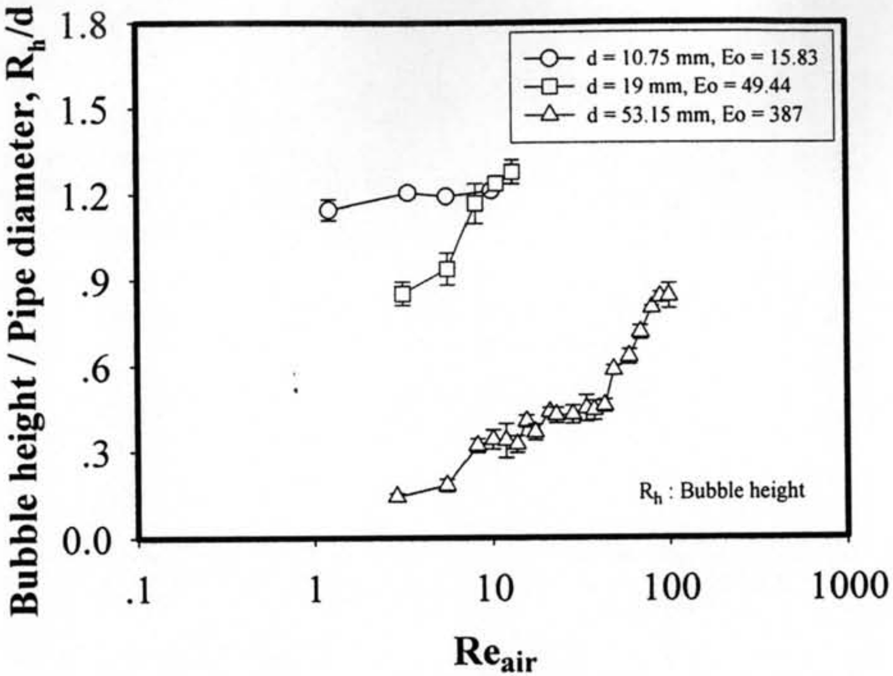


Figure D5 Comparison bubble height from experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at Re_{water} = 1079, 1010 and 1028.

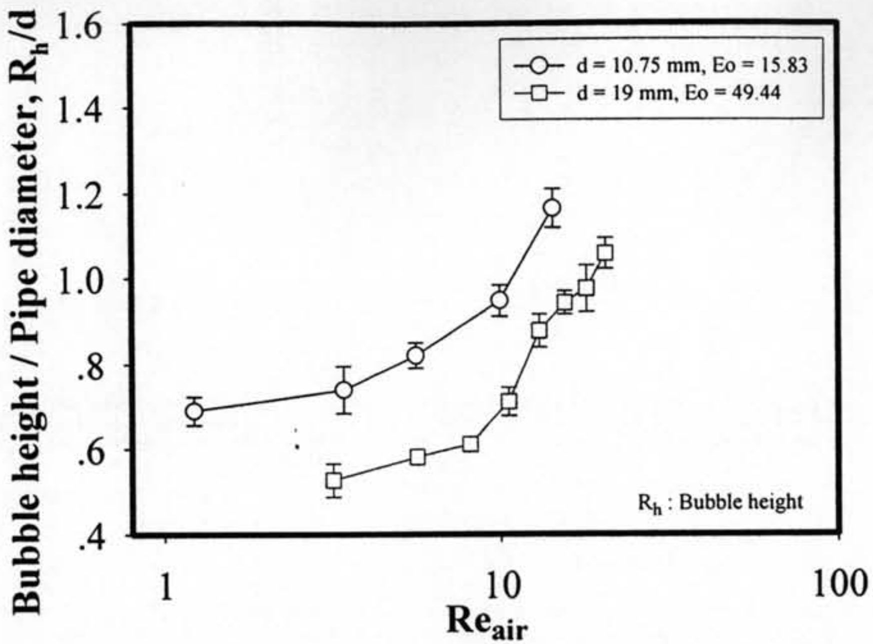


Figure D6 Comparison bubble height from experiment between pipe diameter 10.75 mm and 19 mm vs. air Reynolds number of pure water at Re_{water} = 2727 and 2740.

Table D3 Comparison of slug height for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

temperature, T = 31 °C (± 1 °C)

Pipe diameter, (mm)	Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
			1	2	3		1	2	3	
10.75	0	14.35	14.3	19.3	16.3	16.7 ± 2.5	1.3	1.8	1.5	1.6 ± 0.23
10.75	0	18.72	18.4	26.0	20.8	21.7 ± 3.9	1.7	2.4	1.9	2.0 ± 0.36
10.75	0	23.09	24.6	23.5	23.9	24.0 ± 0.6	2.3	2.2	2.2	2.2 ± 0.05
10.75	0	27.47	25.4	24.4	24.1	24.6 ± 0.7	2.4	2.3	2.2	2.3 ± 0.07
10.75	0	31.84	30.0	28.2	29.7	29.3 ± 0.9	2.8	2.6	2.8	2.7 ± 0.09
10.75	0	36.22	50.3	70.9	51.4	57.5 ± 11.6	4.7	6.6	4.8	5.3 ± 1.08
10.75	0	40.56	68.0	81.5	76.7	75.4 ± 6.9	6.3	7.6	7.1	7.0 ± 0.64
10.75	0	49.63	90.0	77.8	84.7	84.2 ± 6.1	8.4	7.2	7.9	7.8 ± 0.57
10.75	0	58.69	88.5	95.2	94.1	92.6 ± 3.6	8.2	8.9	8.8	8.6 ± 0.33
10.75	0	67.75	103.7	90.4	102.4	98.9 ± 7.3	9.6	8.4	9.5	9.2 ± 0.68
10.75	0	76.82	104.0	111.0	112.0	109.0 ± 4.4	9.7	10.3	10.4	10.1 ± 0.41
10.75	0	85.88	115.5	111.0	131.5	119.3 ± 10.8	10.7	10.3	12.2	11.1 ± 1.00
10.75	0	94.95	127.6	131.7	126.9	128.7 ± 2.6	11.9	12.3	11.8	12.0 ± 0.24
19	0	22.95	31.4	35.5	30.3	32.4 ± 2.8	1.7	1.9	1.6	1.7 ± 0.14
19	0	28.08	39.7	50.0	47.9	45.9 ± 5.4	2.1	2.6	2.5	2.4 ± 0.29
19	0	33.21	53.3	45.3	52.0	50.2 ± 4.3	2.8	2.4	2.7	2.6 ± 0.22
19	0	38.33	55.9	58.2	54.9	56.3 ± 1.7	2.9	3.1	2.9	3.0 ± 0.09
19	0	43.46	57.1	65.5	57.6	60.1 ± 4.7	3.0	3.4	3.0	3.2 ± 0.25
19	0	48.59	59.3	75.8	62.3	65.8 ± 8.7	3.1	4.0	3.3	3.5 ± 0.46
19	0	58.85	82.7	75.9	79.1	79.2 ± 3.4	4.4	4.0	4.2	4.2 ± 0.18
19	0	69.10	83.3	82.2	84.6	83.4 ± 1.2	4.4	4.3	4.5	4.4 ± 0.06
19	0	79.36	84.9	89.7	90.1	88.2 ± 2.9	4.5	4.7	4.7	4.6 ± 0.15
19	0	89.62	90.1	88.8	102.2	93.7 ± 7.4	4.7	4.7	5.4	4.9 ± 0.39
19	0	99.87	101.0	101.4	115.9	106.1 ± 8.5	5.3	5.3	6.1	5.6 ± 0.45
19	0	177	196.8	193.0	196.8	195.5 ± 2.2	10.4	10.2	10.4	10.3 ± 0.12
53.15	0	289	75.0	83.6	97.5	85.4 ± 11.4	1.4	1.6	1.8	1.6 ± 0.21
53.15	0	367	120.0	114.6	127.3	120.6 ± 6.4	2.3	2.2	2.4	2.3 ± 0.12

Pipe diameter, (mm)	Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
			1	2	3		1	2	3	
53.15	0	445	148.1	127.5	108.8	128.1 ± 19.7	2.8	2.4	2.0	2.4 ± 0.37
53.15	0	520	163.6	173.1	168.8	168.5 ± 4.8	3.1	3.3	3.2	3.2 ± 0.09
53.15	0	629	161.1	178.3	190.9	176.8 ± 14.9	3.0	3.4	3.6	3.3 ± 0.28
53.15	0	739	230.0	213.9	258.3	234.1 ± 22.5	4.3	4.0	4.9	4.4 ± 0.42
53.15	0	848	357.0	302.5	302.5	320.7 ± 31.5	6.7	5.7	5.7	6.0 ± 0.59
53.15	0	958	382.5	377.5	342.5	367.5 ± 21.8	7.2	7.1	6.4	6.9 ± 0.41
10.75	1079	23.09	16.6	17.4	15.5	16.5 ± 1.0	1.5	1.6	1.4	1.5 ± 0.09
10.75	1079	27.47	21.3	18.1	19.5	19.6 ± 1.6	2.0	1.7	1.8	1.8 ± 0.15
10.75	1079	31.84	21.1	19.3	20.7	20.4 ± 1.0	2.0	1.8	1.9	1.9 ± 0.09
10.75	1079	36.22	23.1	22.4	21.7	22.4 ± 0.7	2.1	2.1	2.0	2.1 ± 0.06
10.75	1079	40.56	22.8	25.9	25.0	24.6 ± 1.6	2.1	2.4	2.3	2.3 ± 0.15
10.75	1079	49.63	27.7	25.8	26.1	26.5 ± 1.0	2.6	2.4	2.4	2.5 ± 0.10
10.75	1079	58.69	29.3	31.0	29.7	30.0 ± 0.9	2.7	2.9	2.8	2.8 ± 0.08
10.75	1079	67.75	34.9	35.2	33.3	34.5 ± 1.0	3.2	3.3	3.1	3.2 ± 0.10
10.75	1079	76.82	31.2	34.6	36.5	34.1 ± 2.7	2.9	3.2	3.4	3.2 ± 0.25
10.75	1079	85.88	40.3	41.1	40.7	40.7 ± 0.4	3.7	3.8	3.8	3.8 ± 0.04
10.75	1079	94.95	77.1	77.9	83.3	79.4 ± 3.4	7.2	7.2	7.8	7.4 ± 0.32
10.75	1079	104	78.8	83.2	87.2	83.1 ± 4.2	7.3	7.7	8.1	7.7 ± 0.39
10.75	1079	122	89.4	96.4	85.4	90.4 ± 5.5	8.3	9.0	7.9	8.4 ± 0.52
19	1010	33.21	37.1	38.8	41.4	39.1 ± 2.2	2.0	2.0	2.2	2.1 ± 0.11
19	1010	38.33	44.0	42.0	41.0	42.3 ± 1.5	2.3	2.2	2.2	2.2 ± 0.08
19	1010	43.46	48.1	49.0	46.2	47.8 ± 1.5	2.5	2.6	2.4	2.5 ± 0.08
19	1010	48.59	53.0	51.5	50.8	51.8 ± 1.2	2.8	2.7	2.7	2.7 ± 0.06
19	1010	58.85	56.8	56.8	60.2	58.0 ± 2.0	3.0	3.0	3.2	3.1 ± 0.10
19	1010	69.10	71.4	75.9	71.4	72.9 ± 2.6	3.8	4.0	3.8	3.8 ± 0.14
19	1010	79.36	73.6	87.3	81.2	80.7 ± 6.9	3.9	4.6	4.3	4.2 ± 0.36
19	1010	89.62	75.0	90.2	85.9	83.7 ± 7.8	3.9	4.7	4.5	4.4 ± 0.41
19	1010	99.87	101.3	108.8	86.3	98.8 ± 11.5	5.3	5.7	4.5	5.2 ± 0.60

Pipe diameter, (mm)	Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
			1	2	3		1	2	3	
19	1010	177	113.0	117.6	113.0	114.5 ± 2.7	5.9	6.2	5.9	6.0 ± 0.14
53.15	1028	445	115.9	126.7	121.7	121.4 ± 5.4	2.2	2.4	2.3	2.3 ± 0.10
53.15	1028	520	110.0	125.0	132.5	122.5 ± 11.5	2.1	2.4	2.5	2.3 ± 0.22
53.15	1028	629	164.4	208.7	172.5	181.9 ± 23.6	3.1	3.9	3.2	3.4 ± 0.44
53.15	1028	739	190.0	205.0	224.4	206.5 ± 17.2	3.6	3.9	4.2	3.9 ± 0.32
53.15	1028	848	226.4	225.0	240.0	230.5 ± 8.3	4.3	4.2	4.5	4.3 ± 0.16
53.15	1028	958	225.0	290.0	247.5	254.2 ± 33.0	4.2	5.5	4.7	4.8 ± 0.62
53.15	1028	1067	220.0	242.5	295.0	252.5 ± 38.5	4.1	4.6	5.6	4.8 ± 0.72
10.75	2727	36.22	16.8	17.0	17.8	17.2 ± 0.6	1.6	1.6	1.7	1.6 ± 0.05
10.75	2727	40.56	18.6	18.6	17.8	18.3 ± 0.5	1.7	1.7	1.7	1.7 ± 0.04
10.75	2727	49.63	22.5	23.4	21.0	22.3 ± 1.2	2.1	2.2	2.0	2.1 ± 0.11
10.75	2727	58.69	22.8	23.4	22.8	23.0 ± 0.4	2.1	2.2	2.1	2.1 ± 0.03
10.75	2727	67.75	20.0	25.6	26.4	24.0 ± 3.5	1.9	2.4	2.5	2.2 ± 0.32
10.75	2727	76.82	25.7	28.3	26.9	27.0 ± 1.3	2.4	2.6	2.5	2.5 ± 0.12
10.75	2727	85.88	26.6	24.3	28.7	26.5 ± 2.2	2.5	2.3	2.7	2.5 ± 0.20
10.75	2727	94.95	31.1	29.6	32.1	31.0 ± 1.3	2.9	2.8	3.0	2.9 ± 0.12
10.75	2727	104	35.3	32.5	30.3	32.7 ± 2.5	3.3	3.0	2.8	3.0 ± 0.23
10.75	2727	122	45.5	51.6	53.6	50.2 ± 4.2	4.2	4.8	5.0	4.7 ± 0.39
10.75	2727	140	49.9	41.5	55.7	49.0 ± 7.2	4.6	3.9	5.2	4.6 ± 0.67
10.75	2727	158	61.5	61.5	57.5	60.2 ± 2.3	5.7	5.7	5.3	5.6 ± 0.22
10.75	2727	177	63.6	73.9	88.5	75.4 ± 12.5	5.9	6.9	8.2	7.0 ± 1.16
10.75	2727	231	112.2	96.6	105.6	104.8 ± 7.8	10.4	9.0	9.8	9.7 ± 0.73
10.75	2727	294	105.0	106.5	125.3	112.3 ± 11.3	9.8	9.9	11.7	10.4 ± 1.05
10.75	2727	367	138.7	140.7	132.0	137.1 ± 4.5	12.9	13.1	12.3	12.8 ± 0.42
10.75	2727	523	265.3	241.3	216.0	240.9 ± 24.7	24.7	22.4	20.1	22.4 ± 2.29
19	2740	48.59	37.5	40.9	36.4	38.3 ± 2.4	2.0	2.2	1.9	2.0 ± 0.12
19	2740	58.85	42.0	42.9	42.9	42.6 ± 0.5	2.2	2.3	2.3	2.2 ± 0.03

Pipe diameter, (mm)	Re_{water}	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
			1	2	3		1	2	3	
19	2740	69.10	49.1	52.8	59.3	53.7 ± 5.1	2.6	2.8	3.1	2.8 ± 0.27
19	2740	79.36	61.7	64.2	63.3	63.1 ± 1.3	3.2	3.4	3.3	3.3 ± 0.07
19	2740	89.62	70.2	70.2	77.4	72.6 ± 4.2	3.7	3.7	4.1	3.8 ± 0.22
19	2740	99.87	81.3	80.4	80.5	80.7 ± 0.5	4.3	4.2	4.2	4.2 ± 0.03
19	2740	177	126.0	120.0	124.0	123.3 ± 3.1	6.6	6.3	6.5	6.5 ± 0.16
19	2740	296	206.0	209.0	211.0	208.7 ± 2.5	10.8	11.0	11.1	11.0 ± 0.13

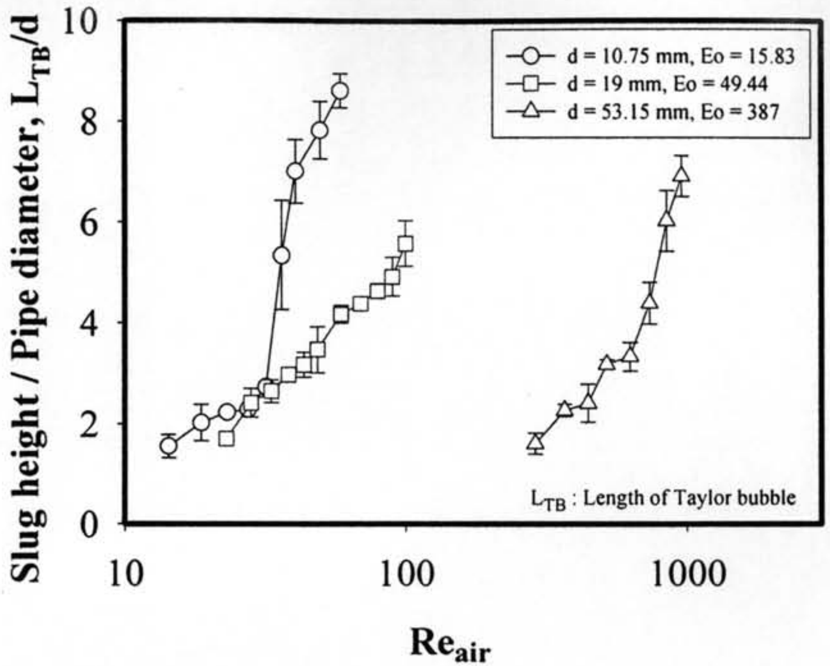


Figure D7 Comparison slug height from experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at $Re_{water} = 0$.

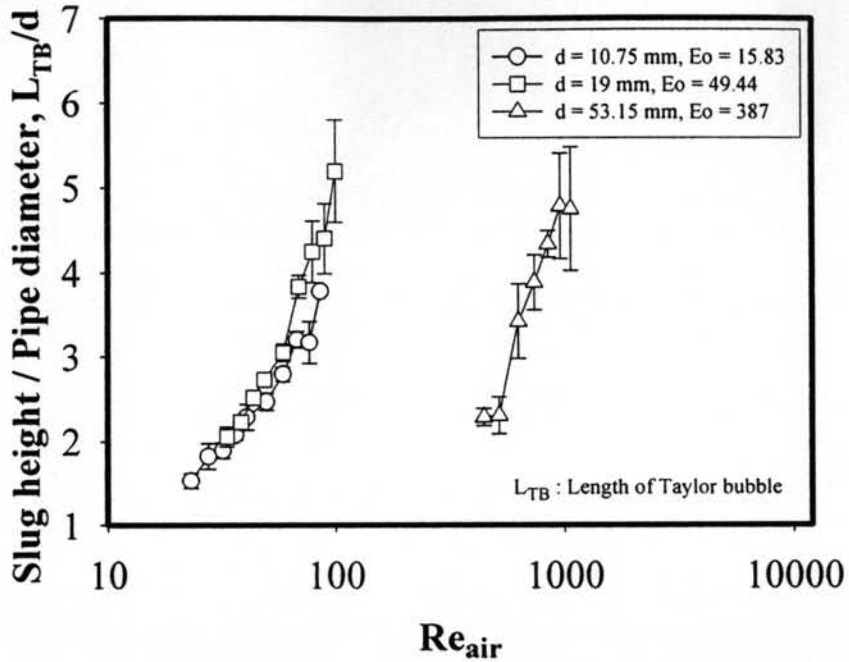


Figure D8 Comparison slug height from experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at Re_{water} = 1079, 1010 and 1028.

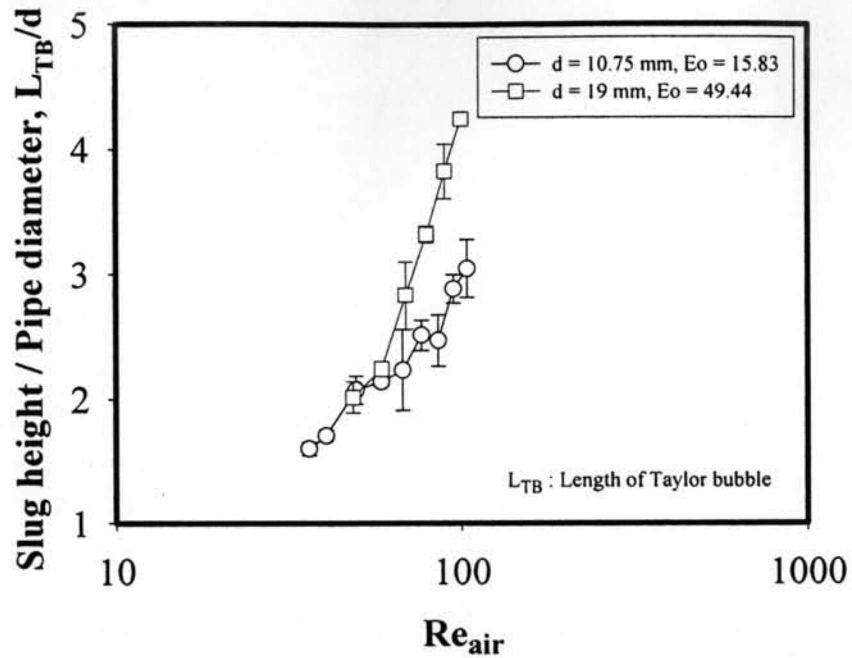


Figure D9 Comparison slug height from experiment between pipe diameter 10.75 mm and 19 mm vs. air Reynolds number of pure water at Re_{water} = 2727 and 2740.

Table D4 Comparison of bubble and slug velocity for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, $\mu_{water} = 8.51 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

temperature, T = 31 °C (± 1 °C)

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
10.75	0	1.22	0.28	0.28	0.28	0.28	0.28	0.28 ± 0.002
10.75	0	3.41	0.30	0.30	0.30	0.30	0.29	0.30 ± 0.003
10.75	0	5.60	0.30	0.32	0.31	0.29	0.31	0.31 ± 0.009
10.75	0	9.97	0.33	0.32	0.32	0.32	0.32	0.32 ± 0.003
10.75	0	14.35	0.33	0.32	0.33	0.33	0.33	0.33 ± 0.004
10.75	0	18.72	0.35	0.35	0.37	0.36	0.35	0.36 ± 0.005
10.75	0	23.09	0.38	0.38	0.38	0.38	0.38	0.38 ± 0.001
10.75	0	27.47	0.40	0.40	0.39	0.39	0.40	0.40 ± 0.005
10.75	0	31.84	0.41	0.41	0.41	0.41	0.41	0.41 ± 0.001
10.75	0	36.22	0.45	0.46	0.47	0.45	0.45	0.46 ± 0.006
10.75	0	40.56	0.49	0.49	0.50	0.49	0.49	0.49 ± 0.005
10.75	0	49.63	0.54	0.55	0.55	0.54	0.54	0.55 ± 0.005
10.75	0	58.69	0.59	0.61	0.57	0.60	0.59	0.59 ± 0.012
10.75	0	67.75	0.61	0.60	0.62	0.61	0.60	0.61 ± 0.007
10.75	0	76.82	0.64	0.65	0.65	0.66	0.64	0.65 ± 0.006
10.75	0	85.88	0.71	0.70	0.71	0.69	0.72	0.71 ± 0.011
10.75	0	94.95	0.74	0.75	0.74	0.74	0.71	0.74 ± 0.015
19	0	3.17	0.33	0.34	0.34	0.34	0.34	0.34 ± 0.004
19	0	4.40	0.35	0.35	0.35	0.35	0.35	0.35 ± 0.001
19	0	5.64	0.36	0.34	0.35	0.37	0.35	0.36 ± 0.011
19	0	6.88	0.36	0.35	0.35	0.36	0.36	0.36 ± 0.002
19	0	8.11	0.37	0.36	0.36	0.35	0.36	0.36 ± 0.005
19	0	10.59	0.37	0.37	0.36	0.37	0.36	0.37 ± 0.003
19	0	13.06	0.37	0.39	0.37	0.38	0.38	0.38 ± 0.006
19	0	15.53	0.38	0.38	0.38	0.38	0.38	0.38 ± 0.002
19	0	18.01	0.39	0.39	0.39	0.38	0.39	0.39 ± 0.005

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
19	0	20.48	0.41	0.39	0.41	0.39	0.40	0.40 ± 0.008
19	0	22.94	0.41	0.41	0.41	0.41	0.41	0.41 ± 0.004
19	0	28.06	0.43	0.43	0.42	0.42	0.43	0.43 ± 0.006
19	0	33.19	0.43	0.43	0.44	0.43	0.43	0.43 ± 0.002
19	0	38.31	0.45	0.44	0.46	0.44	0.45	0.45 ± 0.008
19	0	43.44	0.44	0.46	0.46	0.46	0.45	0.45 ± 0.006
19	0	48.57	0.46	0.46	0.45	0.48	0.46	0.46 ± 0.009
19	0	58.82	0.49	0.48	0.49	0.48	0.49	0.48 ± 0.003
19	0	69.07	0.49	0.51	0.51	0.51	0.50	0.50 ± 0.008
19	0	79.32	0.53	0.53	0.53	0.54	0.52	0.53 ± 0.005
19	0	89.57	0.57	0.56	0.53	0.55	0.55	0.55 ± 0.015
19	0	99.82	0.56	0.57	0.56	0.56	0.56	0.56 ± 0.005
19	0	177	0.72	0.73	0.71	0.74	0.73	0.73 ± 0.011
53.15	0	2.90	0.33	0.33	0.36	0.33	0.34	0.34 ± 0.012
53.15	0	5.56	0.35	0.35	0.35	0.34	0.36	0.35 ± 0.010
53.15	0	8.20	0.40	0.39	0.37	0.38	0.36	0.38 ± 0.015
53.15	0	10.04	0.39	0.33	0.39	0.40	0.34	0.37 ± 0.033
53.15	0	11.87	0.42	0.38	0.37	0.35	0.37	0.38 ± 0.023
53.15	0	13.70	0.38	0.39	0.40	0.40	0.35	0.38 ± 0.020
53.15	0	15.54	0.40	0.40	0.41	0.38	0.40	0.40 ± 0.009
53.15	0	17.37	0.40	0.39	0.40	0.41	0.41	0.40 ± 0.008
53.15	0	21.04	0.44	0.42	0.41	0.41	0.39	0.42 ± 0.019
53.15	0	22.87	0.41	0.43	0.44	0.39	0.40	0.42 ± 0.020
53.15	0	28.37	0.45	0.43	0.43	0.41	0.45	0.44 ± 0.015
53.15	0	33.87	0.44	0.44	0.46	0.41	0.45	0.44 ± 0.018
53.15	0	37.54	0.43	0.44	0.45	0.46	0.46	0.45 ± 0.013

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
53.15	0	43.04	0.45	0.43	0.46	0.44	0.44	0.44 ± 0.008
53.15	0	48.54	0.47	0.47	0.43	0.43	0.43	0.44 ± 0.021
53.15	0	59.53	0.46	0.46	0.43	0.47	0.50	0.46 ± 0.028
53.15	0	68.70	0.47	0.50	0.49	0.50	0.53	0.50 ± 0.022
53.15	0	79.70	0.52	0.52	0.52	0.50	0.54	0.52 ± 0.017
53.15	0	88.87	0.52	0.52	0.54	0.52	0.50	0.52 ± 0.013
53.15	0	99.87	0.61	0.57	0.56	0.59	0.54	0.58 ± 0.026
53.15	0	132	0.66	0.68	0.65	0.65	0.59	0.65 ± 0.032
53.15	0	184	0.69	0.66	0.63	0.69	0.63	0.66 ± 0.028
53.15	0	289	0.65	0.69	0.67	0.71	0.71	0.69 ± 0.026
53.15	0	367	0.79	0.76	0.69	0.65	0.67	0.71 ± 0.061
53.15	0	445	0.79	0.73	0.75	0.78	0.73	0.76 ± 0.028
53.15	0	520	0.75	0.84	0.91	0.79	0.79	0.82 ± 0.062
53.15	0	629	1.00	1.09	1.05	0.89	0.91	0.99 ± 0.088
53.15	0	739	1.11	1.09	1.23	1.23	0.94	1.12 ± 0.118
53.15	0	848	1.33	1.11	1.24	1.37	1.13	1.24 ± 0.114
53.15	0	958	1.45	1.43	1.38	1.43	1.45	1.43 ± 0.025
10.75	1079	1.22	0.60	0.60	0.57	0.58	0.60	0.59 ± 0.011
10.75	1079	3.41	0.60	0.60	0.58	0.61	0.60	0.60 ± 0.010
10.75	1079	5.60	0.60	0.60	0.60	0.61	0.61	0.60 ± 0.005
10.75	1079	10	0.61	0.61	0.62	0.62	0.63	0.62 ± 0.009
10.75	1079	14	0.61	0.62	0.62	0.62	0.62	0.62 ± 0.005
10.75	1079	19	0.63	0.63	0.63	0.63	0.63	0.63 ± 0.002
10.75	1079	23	0.64	0.64	0.65	0.66	0.65	0.64 ± 0.008
10.75	1079	27	0.68	0.68	0.68	0.68	0.70	0.68 ± 0.012
10.75	1079	32	0.71	0.70	0.71	0.70	0.70	0.70 ± 0.005

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
10.75	1079	36	0.73	0.74	0.73	0.72	0.75	0.73 ± 0.012
10.75	1079	41	0.79	0.78	0.79	0.76	0.78	0.78 ± 0.014
10.75	1079	50	0.81	0.81	0.80	0.82	0.80	0.81 ± 0.009
10.75	1079	59	0.87	0.86	0.87	0.89	0.87	0.87 ± 0.009
10.75	1079	67.75	0.92	0.92	0.93	0.91	0.90	0.91 ± 0.012
10.75	1079	76.82	0.92	0.93	0.90	0.92	0.91	0.92 ± 0.013
10.75	1079	85.88	0.97	0.95	0.98	0.99	0.95	0.97 ± 0.021
10.75	1079	94.95	1.02	1.03	1.01	1.05	1.03	1.03 ± 0.013
10.75	1079	104	1.08	1.06	1.08	1.08	1.06	1.07 ± 0.010
10.75	1079	122	1.15	1.19	1.17	1.13	1.13	1.16 ± 0.024
19	1010	3.17	0.48	0.48	0.47	0.48	0.48	0.48 ± 0.004
19	1010	5.64	0.49	0.48	0.49	0.49	0.47	0.48 ± 0.009
19	1010	8.12	0.49	0.49	0.49	0.49	0.49	0.49 ± 0.004
19	1010	10.59	0.50	0.49	0.49	0.49	0.50	0.49 ± 0.009
19	1010	13.07	0.49	0.50	0.48	0.49	0.49	0.49 ± 0.006
19	1010	15.54	0.50	0.50	0.50	0.50	0.50	0.50 ± 0.003
19	1010	18.02	0.51	0.53	0.52	0.52	0.52	0.52 ± 0.005
19	1010	20.49	0.52	0.52	0.52	0.53	0.52	0.52 ± 0.004
19	1010	22.95	0.53	0.53	0.52	0.53	0.52	0.53 ± 0.003
19	1010	28.08	0.55	0.54	0.55	0.55	0.55	0.54 ± 0.002
19	1010	33.21	0.55	0.56	0.56	0.56	0.55	0.56 ± 0.008
19	1010	38.33	0.55	0.57	0.55	0.56	0.56	0.56 ± 0.007
19	1010	43.46	0.58	0.58	0.58	0.60	0.60	0.59 ± 0.009
19	1010	48.59	0.59	0.59	0.60	0.60	0.58	0.59 ± 0.007
19	1010	58.85	0.63	0.63	0.63	0.63	0.63	0.63 ± 0.004
19	1010	69.10	0.66	0.66	0.64	0.64	0.66	0.65 ± 0.009

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
19	1010	79.36	0.66	0.67	0.66	0.67	0.67	0.67 ± 0.006
19	1010	89.62	0.68	0.69	0.68	0.67	0.69	0.69 ± 0.008
19	1010	99.87	0.71	0.70	0.70	0.70	0.71	0.70 ± 0.006
19	1010	177	0.88	0.90	0.83	0.84	0.85	0.86 ± 0.030
19	1010	296	1.21	1.18	1.17	1.17	1.24	1.20 ± 0.027
19	1010	369	1.36	1.30	1.36	1.47	1.36	1.37 ± 0.064
19	1010	515	1.93	1.74	1.67	1.86	1.72	1.79 ± 0.107
53.15	1028	2.90	0.39	0.37	0.40	0.38	0.36	0.38 ± 0.016
53.15	1028	5.56	0.39	0.39	0.39	0.40	0.40	0.39 ± 0.006
53.15	1028	8.20	0.42	0.42	0.42	0.42	0.43	0.42 ± 0.005
53.15	1028	10.04	0.44	0.42	0.46	0.43	0.44	0.44 ± 0.015
53.15	1028	11.87	0.42	0.44	0.43	0.44	0.46	0.44 ± 0.012
53.15	1028	13.70	0.42	0.44	0.43	0.45	0.46	0.44 ± 0.016
53.15	1028	15.54	0.42	0.42	0.43	0.42	0.44	0.43 ± 0.009
53.15	1028	17.37	0.45	0.43	0.43	0.44	0.46	0.44 ± 0.011
53.15	1028	21.04	0.45	0.44	0.43	0.42	0.47	0.44 ± 0.021
53.15	1028	22.87	0.42	0.47	0.42	0.45	0.49	0.45 ± 0.032
53.15	1028	28.37	0.46	0.45	0.51	0.50	0.46	0.47 ± 0.028
53.15	1028	34	0.49	0.48	0.46	0.46	0.51	0.48 ± 0.022
53.15	1028	38	0.51	0.46	0.46	0.52	0.47	0.48 ± 0.029
53.15	1028	43	0.53	0.48	0.49	0.52	0.45	0.49 ± 0.034
53.15	1028	49	0.50	0.49	0.49	0.47	0.46	0.48 ± 0.016
53.15	1028	59.53	0.52	0.48	0.55	0.50	0.50	0.51 ± 0.027
53.15	1028	68.70	0.54	0.48	0.53	0.52	0.48	0.51 ± 0.031
53.15	1028	79.70	0.61	0.58	0.56	0.63	0.58	0.59 ± 0.030
53.15	1028	88.87	0.54	0.54	0.51	0.50	0.59	0.54 ± 0.036

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
53.15	1028	99.87	0.58	0.51	0.59	0.51	0.50	0.54 ± 0.044
53.15	1028	132	0.64	0.66	0.69	0.66	0.69	0.67 ± 0.020
53.15	1028	184	0.62	0.68	0.76	0.65	0.58	0.66 ± 0.069
53.15	1028	289	0.68	0.80	0.75	0.73	0.78	0.75 ± 0.047
53.15	1028	367	0.94	0.87	0.81	0.94	0.95	0.90 ± 0.059
53.15	1028	445	0.86	0.96	0.94	0.98	0.87	0.92 ± 0.054
53.15	1028	520	1.07	0.94	0.91	1.04	1.01	0.99 ± 0.065
53.15	1028	629	0.98	1.33	0.99	1.02	0.99	1.06 ± 0.150
53.15	1028	739	1.08	1.21	1.51	1.01	0.86	1.13 ± 0.248
53.15	1028	848	1.51	1.38	1.38	1.28	1.26	1.36 ± 0.098
53.15	1028	958	1.57	1.41	2.10	1.57	1.41	1.61 ± 0.282
53.15	1028	1067	1.28	1.87	2.10	1.73	2.04	1.80 ± 0.325
10.75	2727	1.22	0.96	0.97	1.00	1.00	0.96	0.98 ± 0.020
10.75	2727	3.41	1.01	1.03	1.03	1.01	1.05	1.03 ± 0.015
10.75	2727	5.60	1.03	1.08	1.09	1.05	1.03	1.06 ± 0.028
10.75	2727	9.97	1.08	1.08	1.10	1.11	1.09	1.09 ± 0.014
10.75	2727	14.35	1.09	1.06	1.08	1.11	1.09	1.09 ± 0.017
10.75	2727	19	1.08	1.10	1.09	1.11	1.11	1.10 ± 0.015
10.75	2727	23	1.11	1.09	1.08	1.09	1.08	1.09 ± 0.014
10.75	2727	27	1.09	1.13	1.08	1.08	1.11	1.10 ± 0.024
10.75	2727	32	1.15	1.15	1.15	1.15	1.17	1.15 ± 0.010
10.75	2727	36.22	1.19	1.19	1.17	1.17	1.19	1.18 ± 0.013
10.75	2727	40.56	1.28	1.28	1.23	1.21	1.25	1.25 ± 0.028
10.75	2727	49.63	1.28	1.23	1.23	1.28	1.25	1.26 ± 0.024
10.75	2727	58.69	1.25	1.25	1.21	1.25	1.28	1.25 ± 0.026
10.75	2727	67.75	1.32	1.28	1.32	1.28	1.31	1.30 ± 0.024

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
10.75	2727	77	1.38	1.36	1.41	1.38	1.32	1.37 ± 0.033
10.75	2727	86	1.41	1.41	1.36	1.38	1.38	1.39 ± 0.022
10.75	2727	95	1.47	1.47	1.40	1.48	1.47	1.46 ± 0.031
10.75	2727	104	1.50	1.44	1.50	1.47	1.50	1.48 ± 0.027
10.75	2727	122	1.53	1.53	1.54	1.53	1.54	1.53 ± 0.006
10.75	2727	140	1.56	1.57	1.54	1.58	1.57	1.57 ± 0.017
10.75	2727	158	1.72	1.72	1.75	1.68	1.72	1.72 ± 0.024
10.75	2727	177	1.87	1.92	1.91	1.86	1.89	1.89 ± 0.026
10.75	2727	231	2.16	2.03	2.09	2.16	2.37	2.16 ± 0.127
10.75	2727	294	2.29	2.29	2.37	2.40	2.42	2.35 ± 0.059
10.75	2727	367	2.76	2.99	3.12	3.17	2.87	2.99 ± 0.170
10.75	2727	523	4.07	3.85	4.15	4.15	4.07	4.05 ± 0.121
19	2740	3.17	0.71	0.71	0.70	0.70	0.70	0.70 ± 0.006
19	2740	5.64	0.73	0.71	0.72	0.71	0.73	0.72 ± 0.010
19	2740	8.11	0.71	0.71	0.70	0.69	0.70	0.70 ± 0.007
19	2740	10.59	0.71	0.70	0.71	0.68	0.69	0.70 ± 0.012
19	2740	13.06	0.70	0.71	0.70	0.71	0.71	0.71 ± 0.006
19	2740	15.53	0.73	0.74	0.72	0.72	0.72	0.73 ± 0.009
19	2740	18.01	0.74	0.73	0.73	0.73	0.72	0.73 ± 0.007
19	2740	20.48	0.73	0.72	0.74	0.75	0.73	0.74 ± 0.011
19	2740	22.94	0.73	0.72	0.73	0.73	0.73	0.73 ± 0.004
19	2740	28.06	0.78	0.79	0.78	0.77	0.79	0.78 ± 0.007
19	2740	33.19	0.75	0.76	0.76	0.76	0.75	0.76 ± 0.006
19	2740	38.31	0.76	0.77	0.76	0.77	0.76	0.77 ± 0.006
19	2740	43.44	0.77	0.76	0.76	0.76	0.76	0.76 ± 0.004
19	2740	48.57	0.80	0.79	0.79	0.78	0.80	0.79 ± 0.007

Pipe diameter, (mm)	Re_{water}	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
19	2740	58.82	0.80	0.79	0.82	0.80	0.81	0.80 ± 0.014
19	2740	69.07	0.85	0.85	0.85	0.86	0.84	0.85 ± 0.009
19	2740	79.32	0.87	0.84	0.85	0.87	0.85	0.85 ± 0.013
19	2740	89.57	0.91	0.90	0.88	0.88	0.90	0.89 ± 0.015
19	2740	99.82	0.90	0.91	0.91	0.91	0.90	0.90 ± 0.008
19	2740	177	1.08	1.13	1.05	1.06	1.06	1.08 ± 0.033
19	2740	296	1.33	1.37	1.36	1.33	1.33	1.34 ± 0.022
19	2740	369	1.62	1.72	1.53	1.69	1.62	1.64 ± 0.075
19	2740	515	2.00	2.08	1.98	1.93	2.08	2.01 ± 0.065

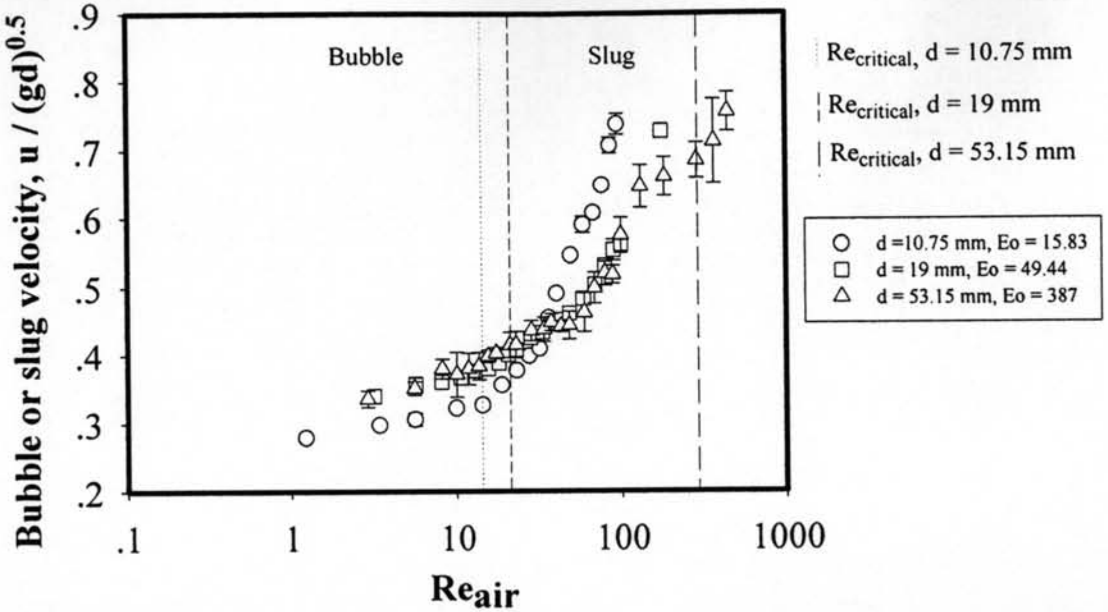


Figure D10 Comparison bubble or slug velocity from experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at $Re_{water} = 0$.

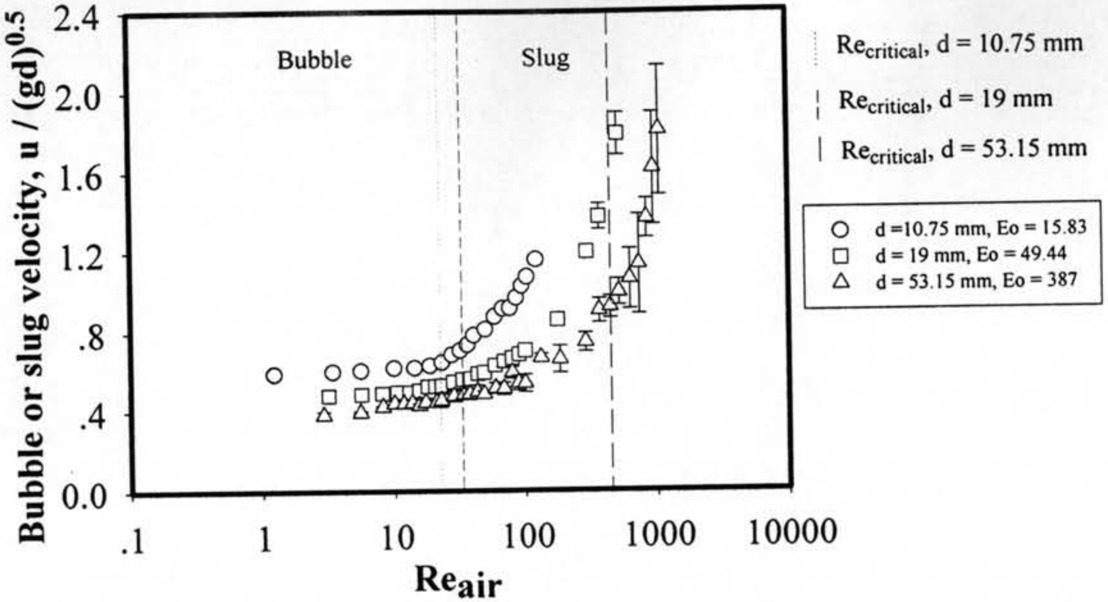


Figure D11 Comparison bubble or slug velocity from experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at Re_{water} = 1079, 1010 and 1028.

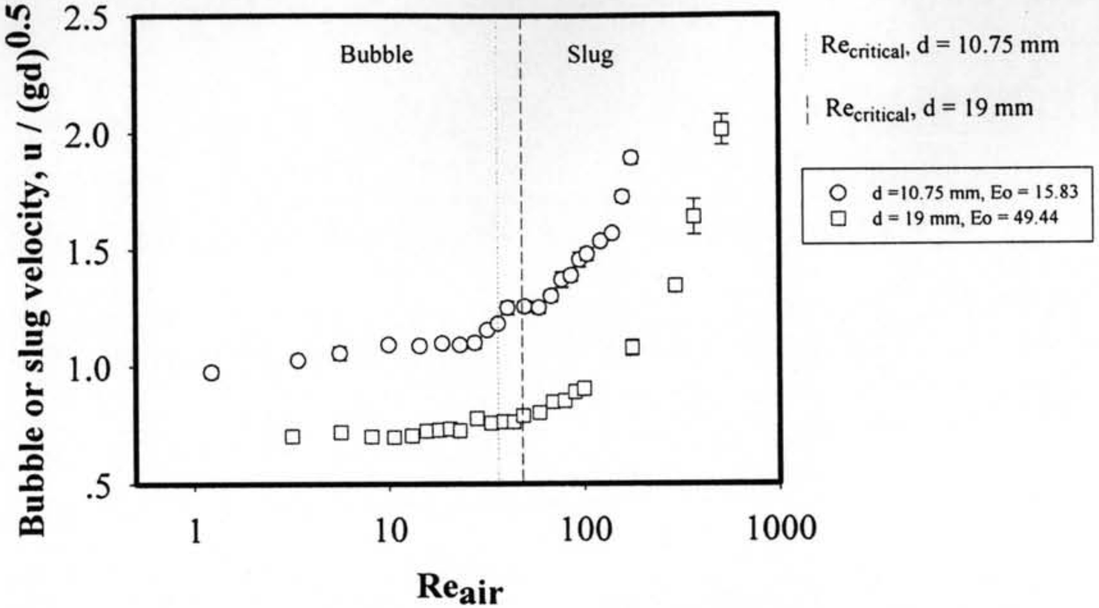


Figure D12 Comparison bubble or slug velocity from experiment between pipe diameter 10.75 mm and 19 mm vs. air Reynolds number of pure water at $Re_{water} = 2727$ and 2740.

Table D5 Comparison of the pressure gradient for pure water from experiment

Physical properties of air and water used in experiment:

density of water, ρ_{water} = 995 kg/m^3; viscosity of water, μ_{water} = 8.51 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

inner pipe diameter = 0.053 m; cross-sectional area of pipe, A = 0.0022 m^2

inner pipe diameter = 0.011 m; cross-sectional area of pipe, A = 0.00009 m^2

temperature, T = 31 °C (± 1 °C)

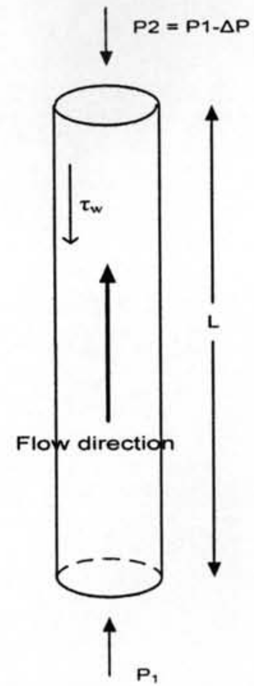


Figure D13 Pressure drop in a vertical pipe.

Upward flow in a vertical pipe is depicted in Fig. D13. A steady-state momentum balance in the direction of flow on the fluid in the pipe gives:

$$(P_1 - P_2)\frac{\pi D^2}{4} - \tau_w \pi D L - \frac{\pi D^2}{4}\rho_w L g = 0 \quad \text{(D1)}$$

$$(P_1 - P_2)\frac{D}{4} - \tau_w L - \frac{D}{4}\rho_w L g = 0 \quad \text{(D2)}$$

$$(P_1 - P_2)\frac{D}{4} - \rho_w L g \frac{D}{4} = \tau_w L \quad \text{(D3)}$$

$$(\frac{P_1 - P_2}{L})\frac{D}{4} - \rho_w g \frac{D}{4} = \tau_w \quad \text{(D4)}$$

We define the pressure drop: $\Delta P = P_1 - P_2$. Equation (D4) can be written as:

$$\frac{D}{4}[(\frac{\Delta P}{L})_d - \rho_w g] = \tau_w \quad \text{(D5)}$$

Elimination of the gravity term from Equation (D5) gives:

$$\frac{D}{4}(\frac{\Delta P}{L})_d = \tau_{w,d} \quad \text{(D6)}$$

From the definition of Darcy friction factor (f_F):

$$f_F = \frac{8\tau_{w,d}}{\rho_w \bar{u}_{liq}^2} \qquad \text{(D7)}$$

Rearrangement of Equation (D7) gives:

$$f_F = \frac{8\frac{D}{4}\left(\frac{\Delta P}{L}\right)_d}{\rho_w \bar{u}_{liq}^2} \qquad \text{(D8)}$$

or

$$f_F = \frac{2D\left(-\frac{dp}{dz}\right)_d}{\rho_w \bar{u}_{liq}^2} \qquad \text{(D9)}$$

Pipe diameter, (mm)	Re_{water}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^2}$										Average dimensionless pressure gradient		
				1	2	3	4	5	6	7	8	9	10			
10.75	1079	3.41	Bubble	2.16E-01	2.16E-01	2.16E-01	2.16E-01	2.16E-01	2.16E-01	2.16E-01	2.16E-01	2.16E-01	2.16E-01	2.16E-01	±	0.00E+00
10.75	1079	5.60	Bubble	3.60E-01	3.60E-01	3.60E-01	3.60E-01	3.60E-01	3.60E-01	3.60E-01	3.60E-01	3.60E-01	3.60E-01	3.60E-01	±	5.85E-17
10.75	1079	9.97	Bubble	8.64E-01	8.64E-01	8.64E-01	8.64E-01	8.64E-01	8.64E-01	8.64E-01	8.64E-01	8.64E-01	8.64E-01	8.64E-01	±	1.17E-16
10.75	1079	14.35	Bubble-Slug	2.23E+00	2.23E+00	2.23E+00	2.23E+00	2.23E+00	2.23E+00	2.23E+00	2.23E+00	2.23E+00	2.23E+00	2.23E+00	±	0.00E+00
10.75	1079	18.72	Bubble-Slug	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	3.38E+00	±	4.68E-16
10.75	1079	23.09	Slug	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.25E+00	4.25E+00	4.25E+00	4.25E+00	4.25E+00	4.18E+00	±	7.59E-02
10.75	1079	27.47	Slug	4.83E+00	4.83E+00	4.83E+00	4.83E+00	4.83E+00	4.97E+00	4.97E+00	4.97E+00	4.97E+00	4.97E+00	4.90E+00	±	7.59E-02
10.75	1079	31.84	Slug	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	±	9.36E-16
10.75	1079	36.22	Slug	7.13E+00	7.13E+00	7.13E+00	7.13E+00	7.13E+00	7.27E+00	7.27E+00	7.27E+00	7.27E+00	7.27E+00	7.20E+00	±	7.59E-02
10.75	1079	40.56	Slug	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	8.14E+00	8.14E+00	8.14E+00	8.14E+00	8.14E+00	8.07E+00	±	7.59E-02
10.75	1079	49.63	Slug	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.15E+00	±	1.87E-15
10.75	1079	58.69	Slug	9.79E+00	9.79E+00	9.79E+00	9.79E+00	9.79E+00	9.87E+00	9.87E+00	9.87E+00	9.87E+00	9.87E+00	9.83E+00	±	3.80E-02
10.75	1079	67.75	Slug	1.04E+01	1.04E+01	1.04E+01	1.04E+01	1.04E+01	1.05E+01	1.05E+01	1.05E+01	1.05E+01	1.05E+01	1.04E+01	±	7.59E-02
10.75	1079	76.82	Slug	1.13E+01	1.13E+01	1.13E+01	1.13E+01	1.13E+01	1.15E+01	1.15E+01	1.15E+01	1.15E+01	1.15E+01	1.14E+01	±	1.14E-01
10.75	1079	85.88	Slug	1.21E+01	1.21E+01	1.21E+01	1.21E+01	1.21E+01	1.22E+01	1.22E+01	1.22E+01	1.22E+01	1.22E+01	1.22E+01	±	7.59E-02
10.75	1079	94.95	Slug	1.24E+01	1.24E+01	1.24E+01	1.24E+01	1.24E+01	1.25E+01	1.25E+01	1.25E+01	1.25E+01	1.25E+01	1.25E+01	±	7.59E-02
10.75	1079	104	Slug	1.30E+01	1.30E+01	1.30E+01	1.30E+01	1.30E+01	1.34E+01	1.34E+01	1.34E+01	1.34E+01	1.34E+01	1.32E+01	±	2.28E-01
10.75	1079	122	Slug	1.43E+01	1.43E+01	1.43E+01	1.43E+01	1.43E+01	1.48E+01	1.48E+01	1.48E+01	1.47E+01	1.48E+01	1.45E+01	±	2.39E-01
10.75	1079	140	Slug-Churn	1.51E+01	1.52E+01	1.51E+01	1.51E+01	1.51E+01	1.57E+01	1.58E+01	1.57E+01	1.58E+01	1.58E+01	1.54E+01	±	3.54E-01
10.75	1079	158	Slug-Churn	1.59E+01	1.59E+01	1.58E+01	1.57E+01	1.58E+01	1.66E+01	1.66E+01	1.69E+01	1.68E+01	1.69E+01	1.63E+01	±	4.95E-01
10.75	1079	177	Slug-Churn	1.64E+01	1.63E+01	1.63E+01	1.63E+01	1.64E+01	1.75E+01	1.75E+01	1.74E+01	1.74E+01	1.74E+01	1.69E+01	±	5.50E-01
10.75	1079	231	Slug-Churn	1.83E+01	1.83E+01	1.83E+01	1.83E+01	1.83E+01	1.91E+01	1.91E+01	1.91E+01	1.91E+01	1.91E+01	1.87E+01	±	4.18E-01
10.75	1079	294	Slug-Churn	1.92E+01	1.92E+01	1.93E+01	1.91E+01	1.91E+01	2.05E+01	2.04E+01	2.05E+01	2.07E+01	2.05E+01	1.98E+01	±	7.05E-01
10.75	1079	367	Slug-Churn	2.02E+01	2.03E+01	2.02E+01	2.03E+01	2.02E+01	2.21E+01	2.20E+01	2.20E+01	2.21E+01	2.21E+01	2.12E+01	±	9.58E-01
10.75	1079	523	Churn	2.20E+01	2.20E+01	2.20E+01	2.20E+01	2.20E+01	2.34E+01	2.34E+01	2.33E+01	2.37E+01	2.35E+01	2.27E+01	±	7.96E-01
10.75	1079	782	Churn	2.22E+01	2.23E+01	2.22E+01	2.23E+01	2.25E+01	2.47E+01	2.51E+01	2.51E+01	2.53E+01	2.52E+01	2.37E+01	±	1.48E+00

Pipe diameter, (mm)	Re_{water}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
				1	2	3	4	5	6	7	8	9	10	
10.75	1079	1427	Churn	2.13E+01	2.14E+01	2.13E+01	2.14E+01	2.13E+01	2.47E+01	2.46E+01	2.45E+01	2.46E+01	2.44E+01	2.30E+01 ± 1.69E+00
10.75	1079	2461	Churn	2.12E+01	2.13E+01	2.14E+01	2.13E+01	2.13E+01	2.27E+01	2.26E+01	2.27E+01	2.26E+01	2.26E+01	2.20E+01 ± 7.00E-01
10.75	1079	3471	Churn	2.17E+01	2.17E+01	2.17E+01	2.18E+01	2.17E+01	2.23E+01	2.25E+01	2.25E+01	2.25E+01	2.25E+01	2.21E+01 ± 3.81E-01
10.75	1079	4554	Annular	2.18E+01	2.18E+01	2.18E+01	2.18E+01	2.18E+01	2.25E+01	2.24E+01	2.24E+01	2.25E+01	2.25E+01	2.21E+01 ± 3.27E-01
10.75	1079	5546	Annular	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.20E+01	2.20E+01	2.20E+01	2.20E+01	2.20E+01	2.20E+01 ± 7.59E-02
10.75	1079	12597	Annular	1.97E+01	1.97E+01	1.97E+01	1.97E+01	1.97E+01	1.97E+01	1.97E+01	1.97E+01	1.97E+01	1.97E+01	1.97E+01 ± 0.00E+00
10.75	1079	25195	Mist	2.16E+00	2.16E+00	2.16E+00	2.16E+00	2.16E+00	2.45E+00	2.45E+00	2.45E+00	2.45E+00	2.45E+00	2.30E+00 ± 1.52E-01
19	1010	3.17	Bubble	1.82E+00	1.36E+00	1.82E+00	1.36E+00	1.82E+00	1.36E+00	1.82E+00	1.36E+00	1.36E+00	1.36E+00	1.54E+00 ± 2.34E-01
19	1010	5.64	Bubble	2.27E+00	2.27E+00	2.27E+00	2.27E+00	2.27E+00	2.72E+00	3.63E+00	3.63E+00	3.63E+00	3.63E+00	2.86E+00 ± 6.79E-01
19	1010	8.12	Bubble	4.54E+00	4.09E+00	4.09E+00	4.09E+00	4.09E+00	5.90E+00	5.45E+00	5.90E+00	5.90E+00	5.90E+00	4.99E+00 ± 8.83E-01
19	1010	10.59	Bubble	5.90E+00	5.90E+00	5.90E+00	5.90E+00	5.90E+00	9.99E+00	1.04E+01	1.04E+01	9.99E+00	1.04E+01	8.08E+00 ± 2.30E+00
19	1010	13.07	Bubble	7.26E+00	7.26E+00	7.26E+00	7.26E+00	7.26E+00	1.04E+01	1.04E+01	1.04E+01	1.09E+01	1.09E+01	8.94E+00 ± 1.78E+00
19	1010	15.54	Bubble-Slug	1.09E+01	1.04E+01	1.09E+01	1.14E+01	1.04E+01	1.27E+01	1.36E+01	1.36E+01	1.32E+01	1.32E+01	1.20E+01 ± 1.34E+00
19	1010	18.02	Bubble-Slug	1.63E+01	1.54E+01	1.54E+01	1.41E+01	1.41E+01	1.73E+01	1.77E+01	1.82E+01	1.68E+01	1.82E+01	1.63E+01 ± 1.54E+00
19	1010	20.49	Bubble-Slug	1.77E+01	1.82E+01	1.68E+01	1.91E+01	1.73E+01	2.09E+01	2.36E+01	2.27E+01	2.32E+01	2.27E+01	2.02E+01 ± 2.69E+00
19	1010	22.95	Bubble-Slug	2.00E+01	1.91E+01	2.00E+01	2.09E+01	1.91E+01	2.45E+01	2.45E+01	2.54E+01	2.68E+01	2.59E+01	2.26E+01 ± 3.08E+00
19	1010	28.08	Bubble-Slug	2.04E+01	2.22E+01	2.22E+01	2.18E+01	2.18E+01	2.68E+01	3.00E+01	3.18E+01	2.91E+01	3.00E+01	2.56E+01 ± 4.32E+00
19	1010	33.21	Slug	2.50E+01	2.54E+01	2.50E+01	2.63E+01	2.63E+01	3.09E+01	3.18E+01	3.18E+01	3.72E+01	3.18E+01	2.92E+01 ± 4.13E+00
19	1010	38.33	Slug	2.86E+01	2.86E+01	2.95E+01	3.00E+01	2.86E+01	3.68E+01	3.63E+01	3.81E+01	3.77E+01	3.90E+01	3.33E+01 ± 4.58E+00
19	1010	43.46	Slug	3.18E+01	3.22E+01	3.36E+01	3.41E+01	3.36E+01	4.09E+01	3.95E+01	4.00E+01	4.09E+01	4.04E+01	3.67E+01 ± 3.90E+00
19	1010	48.59	Slug	3.31E+01	3.41E+01	3.50E+01	3.50E+01	3.59E+01	4.09E+01	3.90E+01	4.13E+01	4.18E+01	4.13E+01	3.77E+01 ± 3.45E+00
19	1010	58.85	Slug	3.90E+01	4.00E+01	4.09E+01	4.04E+01	4.22E+01	4.81E+01	4.81E+01	4.72E+01	4.99E+01	4.77E+01	4.44E+01 ± 4.20E+00
19	1010	69.10	Slug	4.36E+01	4.54E+01	4.59E+01	4.54E+01	4.36E+01	5.31E+01	5.27E+01	6.36E+01	4.99E+01	5.22E+01	4.95E+01 ± 6.19E+00
19	1010	79.36	Slug	4.63E+01	4.63E+01	4.54E+01	4.40E+01	4.72E+01	5.36E+01	5.31E+01	5.81E+01	5.45E+01	5.63E+01	5.05E+01 ± 5.14E+00
19	1010	89.62	Slug	4.77E+01	4.72E+01	4.45E+01	4.63E+01	5.09E+01	5.99E+01	6.36E+01	6.13E+01	6.40E+01	6.22E+01	5.48E+01 ± 8.08E+00
19	1010	99.87	Slug	6.13E+01	6.08E+01	5.99E+01	5.99E+01	5.99E+01	7.26E+01	7.04E+01	7.26E+01	7.31E+01	7.72E+01	6.68E+01 ± 6.96E+00

Pipe diameter, (mm)	Re_{water}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
				1	2	3	4	5	6	7	8	9	10	
19	1010	177	Slug	7.36E+01	7.40E+01	7.72E+01	7.49E+01	7.72E+01	9.35E+01	9.22E+01	8.94E+01	9.31E+01	9.44E+01	8.40E+01 ± 9.21E+00
19	1010	296	Slug-Churn	9.67E+01	8.85E+01	9.67E+01	8.63E+01	9.08E+01	1.25E+02	1.25E+02	1.24E+02	1.42E+02	1.31E+02	1.11E+02 ± 2.07E+01
19	1010	369	Slug-Churn	9.54E+01	9.54E+01	9.49E+01	9.76E+01	9.67E+01	1.34E+02	1.30E+02	1.27E+02	1.33E+02	1.31E+02	1.14E+02 ± 1.86E+01
19	1010	515	Slug-Churn	1.14E+02	1.18E+02	1.14E+02	1.14E+02	1.05E+02	1.47E+02	1.48E+02	1.41E+02	1.51E+02	1.54E+02	1.31E+02 ± 1.90E+01
19	1010	735	Slug-Churn	1.09E+02	1.18E+02	1.17E+02	1.23E+02	1.22E+02	1.63E+02	1.61E+02	1.67E+02	1.67E+02	1.67E+02	1.41E+02 ± 2.53E+01
19	1010	1454	Churn	1.36E+02	1.35E+02	1.36E+02	1.36E+02	1.37E+02	1.66E+02	1.63E+02	1.59E+02	1.61E+02	1.50E+02	1.48E+02 ± 1.31E+01
19	1010	2474	Churn	1.41E+02	1.43E+02	1.41E+02	1.42E+02	1.44E+02	1.52E+02	1.54E+02	1.57E+02	1.56E+02	1.53E+02	1.48E+02 ± 6.57E+00
19	1010	3495	Churn	1.48E+02	1.47E+02	1.47E+02	1.50E+02	1.50E+02	1.54E+02	1.53E+02	1.54E+02	1.56E+02	1.55E+02	1.52E+02 ± 3.50E+00
19	1010	4516	Churn	1.54E+02	1.55E+02	1.55E+02	1.55E+02	1.55E+02	1.59E+02	1.59E+02	1.59E+02	1.59E+02	1.58E+02	1.57E+02 ± 2.08E+00
19	1010	5537	Churn	1.54E+02	1.53E+02	1.53E+02	1.53E+02	1.52E+02	1.57E+02	1.56E+02	1.55E+02	1.54E+02	1.54E+02	1.54E+02 ± 1.69E+00
19	1010	14255	Churn	1.64E+02	1.64E+02	1.64E+02	1.64E+02	1.64E+02	1.67E+02	1.68E+02	1.68E+02	1.68E+02	1.68E+02	1.66E+02 ± 1.88E+00
19	1010	21382	Churn	1.61E+02	1.61E+02	1.61E+02	1.61E+02	1.61E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.62E+02 ± 9.57E-01
19	1010	28510	Annular	1.56E+02	1.56E+02	1.56E+02	1.56E+02	1.56E+02	1.56E+02	1.56E+02	1.56E+02	1.56E+02	1.56E+02	1.56E+02 ± 2.39E-01
19	1010	35637	Annular	1.49E+02	1.49E+02	1.49E+02	1.49E+02	1.49E+02	1.50E+02	1.50E+02	1.50E+02	1.50E+02	1.50E+02	1.50E+02 ± 4.79E-01
19	1010	42765	Annular	1.34E+02	1.34E+02	1.34E+02	1.34E+02	1.34E+02	1.35E+02	1.35E+02	1.35E+02	1.35E+02	1.35E+02	1.35E+02 ± 4.79E-01
19	1010	49892	Annular	1.20E+02	1.20E+02	1.20E+02	1.20E+02	1.20E+02	1.21E+02	1.21E+02	1.21E+02	1.21E+02	1.21E+02	1.20E+02 ± 4.79E-01
19	1010	57020	Mist	1.13E+02	1.13E+02	1.13E+02	1.13E+02	1.13E+02	1.14E+02	1.14E+02	1.14E+02	1.14E+02	1.14E+02	1.14E+02 ± 7.18E-01
19	1010	64147	Mist	1.03E+02	1.03E+02	1.03E+02	1.03E+02	1.03E+02	1.03E+02	1.03E+02	1.03E+02	1.03E+02	1.03E+02	1.03E+02 ± 0.00E+00
19	1010	71275	Mist	9.90E+01	9.90E+01	9.90E+01	9.90E+01	9.90E+01	9.90E+01	9.90E+01	9.90E+01	9.90E+01	9.90E+01	9.90E+01 ± 0.00E+00
53.15	1028	2.90	Bubble	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01 ± 0.00E+00
53.15	1028	5.56	Bubble	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01 ± 0.00E+00
53.15	1028	8.20	Bubble	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01 ± 0.00E+00
53.15	1028	10.04	Bubble	2.88E+01	2.88E+01	2.88E+01	2.88E+01	2.88E+01	2.88E+01	2.88E+01	2.88E+01	2.88E+01	2.88E+01	2.88E+01 ± 3.74E-15
53.15	1028	11.87	Bubble	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01 ± 0.00E+00
53.15	1028	13.70	Bubble	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01	3.84E+01 ± 0.00E+00
53.15	1028	15.54	Bubble	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01 ± 0.00E+00

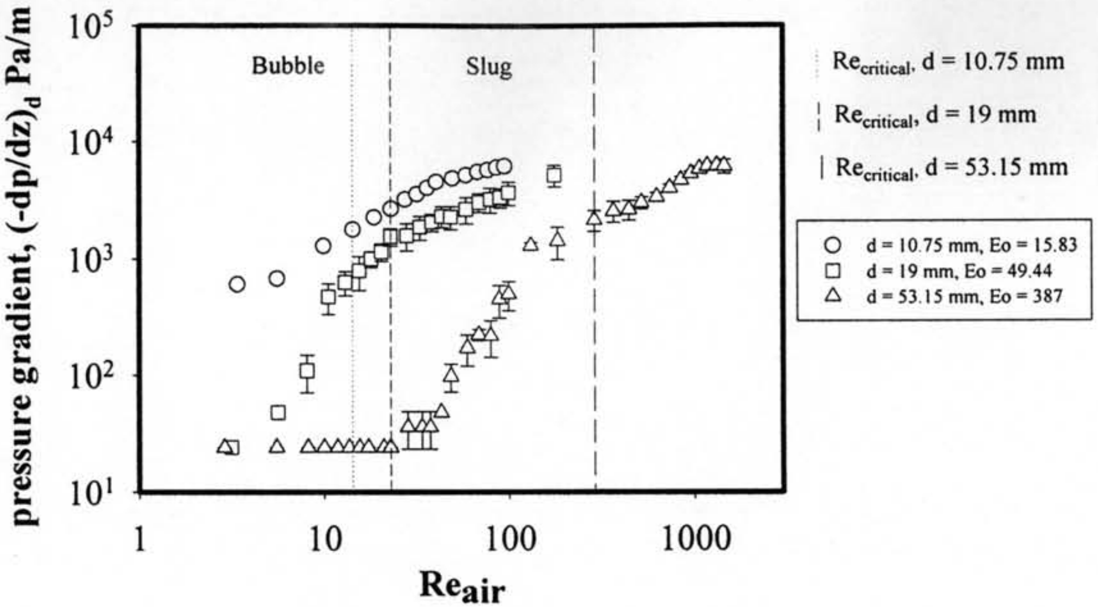
Pipe diameter, (mm)	Re_{water}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^2}$										Average dimensionless pressure gradient		
				1	2	3	4	5	6	7	8	9	10			
53.15	1028	17.37	Bubble	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.80E+01	±	0.00E+00
53.15	1028	21.04	Bubble	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	±	0.00E+00
53.15	1028	22.87	Bubble	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	6.72E+01	±	0.00E+00
53.15	1028	28.37	Bubble	8.64E+01	8.64E+01	8.64E+01	8.64E+01	8.64E+01	8.64E+01	8.64E+01	8.64E+01	8.64E+01	8.64E+01	8.64E+01	±	0.00E+00
53.15	1028	33.87	Bubble	1.15E+02	1.15E+02	1.15E+02	1.15E+02	1.15E+02	1.15E+02	1.15E+02	1.15E+02	1.15E+02	1.15E+02	1.15E+02	±	3.00E-14
53.15	1028	37.54	Bubble	1.25E+02	1.25E+02	1.25E+02	1.25E+02	1.25E+02	1.25E+02	1.25E+02	1.25E+02	1.25E+02	1.25E+02	1.25E+02	±	1.50E-14
53.15	1028	43.04	Bubble	1.44E+02	1.44E+02	1.44E+02	1.44E+02	1.44E+02	1.44E+02	1.44E+02	1.44E+02	1.44E+02	1.44E+02	1.44E+02	±	0.00E+00
53.15	1028	48.54	Bubble	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	1.63E+02	±	0.00E+00
53.15	1028	59.53	Bubble	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	±	0.00E+00
53.15	1028	68.70	Bubble	2.21E+02	2.21E+02	2.21E+02	2.21E+02	2.21E+02	2.40E+02	2.40E+02	2.40E+02	2.40E+02	2.40E+02	2.30E+02	±	1.01E+01
53.15	1028	79.70	Bubble	2.30E+02	2.30E+02	2.30E+02	2.30E+02	2.30E+02	2.59E+02	2.59E+02	2.59E+02	2.59E+02	2.59E+02	2.45E+02	±	1.52E+01
53.15	1028	88.87	Bubble	2.78E+02	2.78E+02	2.78E+02	2.78E+02	2.78E+02	2.98E+02	2.98E+02	2.98E+02	2.98E+02	2.98E+02	2.88E+02	±	1.01E+01
53.15	1028	100	Bubble	2.98E+02	2.98E+02	2.98E+02	2.98E+02	2.98E+02	3.26E+02	3.26E+02	3.26E+02	3.26E+02	3.26E+02	3.12E+02	±	1.52E+01
53.15	1028	132	Bubble	4.03E+02	4.03E+02	4.03E+02	4.03E+02	4.03E+02	4.70E+02	4.70E+02	4.80E+02	4.80E+02	4.90E+02	4.41E+02	±	3.98E+01
53.15	1028	184	Bubble-Slug	4.80E+02	4.99E+02	4.99E+02	4.99E+02	4.99E+02	5.76E+02	5.86E+02	5.86E+02	5.86E+02	5.86E+02	5.39E+02	±	4.70E+01
53.15	1028	289	Bubble-Slug	6.82E+02	6.82E+02	6.91E+02	6.62E+02	6.62E+02	7.58E+02	7.68E+02	7.68E+02	7.68E+02	7.68E+02	7.21E+02	±	4.84E+01
53.15	1028	367	Bubble-Slug	7.87E+02	7.77E+02	7.87E+02	7.68E+02	7.77E+02	8.64E+02	8.64E+02	8.73E+02	8.54E+02	8.64E+02	8.22E+02	±	4.51E+01
53.15	1028	445	Slug	8.54E+02	8.64E+02	8.64E+02	8.73E+02	8.73E+02	9.98E+02	1.02E+03	9.98E+02	1.01E+03	9.98E+02	9.35E+02	±	7.33E+01
53.15	1028	520	Slug	9.60E+02	9.50E+02	9.50E+02	9.50E+02	9.50E+02	1.04E+03	1.03E+03	1.04E+03	1.05E+03	1.03E+03	9.93E+02	±	4.39E+01
53.15	1028	629	Slug	1.09E+03	1.09E+03	1.11E+03	1.10E+03	1.10E+03	1.16E+03	1.19E+03	1.20E+03	1.20E+03	1.19E+03	1.15E+03	±	4.70E+01
53.15	1028	739	Slug	1.21E+03	1.23E+03	1.22E+03	1.22E+03	1.23E+03	1.36E+03	1.35E+03	1.33E+03	1.35E+03	1.36E+03	1.29E+03	±	7.05E+01
53.15	1028	848	Slug	1.38E+03	1.38E+03	1.39E+03	1.38E+03	1.39E+03	1.48E+03	1.46E+03	1.50E+03	1.46E+03	1.48E+03	1.43E+03	±	4.79E+01
53.15	1028	958	Slug	1.48E+03	1.43E+03	1.45E+03	1.45E+03	1.46E+03	1.57E+03	1.58E+03	1.58E+03	1.57E+03	1.58E+03	1.52E+03	±	6.79E+01
53.15	1028	1067	Slug	1.58E+03	1.59E+03	1.58E+03	1.58E+03	1.57E+03	1.77E+03	1.76E+03	1.78E+03	1.76E+03	1.76E+03	1.67E+03	±	9.44E+01
53.15	1028	1176	Slug	1.74E+03	1.74E+03	1.74E+03	1.71E+03	1.71E+03	1.82E+03	1.78E+03	1.80E+03	1.81E+03	1.82E+03	1.77E+03	±	4.67E+01
53.15	1028	1322	Slug	1.79E+03	1.79E+03	1.79E+03	1.79E+03	1.79E+03	1.99E+03	2.00E+03	1.98E+03	1.97E+03	1.97E+03	1.89E+03	±	9.96E+01
53.15	1028	1450	Slug	1.95E+03	1.93E+03	1.94E+03	1.94E+03	1.94E+03	2.06E+03	2.08E+03	2.05E+03	2.05E+03	2.08E+03	2.00E+03	±	6.86E+01

Pipe diameter, (mm)	Re_{water}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^2}$										Average dimensionless pressure gradient
				1	2	3	4	5	6	7	8	9	10	
53.15	1028	2548	Slug-Churn	2.08E+03	2.08E+03	2.09E+03	2.09E+03	2.08E+03	2.25E+03	2.26E+03	2.25E+03	2.25E+03	2.26E+03	2.17E+03 ± 8.61E+01
53.15	1028	5096	Slug-Churn	2.50E+03	2.53E+03	2.53E+03	2.51E+03	2.51E+03	2.73E+03	2.69E+03	2.72E+03	2.67E+03	2.60E+03	2.60E+03 ± 9.18E+01
53.15	1028	7644	Slug-Churn	2.68E+03	2.75E+03	2.71E+03	2.70E+03	2.67E+03	2.86E+03	2.88E+03	2.87E+03	2.84E+03	2.85E+03	2.78E+03 ± 8.79E+01
53.15	1028	10192	Churn	2.71E+03	2.75E+03	2.83E+03	2.77E+03	2.81E+03	3.07E+03	2.98E+03	2.98E+03	2.98E+03	3.36E+03	2.92E+03 ± 1.95E+02
53.15	1028	12740	Churn	2.83E+03	2.84E+03	2.92E+03	2.88E+03	2.88E+03	3.36E+03	3.22E+03	3.34E+03	3.32E+03	3.19E+03	3.08E+03 ± 2.26E+02
53.15	1028	15288	Churn	2.94E+03	2.96E+03	2.98E+03	2.98E+03	2.99E+03	3.36E+03	3.41E+03	3.34E+03	3.34E+03	3.36E+03	3.16E+03 ± 2.09E+02
53.15	1028	17835	Churn	3.07E+03	3.07E+03	3.07E+03	3.03E+03	3.01E+03	3.49E+03	3.36E+03	3.34E+03	3.55E+03	3.34E+03	3.23E+03 ± 2.04E+02
53.15	1028	20383	Churn	3.08E+03	3.06E+03	3.07E+03	3.07E+03	3.10E+03	3.41E+03	3.53E+03	3.52E+03	3.46E+03	3.47E+03	3.28E+03 ± 2.13E+02
53.15	1028	22931	Churn	3.10E+03	3.10E+03	3.10E+03	3.11E+03	3.12E+03	3.55E+03	3.44E+03	3.53E+03	3.56E+03	3.57E+03	3.32E+03 ± 2.27E+02

Pipe diameter, (mm)	Re_{water}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \overline{u}_{liq}^{2}}$										Average dimensionless pressure gradient
				1	2	3	4	5	6	7	8	9	10	
10.75	2727	3.41	Bubble	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02 ± 1.829E-18
10.75	2727	5.60	Bubble	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02	1.13E-02 ± 0.00E+00
10.75	2727	9.97	Bubble	2.26E-02	2.26E-02	2.26E-02	2.26E-02	2.26E-02	3.38E-02	3.38E-02	3.38E-02	3.38E-02	3.38E-02	2.82E-02 ± 5.94E-03
10.75	2727	14.35	Bubble	3.38E-02	3.38E-02	3.38E-02	3.38E-02	3.38E-02	5.64E-02	5.64E-02	5.64E-02	5.64E-02	5.64E-02	4.51E-02 ± 1.19E-02
10.75	2727	18.72	Bubble	1.92E-01	1.92E-01	1.92E-01	1.92E-01	1.92E-01	2.26E-01	2.26E-01	2.26E-01	2.26E-01	2.26E-01	2.09E-01 ± 1.78E-02
10.75	2727	23.09	Bubble	2.93E-01	2.93E-01	2.93E-01	2.93E-01	2.93E-01	3.16E-01	3.16E-01	3.16E-01	3.16E-01	3.16E-01	3.05E-01 ± 1.19E-02
10.75	2727	27.47	Bubble-Slug	3.95E-01	3.95E-01	3.95E-01	3.95E-01	3.95E-01	4.06E-01	4.29E-01	4.29E-01	4.51E-01	4.51E-01	4.14E-01 ± 2.38E-02
10.75	2727	31.84	Bubble-Slug	5.30E-01	5.30E-01	5.30E-01	5.30E-01	5.30E-01	5.53E-01	5.53E-01	5.53E-01	5.53E-01	5.53E-01	5.41E-01 ± 1.19E-02
10.75	2727	36.22	Slug	6.09E-01	6.09E-01	6.09E-01	6.09E-01	6.09E-01	6.32E-01	6.32E-01	6.32E-01	6.32E-01	6.32E-01	6.20E-01 ± 1.19E-02
10.75	2727	40.56	Slug	7.56E-01	7.56E-01	7.56E-01	7.56E-01	7.56E-01	7.78E-01	7.78E-01	7.78E-01	7.78E-01	7.78E-01	7.67E-01 ± 1.19E-02
10.75	2727	49.63	Slug	8.80E-01	8.80E-01	8.80E-01	8.80E-01	8.80E-01	8.80E-01	8.80E-01	8.80E-01	8.80E-01	8.80E-01	8.80E-01 ± 1.17E-16
10.75	2727	58.69	Slug	9.81E-01	9.81E-01	9.81E-01	9.81E-01	9.81E-01	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.93E-01 ± 1.19E-02
10.75	2727	67.75	Slug	1.08E+00	1.08E+00	1.08E+00	1.08E+00	1.08E+00	1.11E+00	1.11E+00	1.11E+00	1.11E+00	1.11E+00	1.09E+00 ± 1.19E-02
10.75	2727	76.82	Slug	1.17E+00	1.17E+00	1.17E+00	1.17E+00	1.17E+00	1.20E+00	1.20E+00	1.20E+00	1.20E+00	1.20E+00	1.18E+00 ± 1.19E-02
10.75	2727	85.88	Slug	1.26E+00	1.26E+00	1.26E+00	1.26E+00	1.26E+00	1.29E+00	1.29E+00	1.29E+00	1.29E+00	1.29E+00	1.27E+00 ± 1.19E-02
10.75	2727	94.95	Slug	1.35E+00	1.35E+00	1.35E+00	1.35E+00	1.35E+00	1.38E+00	1.38E+00	1.38E+00	1.38E+00	1.38E+00	1.36E+00 ± 1.19E-02
10.75	2727	104	Slug	1.42E+00	1.42E+00	1.42E+00	1.42E+00	1.42E+00	1.42E+00	1.42E+00	1.42E+00	1.42E+00	1.42E+00	1.42E+00 ± 2.34E-16
10.75	2727	122	Slug	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.58E+00	1.58E+00	1.58E+00	1.58E+00	1.58E+00	1.57E+00 ± 1.19E-02
10.75	2727	140	Slug	1.66E+00	1.66E+00	1.66E+00	1.66E+00	1.66E+00	1.68E+00	1.68E+00	1.68E+00	1.68E+00	1.68E+00	1.67E+00 ± 1.19E-02
10.75	2727	158	Slug	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.84E+00	1.84E+00	1.84E+00	1.84E+00	1.84E+00	1.83E+00 ± 5.94E-03
10.75	2727	177	Slug	1.91E+00	1.91E+00	1.91E+00	1.91E+00	1.91E+00	1.94E+00	1.94E+00	1.94E+00	1.93E+00	1.93E+00	1.92E+00 ± 1.60E-02
10.75	2727	231	Slug-Churn	2.17E+00	2.17E+00	2.17E+00	2.17E+00	2.17E+00	2.22E+00	2.22E+00	2.22E+00	2.22E+00	2.22E+00	2.19E+00 ± 2.97E-02
10.75	2727	294	Slug-Churn	2.37E+00	2.37E+00	2.37E+00	2.37E+00	2.37E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.40E+00	2.39E+00 ± 1.78E-02
10.75	2727	367	Slug-Churn	2.56E+00	2.57E+00	2.56E+00	2.57E+00	2.56E+00	2.66E+00	2.67E+00	2.66E+00	2.66E+00	2.66E+00	2.61E+00 ± 5.26E-02
10.75	2727	523	Slug-Churn	2.84E+00	2.83E+00	2.84E+00	2.84E+00	2.84E+00	2.99E+00	2.98E+00	2.98E+00	2.99E+00	2.99E+00	2.91E+00 ± 7.63E-02
10.75	2727	782	Slug-Churn	3.01E+00	2.99E+00	2.99E+00	2.99E+00	2.99E+00	3.29E+00	3.29E+00	3.28E+00	3.29E+00	3.29E+00	3.14E+00 ± 1.57E-01

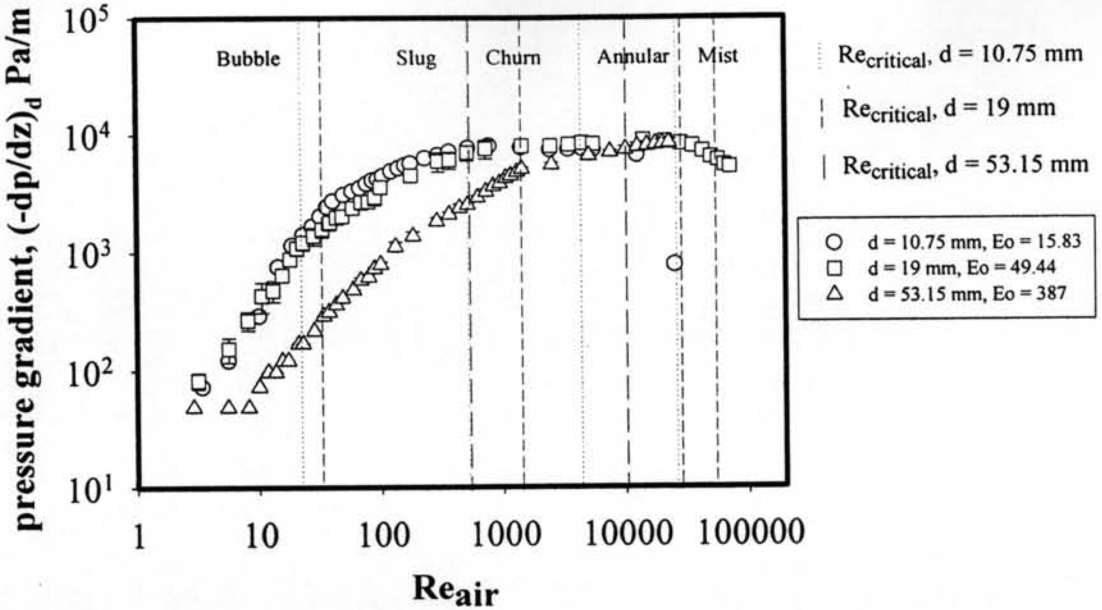
Pipe diameter, (mm)	Re_{water}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \overline{u}_{liq}^2}$										Average dimensionless pressure gradient		
				1	2	3	4	5	6	7	8	9	10			
10.75	2727	1427	Churn	2.89E+00	2.92E+00	2.90E+00	2.88E+00	2.92E+00	3.42E+00	3.41E+00	3.39E+00	3.39E+00	3.41E+00	3.15E+00	±	2.66E-01
10.75	2727	2461	Churn	2.56E+00	2.63E+00	2.62E+00	2.63E+00	2.64E+00	3.02E+00	3.02E+00	3.03E+00	3.05E+00	3.02E+00	2.82E+00	±	2.20E-01
10.75	2727	3471	Churn	2.67E+00	2.67E+00	2.67E+00	2.67E+00	2.67E+00	2.90E+00	2.94E+00	2.93E+00	2.93E+00	2.94E+00	2.80E+00	±	1.36E-01
10.75	2727	4554	Churn	2.62E+00	2.63E+00	2.62E+00	2.62E+00	2.63E+00	2.76E+00	2.75E+00	2.74E+00	2.76E+00	2.76E+00	2.69E+00	±	7.18E-02
10.75	2727	5546	Churn	2.32E+00	2.33E+00	2.32E+00	2.32E+00	2.31E+00	2.41E+00	2.40E+00	2.41E+00	2.40E+00	2.42E+00	2.37E+00	±	4.71E-02
10.75	2727	12597	Annular	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	1.70E+00	±	0.00E+00
10.75	2727	25195	Mist	2.03E-01	2.03E-01	2.03E-01	2.03E-01	2.03E-01	2.26E-01	2.26E-01	2.26E-01	2.26E-01	2.26E-01	2.14E-01	±	1.19E-02
19	2740	3.17	Bubble	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	±	0.00E+00
19	2740	5.64	Bubble	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	±	0.00E+00
19	2740	8.12	Bubble	6.17E-02	6.17E-02	6.17E-02	6.17E-02	6.17E-02	1.23E-01	1.23E-01	1.23E-01	1.23E-01	1.23E-01	9.25E-02	±	3.25E-02
19	2740	10.59	Bubble	1.23E-01	1.23E-01	1.23E-01	1.23E-01	1.23E-01	4.32E-01	4.32E-01	4.32E-01	4.32E-01	4.32E-01	2.78E-01	±	1.63E-01
19	2740	13.07	Bubble	3.08E-01	3.08E-01	3.08E-01	3.08E-01	3.08E-01	6.17E-01	6.17E-01	6.17E-01	6.17E-01	6.17E-01	4.63E-01	±	1.63E-01
19	2740	15.54	Bubble	4.94E-01	5.55E-01	6.17E-01	6.17E-01	6.17E-01	9.25E-01	8.02E-01	8.64E-01	8.02E-01	8.64E-01	7.16E-01	±	1.52E-01
19	2740	18.02	Bubble	8.02E-01	8.02E-01	8.02E-01	8.02E-01	8.02E-01	1.05E+00	1.11E+00	1.11E+00	1.11E+00	1.11E+00	9.50E-01	±	1.57E-01
19	2740	20.49	Bubble	9.25E-01	1.17E+00	9.87E-01	1.05E+00	9.87E-01	1.60E+00	1.54E+00	1.48E+00	1.48E+00	1.54E+00	1.28E+00	±	2.76E-01
19	2740	22.95	Bubble	1.42E+00	1.36E+00	1.23E+00	1.23E+00	1.36E+00	2.04E+00	2.10E+00	2.22E+00	2.10E+00	2.04E+00	1.71E+00	±	4.16E-01
19	2740	28.08	Bubble	1.91E+00	1.73E+00	1.85E+00	1.91E+00	1.85E+00	2.28E+00	2.34E+00	2.28E+00	2.34E+00	2.34E+00	2.09E+00	±	2.53E-01
19	2740	33.21	Bubble	2.41E+00	2.16E+00	2.34E+00	2.34E+00	2.34E+00	2.71E+00	2.71E+00	2.71E+00	2.65E+00	2.65E+00	2.50E+00	±	2.06E-01
19	2740	38.33	Bubble-Slug	2.28E+00	2.47E+00	2.47E+00	2.41E+00	2.53E+00	3.21E+00	3.08E+00	3.21E+00	3.33E+00	3.15E+00	2.81E+00	±	4.13E-01
19	2740	43.46	Bubble-Slug	2.78E+00	2.84E+00	2.78E+00	2.65E+00	2.65E+00	3.58E+00	3.58E+00	3.64E+00	3.52E+00	3.58E+00	3.16E+00	±	4.47E-01
19	2740	48.59	Slug	3.27E+00	3.39E+00	3.39E+00	3.27E+00	3.33E+00	4.32E+00	4.01E+00	4.13E+00	4.20E+00	4.07E+00	3.74E+00	±	4.38E-01
19	2740	58.85	Slug	3.58E+00	3.58E+00	3.58E+00	3.52E+00	3.70E+00	4.87E+00	5.24E+00	5.00E+00	4.87E+00	4.94E+00	4.29E+00	±	7.43E-01
19	2740	69.10	Slug	4.20E+00	4.32E+00	3.89E+00	4.20E+00	4.20E+00	5.55E+00	5.37E+00	5.18E+00	5.31E+00	5.31E+00	4.75E+00	±	6.40E-01
19	2740	79.36	Slug	4.69E+00	4.63E+00	4.63E+00	4.69E+00	4.63E+00	5.68E+00	5.68E+00	5.86E+00	5.80E+00	5.80E+00	5.21E+00	±	5.88E-01
19	2740	89.62	Slug	4.94E+00	4.75E+00	4.69E+00	4.94E+00	4.94E+00	6.11E+00	6.48E+00	6.29E+00	6.11E+00	6.54E+00	5.58E+00	±	7.83E-01
19	2740	99.87	Slug	5.06E+00	4.87E+00	4.94E+00	4.81E+00	4.94E+00	6.54E+00	6.48E+00	6.48E+00	6.72E+00	6.91E+00	5.77E+00	±	9.08E-01

Pipe diameter, (mm)	Re_{water}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
				1	2	3	4	5	6	7	8	9	10	
19	2740	177	Slug	8.14E+00	8.14E+00	8.33E+00	7.90E+00	8.02E+00	1.05E+01	1.05E+01	1.05E+01	1.05E+01	1.05E+01	9.31E+00 ± 1.27E+00
19	2740	296	Slug	1.02E+01	1.11E+01	1.11E+01	1.11E+01	1.05E+01	1.38E+01	1.46E+01	1.51E+01	1.46E+01	1.59E+01	1.28E+01 ± 2.20E+00
19	2740	369	Slug-Churn	1.23E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.63E+01	1.70E+01	1.60E+01	1.60E+01	1.54E+01	1.41E+01 ± 2.18E+00
19	2740	515	Slug-Churn	1.36E+01	1.36E+01	1.33E+01	1.33E+01	1.33E+01	1.79E+01	1.79E+01	1.76E+01	1.85E+01	1.85E+01	1.57E+01 ± 2.49E+00
19	2740	735	Slug-Churn	1.51E+01	1.54E+01	1.55E+01	1.51E+01	1.45E+01	1.76E+01	1.84E+01	1.91E+01	1.92E+01	1.85E+01	1.69E+01 ± 1.88E+00
19	2740	1454	Slug-Churn	1.54E+01	1.76E+01	1.73E+01	1.76E+01	1.72E+01	1.99E+01	2.01E+01	2.04E+01	1.86E+01	2.01E+01	1.84E+01 ± 1.66E+00
19	2740	2474	Churn	1.79E+01	1.70E+01	1.82E+01	1.79E+01	1.78E+01	1.96E+01	1.94E+01	2.07E+01	2.01E+01	1.94E+01	1.88E+01 ± 1.20E+00
19	2740	3495	Churn	1.85E+01	1.85E+01	1.85E+01	1.85E+01	1.85E+01	2.09E+01	1.97E+01	1.96E+01	1.96E+01	1.96E+01	1.92E+01 ± 8.13E-01
19	2740	4516	Churn	1.89E+01	1.89E+01	1.89E+01	1.89E+01	1.89E+01	1.99E+01	1.99E+01	1.99E+01	1.99E+01	1.99E+01	1.94E+01 ± 4.88E-01
19	2740	5537	Churn	1.74E+01	1.76E+01	1.76E+01	1.76E+01	1.76E+01	1.89E+01	1.92E+01	1.92E+01	1.93E+01	1.94E+01	1.84E+01 ± 9.01E-01
19	2740	14255	Churn	1.90E+01	1.90E+01	1.90E+01	1.90E+01	1.90E+01	1.96E+01	1.97E+01	1.97E+01	1.97E+01	1.97E+01	1.93E+01 ± 3.47E-01
19	2740	21382	Churn	1.84E+01	1.84E+01	1.84E+01	1.84E+01	1.84E+01	1.87E+01	1.87E+01	1.87E+01	1.87E+01	1.87E+01	1.86E+01 ± 1.30E-01
19	2740	28510	Annular	1.64E+01	1.64E+01	1.64E+01	1.64E+01	1.64E+01	1.65E+01	1.65E+01	1.65E+01	1.65E+01	1.65E+01	1.65E+01 ± 6.50E-02
19	2740	35637	Annular	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.42E+01	1.43E+01	1.43E+01	1.43E+01	1.43E+01	1.43E+01	1.42E+01 ± 3.25E-02
19	2740	42765	Annular	1.25E+01	1.25E+01	1.25E+01	1.25E+01	1.25E+01	1.26E+01	1.26E+01	1.26E+01	1.26E+01	1.26E+01	1.25E+01 ± 6.50E-02
19	2740	49892	Annular	1.12E+01	1.12E+01	1.12E+01	1.12E+01	1.12E+01	1.13E+01	1.13E+01	1.13E+01	1.13E+01	1.13E+01	1.13E+01 ± 3.25E-02
19	2740	57020	Mist	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00 ± 1.87E-15
19	2740	64147	Mist	7.40E+00	7.40E+00	7.40E+00	7.40E+00	7.40E+00	7.40E+00	7.40E+00	7.40E+00	7.40E+00	7.40E+00	7.40E+00 ± 0.00E+00
19	2740	71275	Mist	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00	5.98E+00 ± 0.00E+00



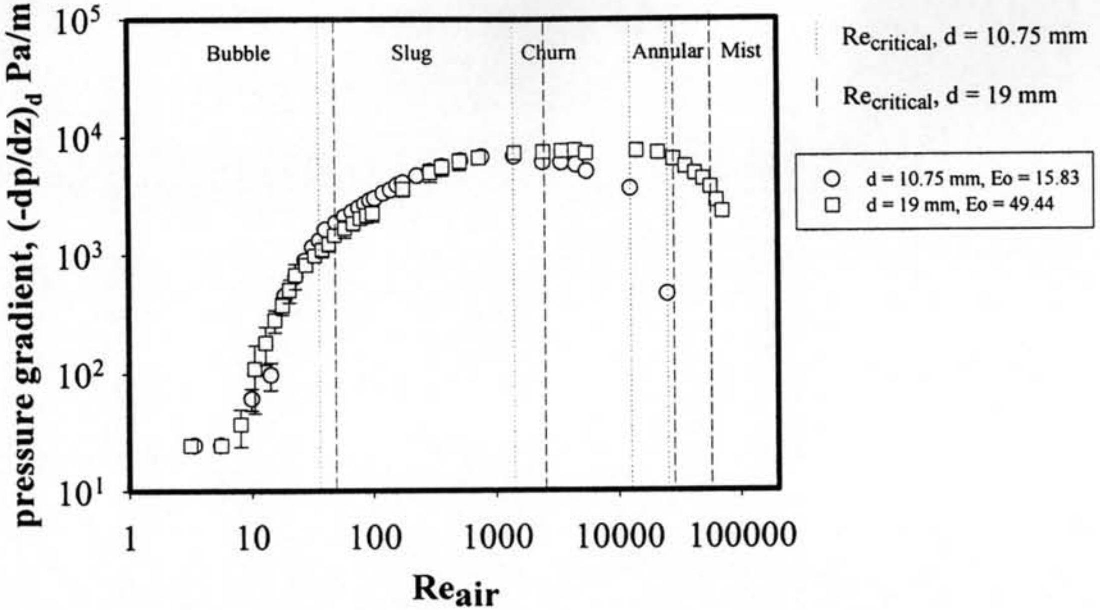
$(-dp/dz)_d$: Dynamic pressure gradient

Figure D14 Comparison the Dynamic pressure gradient from the experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at $Re_{water} = 0$.



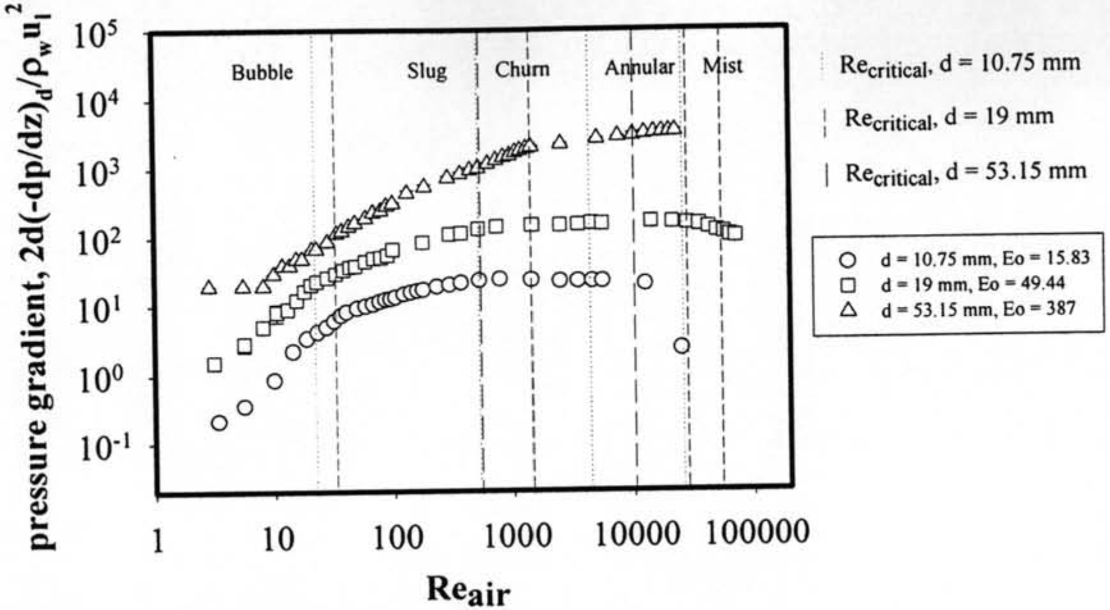
$(-dp/dz)_d$: Dynamic pressure gradient

Figure D15 Comparison the dynamic pressure gradient from the experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at Re_{water} = 1079, 1010 and 1028.



$(-dp/dz)_d$: Dynamic pressure gradient

Figure D16 Comparison the dynamic pressure gradient from the experiment between pipe diameter 10.75 mm and 19 mm vs. air Reynolds number of pure water at Re_{water} = 2727 and 2740.

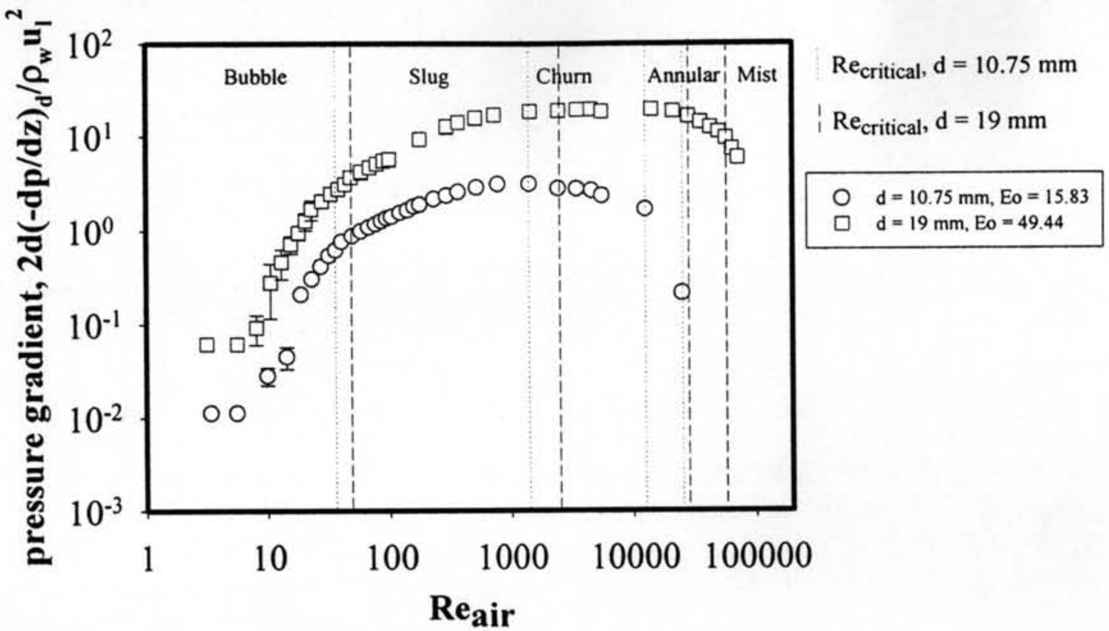


$(-dp/dz)_d$: Dynamic pressure gradient

ρ_w : Water density

u_l : liquid velocity, (Liquid flow rate / Cross section area)

Figure D17 Comparison the dimensionless pressure gradient from the experiment between pipe diameter 10.75 mm, 19 mm and 53.15 mm vs. air Reynolds number of pure water at Re_{water} = 1079, 1010 and 1028.



(-dp/dz)$_d$: Dynamic pressure gradient

ρ_w : Water density

u_l : liquid velocity, (Liquid flow rate / Cross section area)

Figure D18 Comparison the dimensionless pressure gradient from the experiment between pipe diameter 10.75 mm and 19 mm vs. air Reynolds number of pure water at Re_{water} = 2727 and 2740.

Table D6 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes by using pipe diameter of 10.75, 19 and 53.15 mm

Pipe diameter (mm)	Re_{water}	Re_{air}(critical) for each flow regime					
		Bubble-slug	Slug	Slug-churn	Churn	Annular	Mist
10.75	0	5.6	14.35	-	-	-	-
	1079	14.35	23.09	140	523	4554	25195
	2727	27.47	36.22	231	1427	12597	25195
19	0	10.59	22.95	-	-	-	-
	1010	15.54	33.21	296	1454	28510	57020
	2740	38.33	48.59	369	2474	28510	57020
53.15	0	132	289	-	-	-	-
	1028	184	445	2548	10192	-	-

Appendix E Physical Properties of Octylbenzyldimethylammonium Chloride Surfactant (C_8H_{17}-$N^+(CH_3)_2$-CH_2-C_6H_5 Cl^-)

Table E1 Determination the density of solution by using Syringe (SGE, Australia)

Procedure to determine the density of solution:

1. Weigh the empty dry beaker and record the mass.
2. Fill the beaker with solution by using syringe (100 μL) and take the mass of the filled beaker.
3. The difference between the mass of the empty beaker and the beaker when it is filled with the mass of the solution.
4. Knowing the mass of the solution and the volume of the solution (100 μL), the density of the solution can be calculated

using the equation:

$$\rho = \frac{M}{V} \tag{E1}$$

Note: system temperature, T = 31±0.3 °C

Conc. (g/L)	Empty bottle (g)			Average (g)	Empty bottle + solution (g)			Average (g)	Solution weight (g)			Average solution weight (g)	Density (ρ), kg/m³			Average density (ρ), kg/m³
	1	2	3		1	2	3		1	2	3		1	2	3	
0	54.35	54.35	54.35	54.35 ± 0.0024	54.45	54.45	54.45	54.45 ± 0.0024	0.0995	0.0995	0.0995	0.0995 ± 0.00	995	995	995	995 ± 0
30.8	53.54	53.54	53.54	53.54 ± 0.0013	53.64	53.64	53.64	53.64 ± 0.0013	0.0998	0.0997	0.0998	0.0998 ± 6E-05	998	997	998	997.7 ± 0.58
61.6	54.36	54.36	54.36	54.36 ± 0.0004	54.46	54.46	54.46	54.46 ± 0.0004	0.0998	0.0998	0.0998	0.0998 ± 0.00	998	998	998	998.0 ± 0
123	54.36	54.36	54.36	54.36 ± 0.0008	54.46	54.46	54.46	54.46 ± 0.0008	0.0998	0.0998	0.0999	0.0998 ± 6E-05	998	998	999	998.3 ± 0.58
185	54.36	54.36	54.36	54.36 ± 0.0003	54.46	54.46	54.46	54.46 ± 0.0004	0.0998	0.0998	0.0999	0.0998 ± 6E-05	998	998	999	998.3 ± 0.58
246	54.35	54.35	54.35	54.35 ± 0.0010	54.45	54.45	54.45	54.45 ± 0.0010	0.0998	0.0999	0.0999	0.0999 ± 6E-05	998	999	999	998.7 ± 0.58

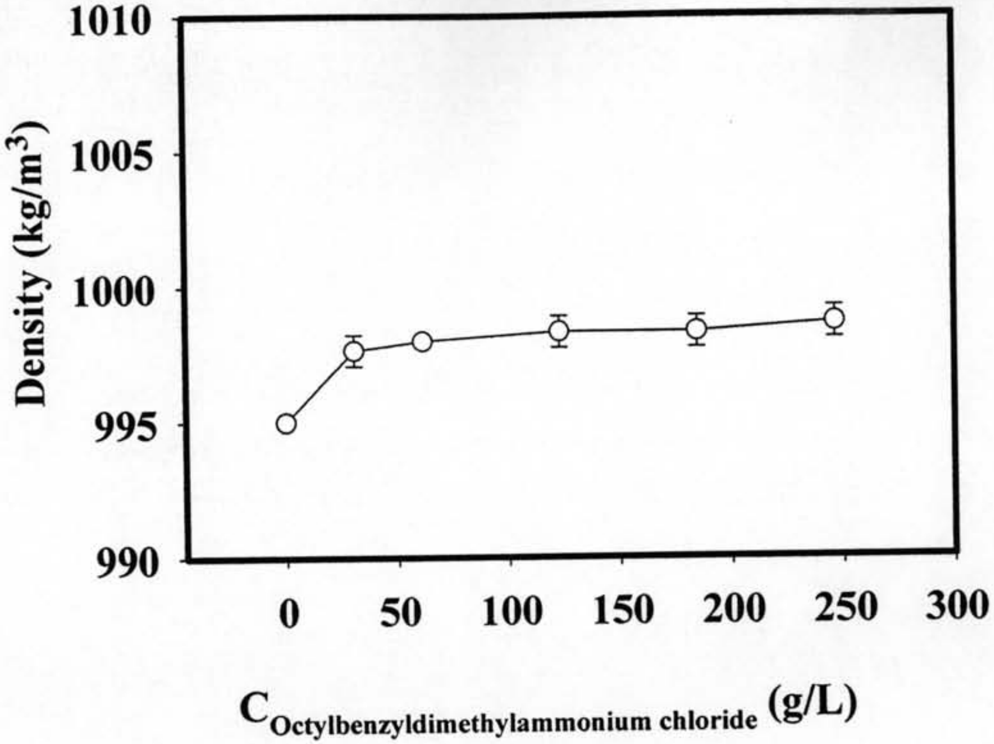


Figure E1 Octylbenzyldimethylammonium chloride solution density.

Table E2 Determination the viscosity of solution by Cannon-Ubbelohe viscometer

Procedure to determine the viscosity of solution:

1. Use the Cannon-Ubbelohde viscometer size no. 50 which has the approximate constant equal to 0.004 (Figure E2).
2. Fill the solution into Cannon-Ubbelohde viscometer.
3. Mount the Cannon-Ubbelohde viscometer in the constant-temperature (31±0.3 °C) bath and keeping the tube vertical.
4. Apply vacuum to tube N and closing tube M by a finger or rubber stopper to make the solution filling upper bulb D.
5. Let the solution flow by gravitation and timing the level of solution from mark E to mark F. Use the time average value for calculating the kinematic viscosity.
6. Calculate the kinematic viscosity (ν) by using equation:

$$\text{Kinematic viscosity } (\nu),\ mm^2/s = \text{Time(s)} \times \text{approximate constant } ((mm^2/s)/s) \qquad (E2)$$

7. Calculate the viscosity (μ) by using equation:

$$\mu = \upsilon\rho \qquad (E3)$$

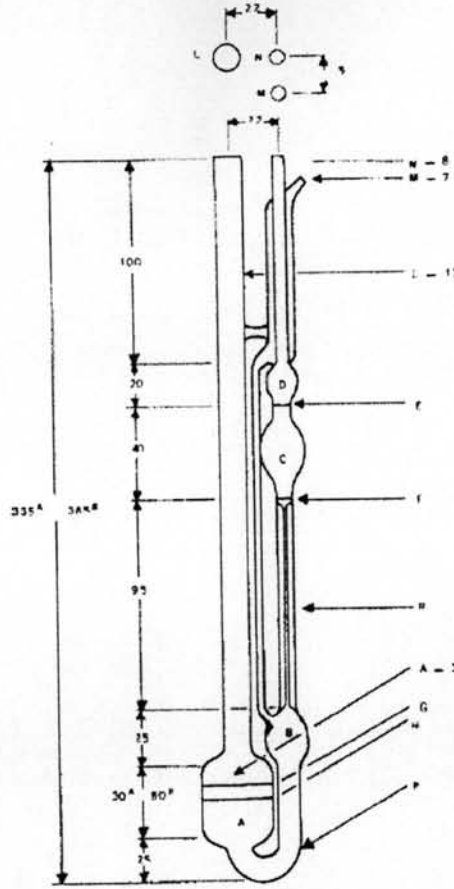


Figure E2 Cannon-Ubbelohde (ASTM D 446-04).

Conc. (g/L)	Time (sec)			Time average (sec)	Kinematic viscosity (v), m^2/s			Average kinematic viscosity (v), (m^2/s)	Viscosity (μ), Pa.s			Average viscosity (μ), Pa.s
	1	2	3		1	2	3		1	2	3	
0	214.5	214.7	214.3	214.5 ± 0.18	8.6E-07	8.6E-07	8.6E-07	8.6E-07 ± 7E-10	0.00085	0.00085	0.00085	0.00085 ± 7.2E-07
30.8	231.9	233.0	231.0	232.0 ± 0.97	9.3E-07	9.3E-07	9.2E-07	9.3E-07 ± 4E-09	0.00093	0.00093	0.00092	0.00093 ± 3.9E-06
61.6	243.2	243.6	244.8	243.8 ± 0.85	9.7E-07	9.7E-07	9.8E-07	9.8E-07 ± 3E-09	0.00097	0.00097	0.00098	0.00097 ± 3.4E-06
123	298.7	297.4	297.3	297.8 ± 0.76	1.2E-06	1.2E-06	1.2E-06	1.2E-06 ± 3E-09	0.00119	0.00119	0.00119	0.00119 ± 3E-06
185	328.8	331.0	329.4	329.7 ± 1.12	1.3E-06	1.3E-06	1.3E-06	1.3E-06 ± 4E-09	0.00131	0.00132	0.00132	0.00132 ± 4.5E-06
246	359.7	357.3	358.4	358.5 ± 1.21	1.4E-06	1.4E-06	1.4E-06	1.4E-06 ± 5E-09	0.00144	0.00143	0.00143	0.00143 ± 4.8E-06

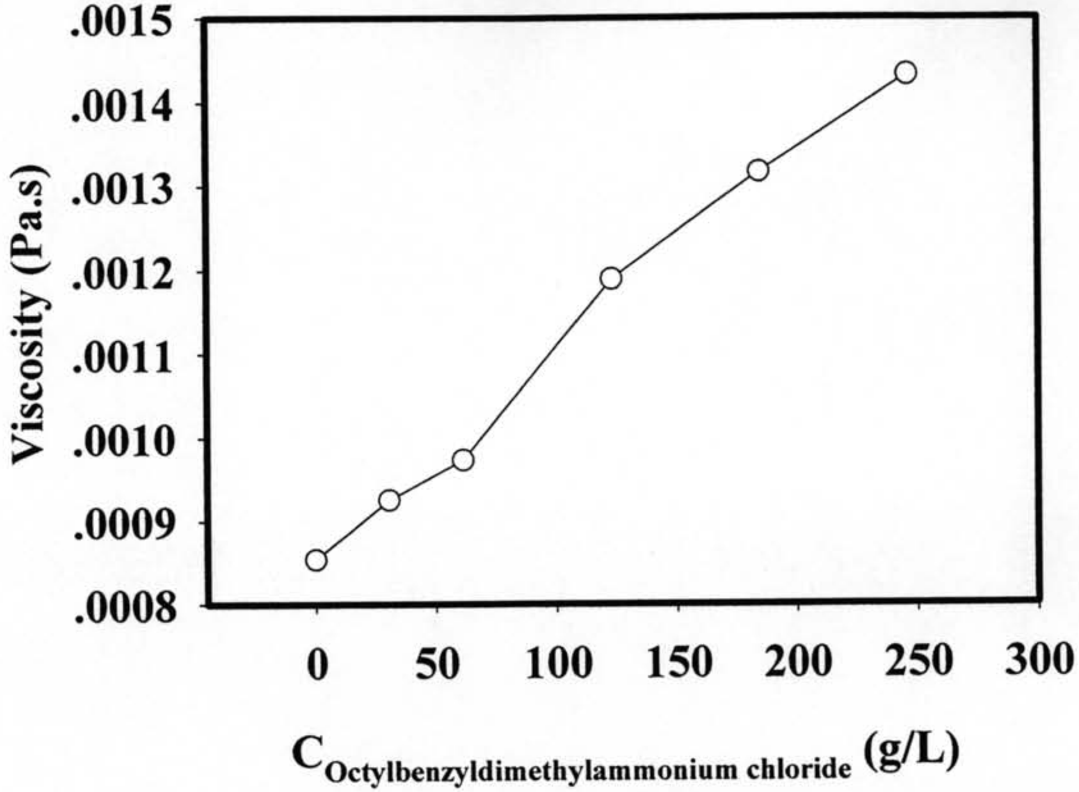


Figure E3 Octylbenzyldimethylammonium chloride solution viscosity.

Table E3 Determination the electrical conductivity of solution by TDS meter

Procedure to determine the electrical conductivity of solution:

1. Fill the empty dry beaker with the solution.
2. Put the probe of the TDS meter (ORION model 124) in the solution to measure the electrical conductivity.
3. Read the value from the monitor.

Conc. (g/L)	Conductivity (µS/cm)			Average conductivity (µS/cm)
	1	2	3	
0	1.3	1.3	1.3	1.3 ± 0
0.13	22.4	22.4	22.4	22.4 ± 0
0.28	49.9	49.9	49.9	49.9 ± 0
0.54	86.7	86.7	86.7	86.7 ± 0
0.77	123.1	123.1	123.1	123 ± 0
1.05	162.9	163	162.9	163 ± 0.06
2.53	410	410	410	410 ± 0
5.12	746	746	746	746 ± 0
7.62	1129	1127	1129	1128 ± 1.15
10.2	1479	1480	1480	1480 ± 0.58
25.0	3300	3300	3300	3300 ± 0
30.1	3940	3940	3940	3940 ± 0
40.2	5060	5060	5060	5060 ± 0
50.1	6170	6170	6170	6170 ± 0
60.2	7240	7240	7240	7240 ± 0
76.2	8670	8670	8670	8670 ± 0
80.1	8930	8930	8930	8930 ± 0
91.1	9960	9960	9960	9960 ± 0
100	10630	10630	10630	10630 ± 0

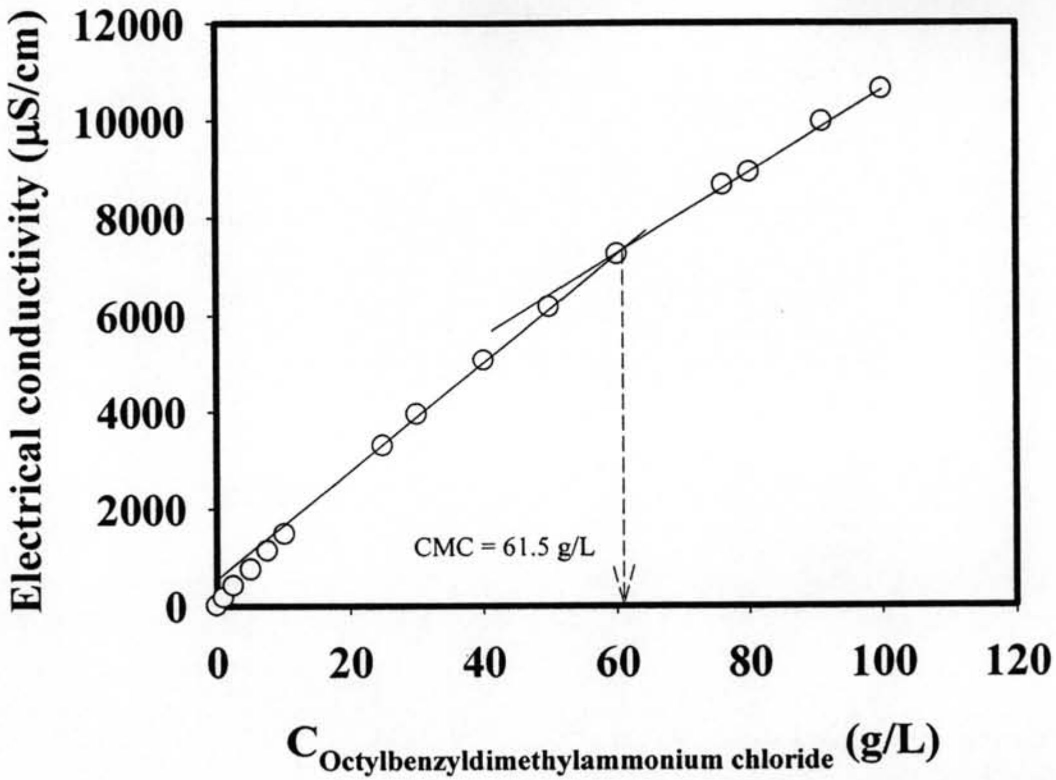


Figure E4 Octylbenzyldimethylammonium chloride solution electrical conductivity.

Table E4 Determination the surface tension of solution by Tensiometer

Procedure to determine the surface tension of solution:

1. Fill the empty dry beaker with the solution.
2. Put the beaker with the solution into Tensiometer (Dataphysics, Germany, model DCAT 11, Serial G01 Bogo 2 F97c)
3. Read the value from the monitor.

Conc. (g/L)	Surface tension (mN/m)			Average surface tension (mN/m)
	1	2	3	
5.06	47.23	47.23	47.23	47.23 ± 0.0012
17.0	40.54	40.54	40.54	40.54 ± 0.0015
30.8	34.86	34.52	34.52	34.64 ± 0.1949
61.6	30.66	30.66	30.66	30.66 ± 0.0006
68.2	30.73	30.73	30.73	30.73 ± 0.0000
102	32.36	32.36	32.36	32.36 ± 0.0017
123	33.85	33.85	33.86	33.85 ± 0.0055
136	34.37	34.38	34.38	34.38 ± 0.0035
185	35.85	35.85	35.85	35.85 ± 0.0012
246	35.85	35.85	35.84	35.85 ± 0.0035

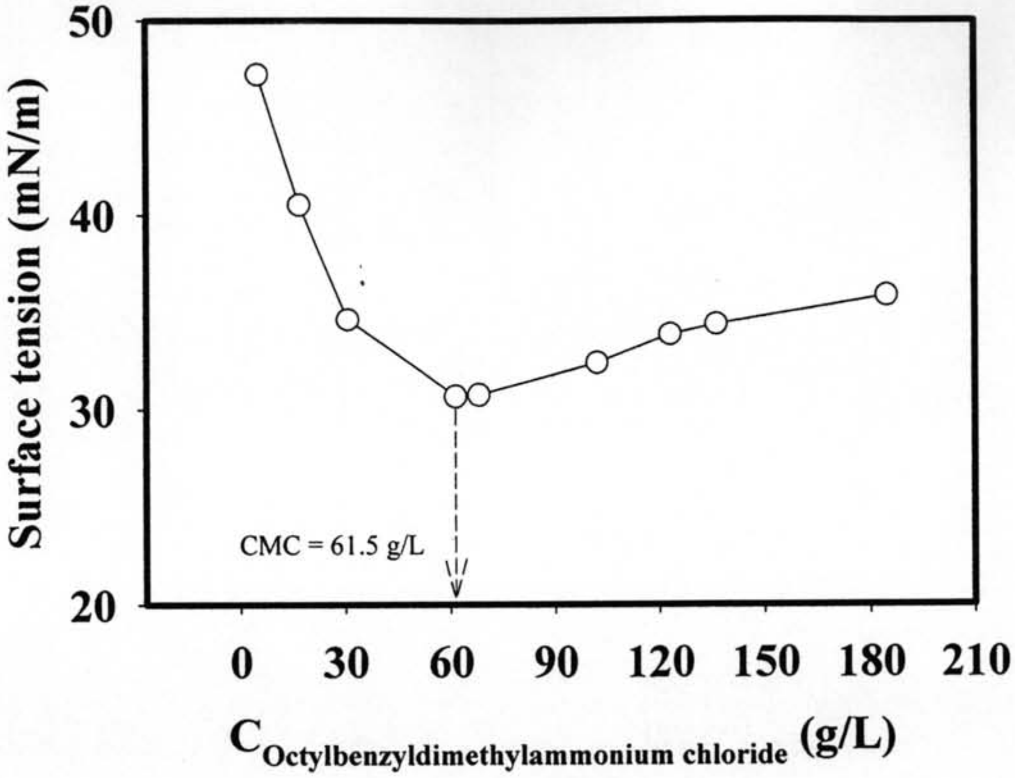


Figure E5 Octylbenzyldimethylammonium chloride solution surface tension.

Appendix F Physical Properties of Dodecylbenzyldimethylammonium Chloride Surfactant ($C_{12}H_{25}$-$N^+(CH_3)_2$-CH_2-C_6H_5 Cl^-)

Table F1 Determination the density of solution by using Syringe (SGE, Australia)

Procedure to determine the density of solution:

1. Weigh the empty dry beaker and record the mass.
2. Fill the beaker with solution by using syringe (100 μL) and take the mass of the filled beaker.
3. The difference between the mass of the empty beaker and the beaker when it is filled with the mass of the solution.
4. Knowing the mass of the solution and the volume of the solution (100μL), the density of the solution can be calculated

using the equation:

$$\rho = \frac{M}{V} \qquad \text{(F1)}$$

Note: system temperature, T = 31±0.3 °C

Conc. (g/L)	Empty bottle (g)			Average (g)	Empty bottle + solution (g)			Average (g)	Solution weight (g)			Average solution weight (g)	Density (ρ), kg/m^3			Average density (ρ), kg/m^3
	1	2	3		1	2	3		1	2	3		1	2	3	
2.88	53.53	53.53	53.53	53.53 ± 0.0014	53.63	53.63	53.63	53.63 ± 0.0014	0.0996	0.0996	0.0995	0.0996 ± 6E-05	996	996	995	995.7 ± 0.58
5.8	54.36	54.36	54.36	54.36 ± 0.0003	54.46	54.46	54.46	54.46 ± 0.0003	0.0998	0.0997	0.0997	0.0997 ± 6E-05	998	997	997	997.3 ± 0.58
11.7	54.36	54.36	54.36	54.36 ± 0.0005	54.46	54.46	54.46	54.46 ± 0.0004	0.0998	0.0997	0.0998	0.0998 ± 6E-05	998	997	998	997.7 ± 0.58
17.5	54.36	54.36	54.35	54.36 ± 0.0056	54.46	54.46	54.45	54.46 ± 0.0056	0.0998	0.0997	0.0999	0.0998 ± 1E-04	998	997	999	998.0 ± 1
23.2	54.35	54.35	54.35	54.35 ± 0.0008	54.45	54.45	54.45	54.45 ± 0.0008	0.0999	0.0998	0.0998	0.0998 ± 6E-05	999	998	998	998.3 ± 0.58

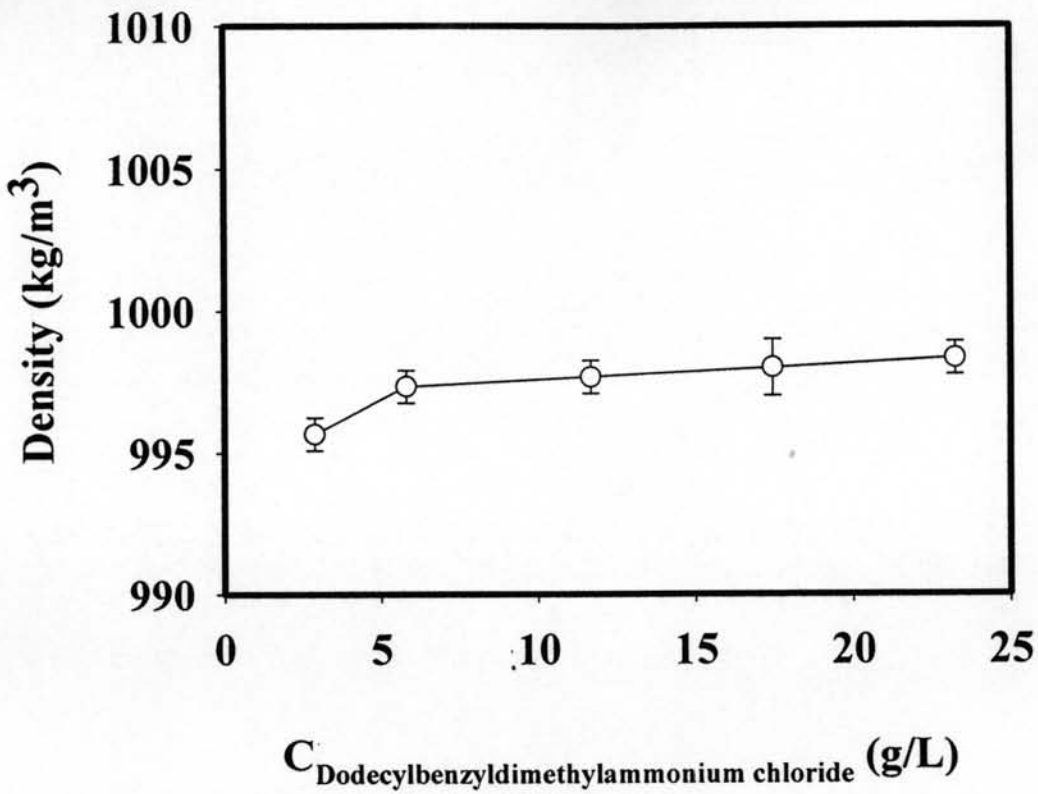


Figure F1 Dodecylbenzyldimethylammonium chloride solution density.

Table F2 Determination the viscosity of solution by Cannon-Ubbelohe viscometer

Procedure to determine the viscosity of solution:

1. Use the Cannon-Ubbelohde viscometer size no. 50 which has the approximate constant equal to 0.004 (Figure F2).
2. Fill the solution into Cannon-Ubbelohde viscometer.
3. Mount the Cannon-Ubbelohde viscometer in the constant-temperature (31±0.3 °C) bath and keeping the tube vertical.
4. Apply vacuum to tube N and closing tube M by a finger or rubber stopper to make the solution filling upper bulb D.
5. Let the solution flow by gravitation and timing the level of solution from mark E to mark F. Use the time average value for calculating the kinematic viscosity.
6. Calculate the kinematic viscosity (v) by using equation:

$$\text{Kinematic viscosity } (v), \text{mm}^2/\text{s} = \text{Time(s)} \times \text{approximate constant } ((\text{mm}^2/\text{s})/\text{s}) \quad \text{(F2)}$$

7. Calculate the viscosity (μ) by using equation:

$$\mu = \upsilon\rho \quad \text{(F3)}$$

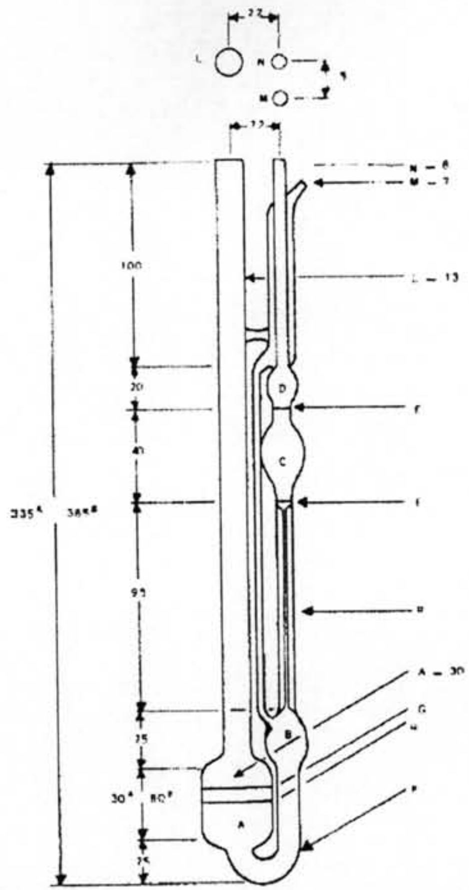


Figure F2 Cannon-Ubbelohde (ASTM D 446-04).

Conc. (g/L)	Time (sec)			Time average (sec)	Kinematic viscosity (v), m^2/s			Average kinematic viscosity (v), (m^2/s)	Viscosity (μ), Pa.s			Average viscosity (μ), Pa.s
	1	2	3		1	2	3		1	2	3	
2.88	249.1	248.4	248.8	248.8 ± 0.31	1E-06	9.9E-07	1E-06	1E-06 ± 1E-09	0.00099	0.00099	0.00099	0.00099 ± 1.2E-06
5.81	251.7	251.1	251.4	251.4 ± 0.29	1E-06	1E-06	1E-06	1E-06 ± 1E-09	0.00100	0.00100	0.00100	0.00100 ± 1.2E-06
11.7	256.4	257.9	256.7	257.0 ± 0.78	1E-06	1E-06	1E-06	1E-06 ± 3E-09	0.00102	0.00103	0.00102	0.00103 ± 3.1E-06
17.5	267.4	265.8	265.3	266.2 ± 1.13	1.1E-06	1.1E-06	1.1E-06	1.1E-06 ± 5E-09	0.00107	0.00106	0.00106	0.00106 ± 4.5E-06
23.2	271.8	272.1	272.7	272.2 ± 0.45	1.1E-06	1.1E-06	1.1E-06	1.1E-06 ± 2E-09	0.00109	0.00109	0.00109	0.00109 ± 1.8E-06

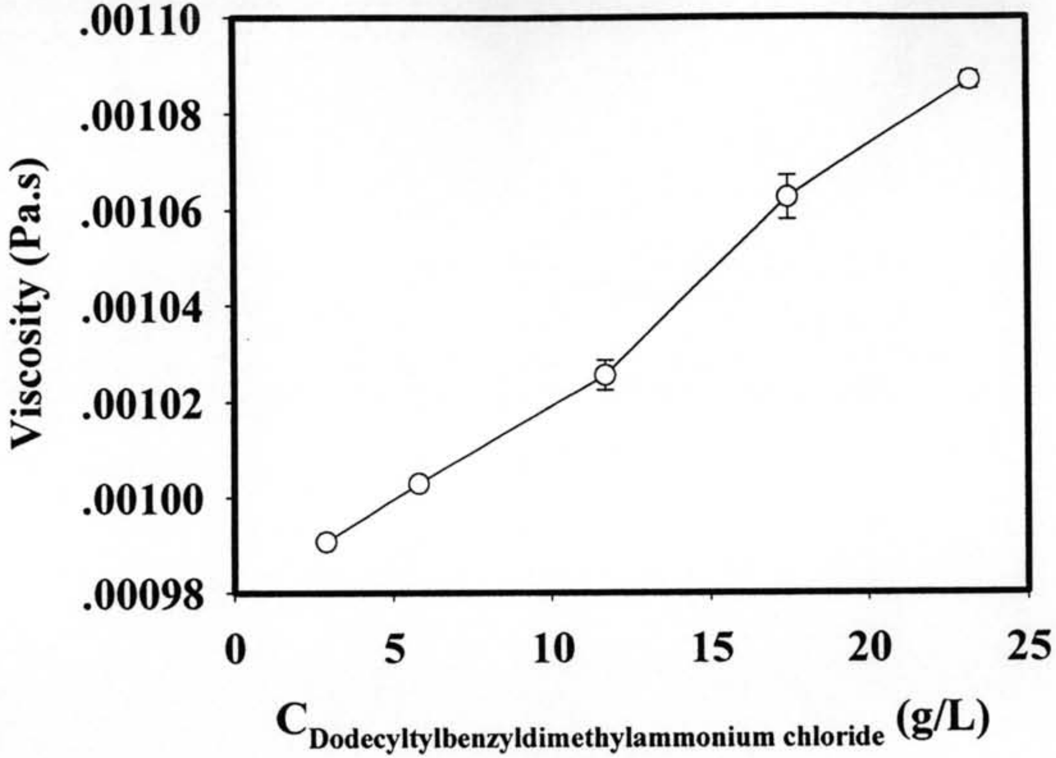


Figure F3 Dodecylbenzyldimethylammonium chloride solution viscosity.

Table F3 Determination the electrical conductivity of solution by TDS meter

Procedure to determine the electrical conductivity of solution:

1. Fill the empty dry beaker with the solution.
2. Put the probe of the TDS meter (ORION model 124) in the solution to measure the electrical conductivity.
3. Read the value from the monitor.

Conc. (g/L)	Conductivity (μS/cm)			Average conductivity (μS/cm)
	1	2	3	
0.00	1.3	1.3	1.3	1.3 ± 0
0.01	9.2	9.2	9.2	9.2 ± 0
0.06	16.1	16.1	16.1	16.1 ± 0
0.12	23.3	23.3	23.3	23.3 ± 0
0.64	88	88	88	88 ± 0
1.01	134	134	134	133.8 ± 0.12
2.07	287	285	285	285.7 ± 1.15
2.57	345	345	345	345 ± 0
3.11	406	406	406	406 ± 0
3.54	471	469	473	471 ± 2
4.01	518	516	516	516.7 ± 1.15
4.55	581	581	581	581 ± 0
5.00	639	639	639	639 ± 0
5.05	645	645	645	645 ± 0
6.05	722	722	722	722 ± 0
7.10	799	799	799	799 ± 0
8.00	871	871	871	871 ± 0
9.14	936	936	936	936 ± 0
10.1	965	965	965	965 ± 0
100	5640	5640	5640	5640 ± 0

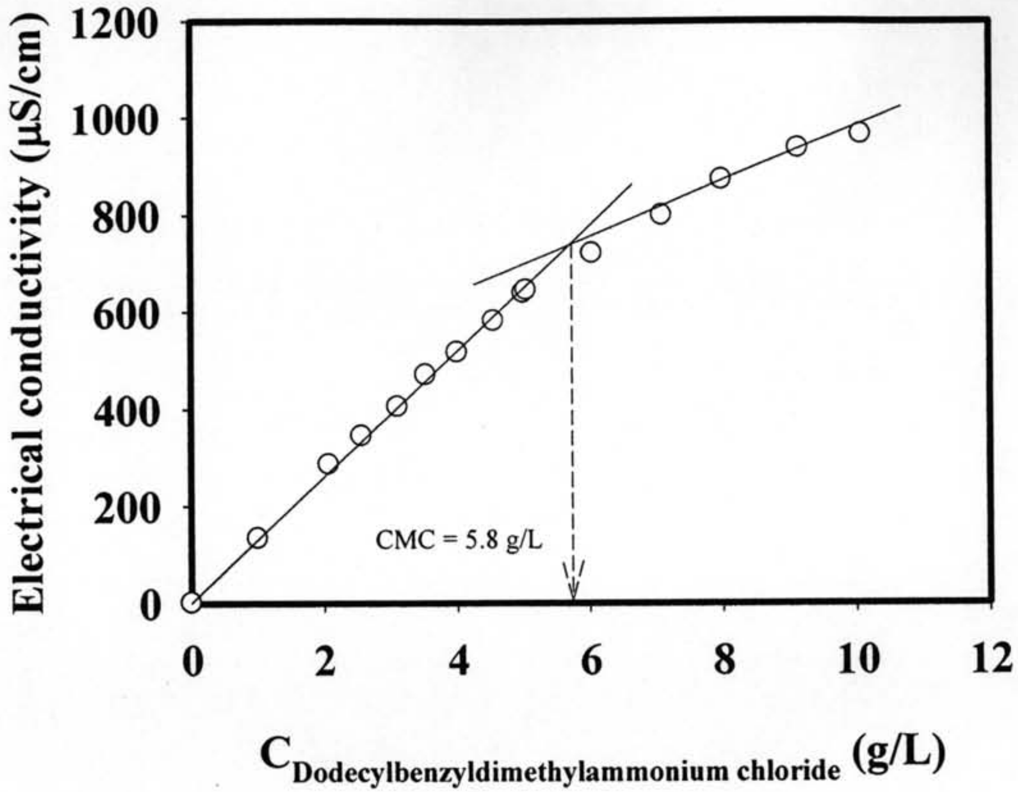


Figure F4 Dodecylbenzyldimethylammonium chloride solution electrical conductivity.

Table F4 Determination the surface tension of solution by Tensiometer

Procedure to determine the surface tension of solution:

1. Fill the empty dry beaker with the solution.
2. Put the beaker with the solution into Tensiometer (Dataphysics, Germany, model DCAT 11, Serial G01 Bogo 2 F97c)
3. Read the value from the monitor.

Conc. (g/L)	Surface tension (mN/m)			Average surface tension (mN/m)
	1	2	3	
0.01	53.53	53.50	53.50	53.51 ± 0.017
0.12	49.62	49.68	49.63	49.64 ± 0.028
0.64	38.99	38.99	38.99	38.99 ± 0.002
1.08	34.50	34.50	34.50	34.50 ± 0.002
2.88	29.06	29.06	29.06	29.06 ± 0.001
5.81	29.03	29.01	29.05	29.03 ± 0.018
7.25	29.28	29.28	29.28	29.28 ± 0.005
10.1	34.09	34.09	34.09	34.09 ± 6E-04
11.7	34.34	34.34	34.35	34.34 ± 0.007
17.5	34.26	34.26	34.25	34.26 ± 0.002
23.2	34.30	34.30	34.29	34.30 ± 0.005

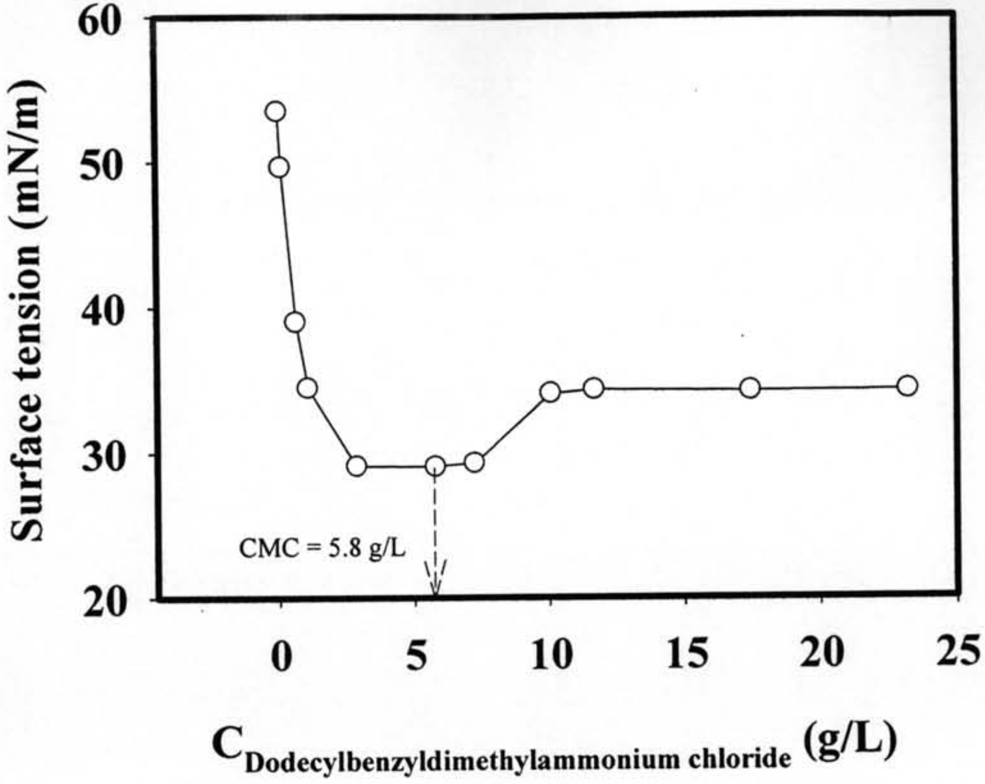


Figure F5 Dodecylbenzyldimethylammonium chloride solution surface tension.

Appendix G Physical Properties of Hexadecylbenzyldimethylammonium Chloride Surfactant ($C_{16}H_{33}$-$N^{+}(CH_3)_2$-CH_2-C_6H_5 Cl^{-})

Table G1 Determination the density of solution by using Syringe (SGE, Australia)

Procedure to determine the density of solution:

1. Weigh the empty dry beaker and record the mass.
2. Fill the beaker with solution by using syringe (100 μL) and take the mass of the filled beaker.
3. The difference between the mass of the empty beaker and the beaker when it is filled with the mass of the solution.
4. Knowing the mass of the solution and the volume of the solution (100μL), the density of the solution can be calculated

using the equation:

$$\rho = \frac{M}{V} \tag{G1}$$

Note: system temperature, T = 31±0.3 °C

Conc. (g/L)	Empty bottle (g)			Average (g)	Empty bottle + solution (g)			Average (g)	Solution weight (g)			Average solution weight (g)	Density (ρ), kg/m³			Average density (ρ), kg/m³
	1	2	3		1	2	3		1	2	3		1	2	3	
0.18	45.22	45.22	45.22	45.22 ± 0.0002	45.32	45.32	45.32	45.32 ± 0.0002	0.0996	0.0996	0.0997	0.0996 ± 0.0001	996	996	997	996.3 ± 0.58
0.38	45.22	45.22	45.22	45.22 ± 0.0002	45.32	45.32	45.32	45.32 ± 0.0003	0.0996	0.0997	0.0999	0.0997 ± 0.0002	996	997	999	997.3 ± 1.53
0.72	45.22	45.22	45.22	45.22 ± 0.0002	45.32	45.32	45.32	45.32 ± 0.0002	0.0998	0.0997	0.0998	0.0998 ± 0.0001	998	997	998	997.7 ± 0.58
1.11	45.22	45.22	45.22	45.22 ± 0.0002	45.32	45.32	45.32	45.32 ± 0.0002	0.0998	0.0997	0.0998	0.0998 ± 0.0001	998	997	998	997.7 ± 0.58
1.45	45.22	45.22	45.22	45.22 ± 0.0003	45.32	45.32	45.32	45.32 ± 0.0003	0.0999	0.0998	0.0999	0.0999 ± 0.0001	999	998	999	998.7 ± 0.58

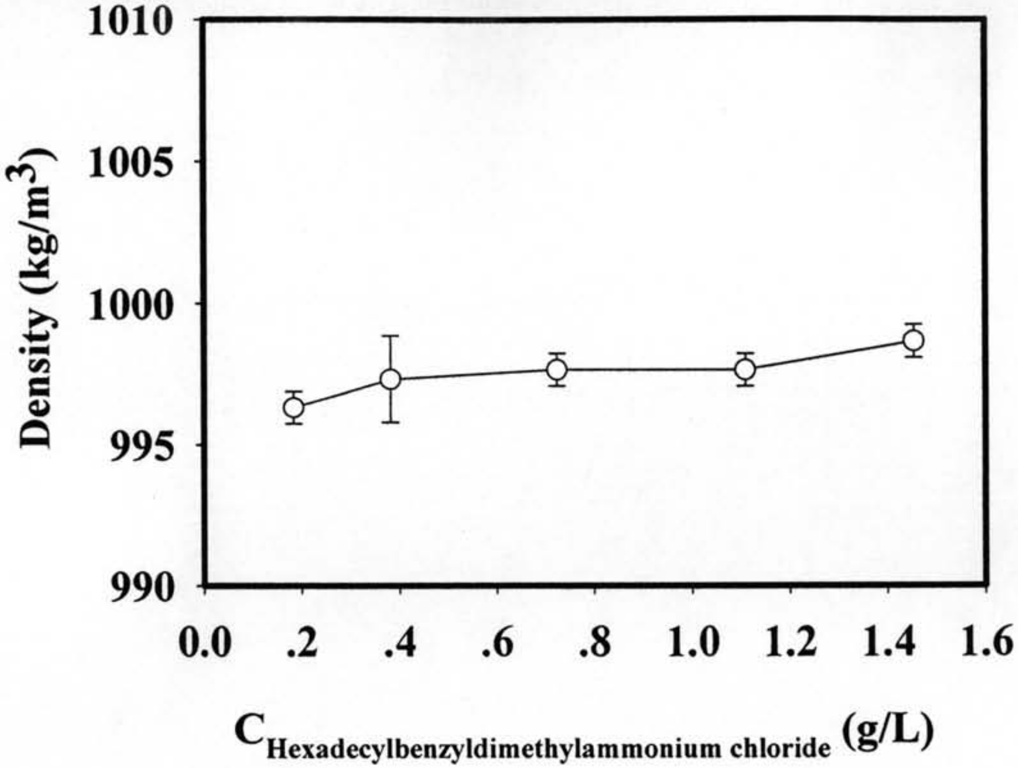


Figure G1 Hexadecylbenzyldimethylammonium chloride solution density.

Table G2 Determination the viscosity of solution by Cannon-Ubbelohe viscometer

Procedure to determine the viscosity of solution:

1. Use the Cannon-Ubbelohde viscometer size no. 50 which has the approximate constant equal to 0.004 (Figure G2).
2. Fill the solution into Cannon-Ubbelohde viscometer.
3. Mount the Cannon-Ubbelohde viscometer in the constant-temperature (31±0.3 °C) bath and keeping the tube vertical.
4. Apply vacuum to tube N and closing tube M by a finger or rubber stopper to make the solution filling upper bulb D.
5. Let the solution flow by gravitation and timing the level of solution from mark E to mark F. Use the time average value for calculating the kinematic viscosity.
6. Calculate the kinematic viscosity (v) by using equation:

$$\text{Kinematic viscosity } (v),\ mm^2/s = \text{Time(s)} \times \text{approximate constant } ((mm^2/s)/s) \quad \text{(G2)}$$

7. Calculate the viscosity (μ) by using equation:

$$\mu = \upsilon\rho \quad \text{(G3)}$$

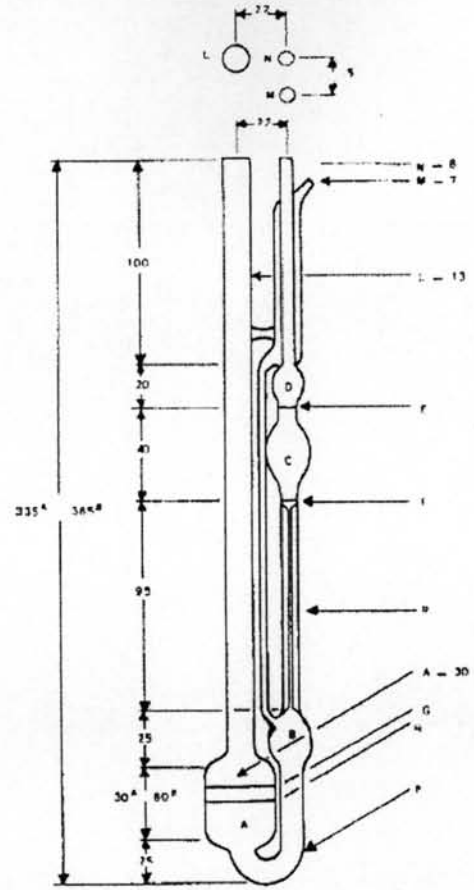


Figure G2 Cannon-Ubbelohde (ASTM D 446-04).

Conc. (g/L)	Time (sec)			Time average (sec)	Kinematic viscosity (ν), m^2/s			Average kinematic viscosity (ν), (m^2/s)	Viscosity (μ), Pa.s			Average viscosity (μ), Pa.s
	1	2	3		1	2	3		1	2	3	
0.18	263.5	261.3	262.3	262.4 ± 1.09	1.1E-06	1E-06	1E-06	1E-06 ± 4E-09	0.00105	0.00104	0.00105	0.00105 ± 4.3E-06
0.38	275.7	278.5	275.2	276.5 ± 1.76	1.1E-06	1.1E-06	1.1E-06	1.1E-06 ± 7E-09	0.00110	0.00111	0.00110	0.00110 ± 7E-06
0.72	283.0	280.1	282.5	281.9 ± 1.55	1.1E-06	1.1E-06	1.1E-06	1.1E-06 ± 6E-09	0.00113	0.00112	0.00113	0.00112 ± 6.2E-06
1.11	289.2	287.1	289.6	288.6 ± 1.34	1.2E-06	1.1E-06	1.2E-06	1.2E-06 ± 5E-09	0.00115	0.00115	0.00116	0.00115 ± 5.3E-06
1.45	294.6	296.8	295.3	295.6 ± 1.17	1.2E-06	1.2E-06	1.2E-06	1.2E-06 ± 5E-09	0.00118	0.00119	0.00118	0.00118 ± 4.7E-06

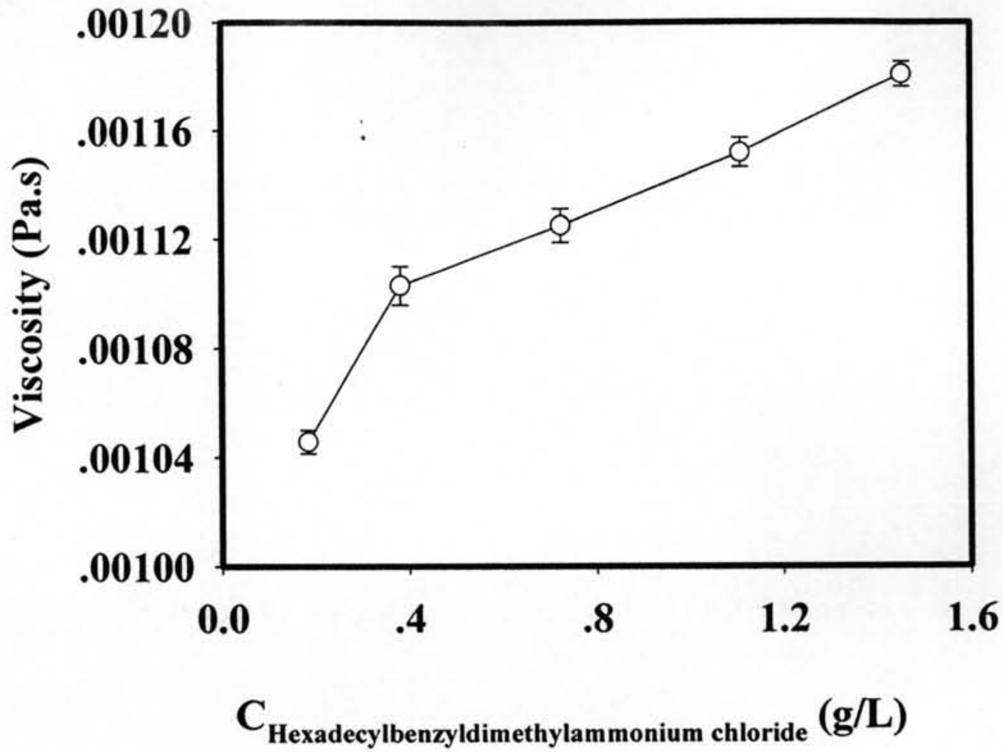


Figure G3 Hexadecylbenzyldimethylammonium chloride solution viscosity.

Table G3 Determination the electrical conductivity of solution by TDS meter

Procedure to determine the electrical conductivity of solution:

1. Fill the empty dry beaker with the solution.
2. Put the probe of the TDS meter (ORION model 124) in the solution to measure the electrical conductivity.
3. Read the value from the monitor.

Conc. (g/L)	Conductivity (µS/cm)			Average conductivity (µS/cm)
	1	2	3	
0.06	9.98	10.00	9.98	10.0 ± 0.01
0.15	21.7	21.5	21.5	21.6 ± 0.12
0.23	27.2	27.2	27.2	27.2 ± 0
0.32	37.7	37.7	37.7	37.7 ± 0
0.44	57.2	57.2	57.2	57.2 ± 0
0.59	73.4	73.6	73.4	73.5 ± 0.12
0.74	91.8	91.8	91.8	91.8 ± 0
0.81	103.4	103.4	103.4	103 ± 0
1.01	126.7	126.7	126.7	127 ± 0
1.44	171.4	171.4	171.3	171 ± 0.06
2.04	231	231	231	231 ± 0
3.02	346	344	344	345 ± 1.15
4.05	438	438	438	438 ± 0
5.06	510	510	510	510 ± 0
6.12	594	594	594	594 ± 0
7.13	666	666	666	666 ± 0
8.10	730	730	732	731 ± 1.15
9.13	798	798	798	798 ± 0
10.1	853	853	853	853 ± 0

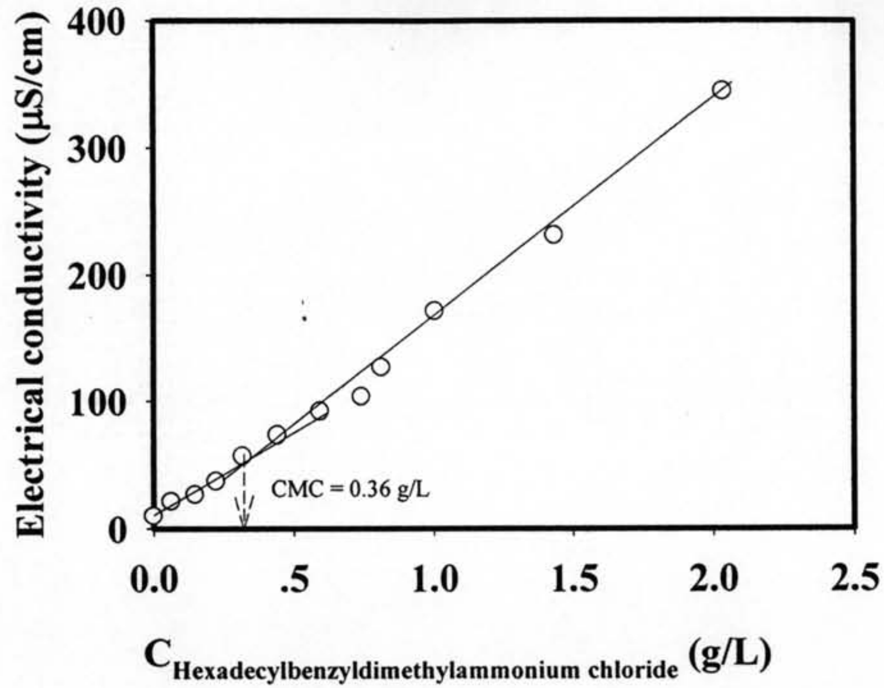


Figure G4 Hexadecylbenzyldimethylammonium chloride solution electrical conductivity.

Table G4 Determination the surface tension of solution by Tensiometer

Procedure to determine the surface tension of solution:

1. Fill the empty dry beaker with the solution.
2. Put the beaker with the solution into Tensiometer (Dataphysics, Germany, model DCAT 11, Serial G01 Bogo 2 F97c)
3. Read the value from the monitor.

Conc. (g/L)	Surface tension (mN/m)			Average surface tension (mN/m)
	1	2	3	
0.07	42.68	42.55	42.71	42.65 ± 0.086
0.16	36.58	36.64	36.55	36.59 ± 0.047
0.24	33.67	33.56	33.71	33.65 ± 0.076
0.36	31.21	31.32	31.42	31.31 ± 0.108
0.44	31.49	31.47	31.51	31.49 ± 0.021
0.49	31.75	31.68	31.67	31.70 ± 0.043
0.52	32.00	32.01	32.09	32.03 ± 0.045
0.62	32.01	32.06	32.01	32.03 ± 0.028
0.77	32.04	32.08	32.09	32.07 ± 0.025
0.94	32.35	32.54	32.39	32.42 ± 0.1
2.04	31.94	32.68	32.98	32.53 ± 0.538
3.02	32.11	32.53	32.44	32.36 ± 0.221
4.05	32.51	32.48	32.77	32.59 ± 0.156
5.06	34.37	34.54	34.65	34.52 ± 0.142
6.12	34.40	34.54	34.39	34.44 ± 0.087

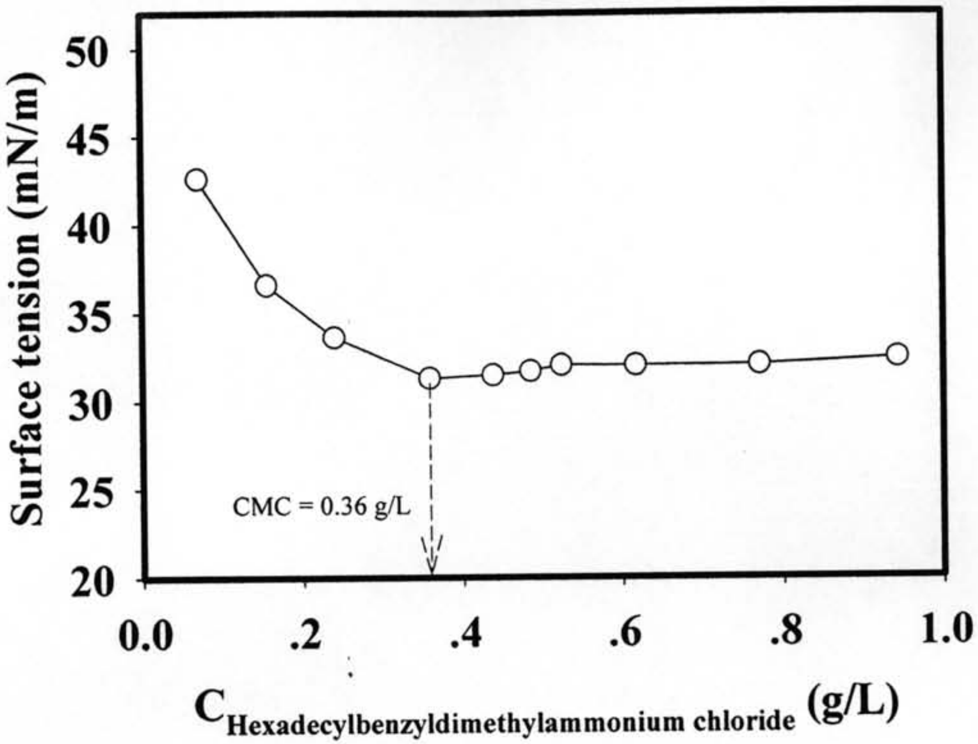


Figure G5 Hexadecylbenzyldimethylammonium chloride solution surface tension.

Appendix H Octylbenzyldimethylammonium Chloride Surfactant (1CMC) – Air Flow for the Pipe Diameter of 19 mm

Table H1 Determination of bubble size from octylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$ = 9.73×10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85×10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the bubble size:

1. Make a movie of the bubble flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the bubble size by Scion Image software program.

Equivalent diameter (D_e) of the bubble is defined as the diameter of a sphere that has the same volume as the bubble.

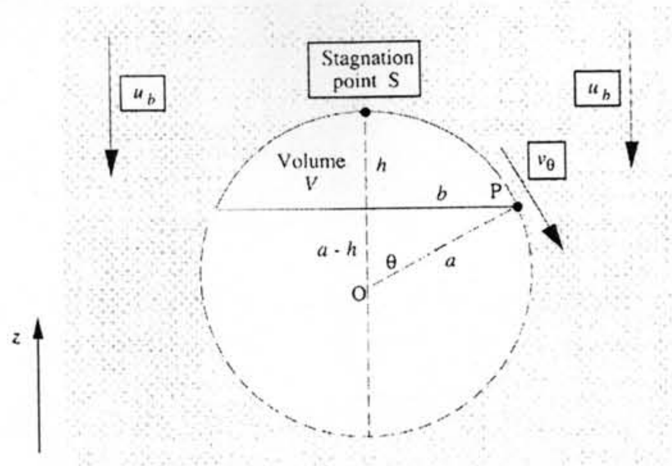


Figure H1 Flow around a spherical cap bubble (Wilkes, 1999).

$$\text{Equivalent diameter } (D_e) = \sqrt[3]{3.94h\left[\frac{h^2+b^2}{2h}\right]^2 - 1.94b^2\left[\left(\frac{h^2+b^2}{2h}\right) - h\right]} \qquad \text{(H1)}$$

$Re_{solution}$	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble width, W_b (mm)			Average bubble width (mm)	Equivalent diameter, D_e (mm)			Average equivalent diameter, De (mm)
		1	2	3		1	2	3		1	2	3	
0	3.17	14.3	15.2	15.9	15.1 ± 0.8	12.0	12.6	11.7	12.1 ± 0.4	16.4	17.4	17.7	17.2 ± 0.7
0	4.40	16.0	16.4	15.3	15.9 ± 0.5	11.4	13.1	12.3	12.3 ± 0.9	17.7	18.6	17.4	17.9 ± 0.6
0	5.64	16.3	16.0	16.6	16.3 ± 0.3	12.9	12.5	12.6	12.7 ± 0.2	18.5	18.1	18.6	18.4 ± 0.3
0	6.88	18.0	18.1	18.6	18.2 ± 0.3	13.0	13.0	12.1	12.7 ± 0.5	19.9	20.1	20.3	20.1 ± 0.2
1001	3.17	21.5	22.1	22.3	21.9 ± 0.4	12.7	13.2	12.4	12.7 ± 0.4	23.1	23.8	23.7	23.5 ± 0.4
1001	5.64	22.0	22.9	22.6	22.5 ± 0.4	12.8	12.9	12.8	12.8 ± 0.1	23.6	24.4	24.1	24.0 ± 0.4
1001	8.12	23.3	24.8	23.4	23.8 ± 0.8	13.2	12.8	13.2	13.1 ± 0.2	24.9	26.2	25.0	25.4 ± 0.7
1001	10.59	24.0	24.1	24.3	24.1 ± 0.2	13.4	13.2	12.8	13.2 ± 0.3	25.6	25.7	25.8	25.7 ± 0.1
2749	3.17	7.9	7.6	7.1	7.5 ± 0.4	10.3	11.1	8.9	10.1 ± 1.1	10.3	10.4	9.1	10.0 ± 0.7
2749	5.64	8.3	8.5	8.8	8.5 ± 0.3	10.2	11.4	10.4	10.7 ± 0.6	10.6	11.3	11.1	11.0 ± 0.4
2749	8.12	8.8	8.3	8.8	8.7 ± 0.3	11.3	11.8	11.3	11.5 ± 0.3	11.5	11.3	11.5	11.4 ± 0.1
2749	10.59	9.3	9.2	9.0	9.2 ± 0.2	11.6	11.9	11.3	11.6 ± 0.3	12.0	12.0	11.6	11.9 ± 0.2
2749	13.07	10.1	9.4	10.1	9.9 ± 0.4	12.6	11.5	12.1	12.1 ± 0.6	13.0	12.0	12.8	12.6 ± 0.5
2749	15.54	10.9	11.3	10.8	11.0 ± 0.3	12.4	11.6	12.0	12.0 ± 0.4	13.6	13.6	13.3	13.5 ± 0.2
2749	18.02	12.6	11.4	12.5	12.2 ± 0.6	12.1	12.7	11.9	12.2 ± 0.4	14.9	14.1	14.7	14.6 ± 0.4
2749	20.49	13.6	14.3	15.3	14.4 ± 0.8	12.9	12.2	13.3	12.8 ± 0.6	16.1	16.5	17.6	16.7 ± 0.8
2749	22.95	16.3	16.8	15.4	16.2 ± 0.7	13.0	12.9	13.4	13.1 ± 0.2	18.41	18.87	17.80	18.4 ± 0.5
2749	28.1	20.8	19.8	19.6	20.0 ± 0.6	13.2	12.9	13.1	13.1 ± 0.1	22.53	21.63	21.41	21.9 ± 0.6

$Re_{solution}$	Re_{air}	Bubble height / Pipe diameter			Average, R_h/D	Bubble width / Pipe diameter			Average, W_b/D	Equivalent diameter / Pipe diameter			Average equivalent diameter, De/D
		1	2	3		1	2	3		1	2	3	
0	3.17	0.75	0.80	0.84	0.80 ± 0.04	0.63	0.66	0.62	0.64 ± 0.02	0.86	0.92	0.93	0.90 ± 0.04
0	4.40	0.84	0.86	0.81	0.84 ± 0.03	0.60	0.69	0.65	0.65 ± 0.05	0.93	0.98	0.91	0.94 ± 0.03
0	5.64	0.86	0.84	0.87	0.86 ± 0.01	0.68	0.66	0.67	0.67 ± 0.01	0.97	0.95	0.98	0.97 ± 0.01
0	6.88	0.94	0.95	0.98	0.96 ± 0.02	0.69	0.69	0.64	0.67 ± 0.03	1.05	1.06	1.07	1.06 ± 0.01
1001	3.17	1.13	1.16	1.17	1.15 ± 0.02	0.67	0.69	0.65	0.67 ± 0.02	1.21	1.25	1.25	1.24 ± 0.02
1001	5.64	1.16	1.20	1.19	1.18 ± 0.02	0.67	0.68	0.67	0.68 ± 0.00	1.24	1.29	1.27	1.27 ± 0.02
1001	8.12	1.23	1.30	1.23	1.25 ± 0.04	0.70	0.68	0.69	0.69 ± 0.01	1.31	1.38	1.31	1.33 ± 0.04
1001	10.59	1.26	1.27	1.28	1.27 ± 0.01	0.71	0.70	0.67	0.69 ± 0.02	1.35	1.35	1.36	1.35 ± 0.00
2749	3.17	0.42	0.40	0.37	0.40 ± 0.02	0.54	0.59	0.47	0.53 ± 0.06	0.54	0.55	0.48	0.52 ± 0.04
2749	5.64	0.43	0.45	0.46	0.45 ± 0.01	0.54	0.60	0.55	0.56 ± 0.03	0.56	0.59	0.58	0.58 ± 0.02
2749	8.12	0.46	0.44	0.46	0.46 ± 0.01	0.59	0.62	0.60	0.60 ± 0.02	0.60	0.59	0.60	0.60 ± 0.01
2749	10.59	0.49	0.48	0.47	0.48 ± 0.01	0.61	0.62	0.60	0.61 ± 0.01	0.63	0.63	0.61	0.62 ± 0.01
2749	13.07	0.53	0.50	0.53	0.52 ± 0.02	0.66	0.60	0.64	0.63 ± 0.03	0.68	0.63	0.68	0.66 ± 0.03
2749	15.54	0.57	0.60	0.57	0.58 ± 0.01	0.65	0.61	0.63	0.63 ± 0.02	0.72	0.72	0.70	0.71 ± 0.01
2749	18.02	0.66	0.60	0.66	0.64 ± 0.03	0.64	0.67	0.63	0.64 ± 0.02	0.79	0.74	0.78	0.77 ± 0.02
2749	20.49	0.71	0.75	0.80	0.76 ± 0.04	0.68	0.64	0.70	0.67 ± 0.03	0.85	0.87	0.93	0.88 ± 0.04
2749	22.95	0.86	0.88	0.81	0.85 ± 0.04	0.68	0.68	0.70	0.69 ± 0.01	0.97	0.99	0.94	0.966 ± 0.03
2749	28.1	1.09	1.04	1.03	1.05 ± 0.03	0.69	0.68	0.69	0.69 ± 0.01	1.19	1.14	1.13	1.15 ± 0.03

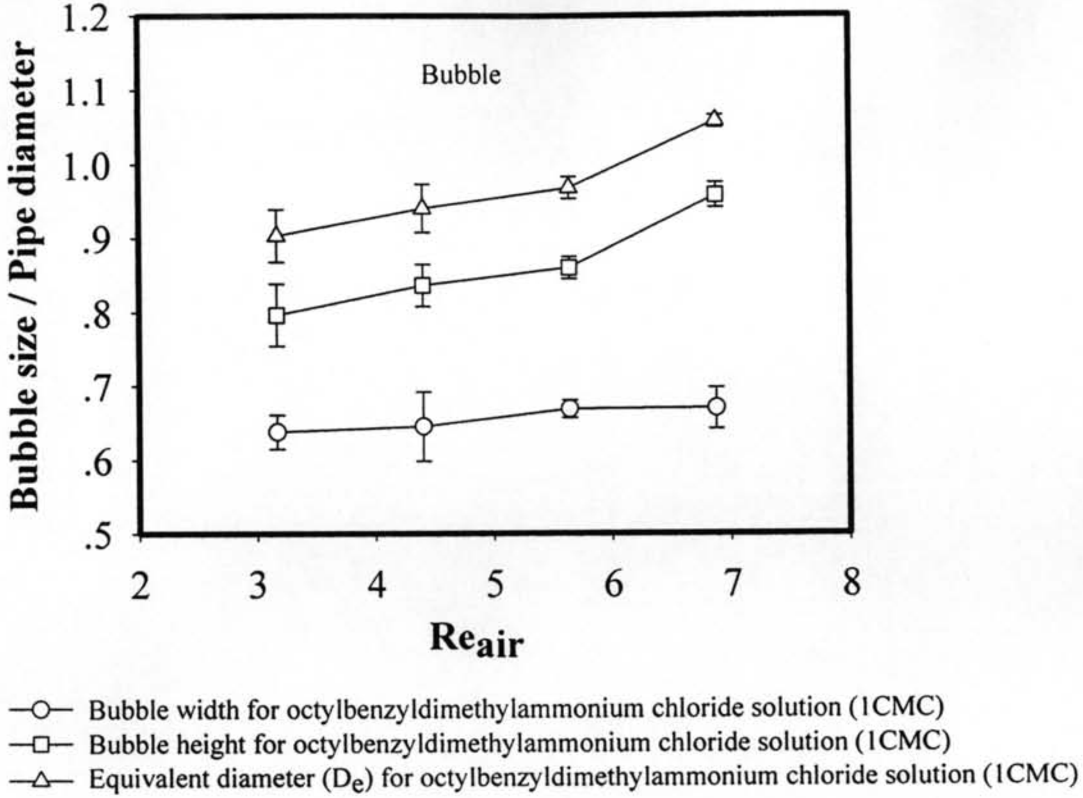


Figure H2 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) at $Re_{solution}$ = 0 by using pipe diameter of 19 mm.

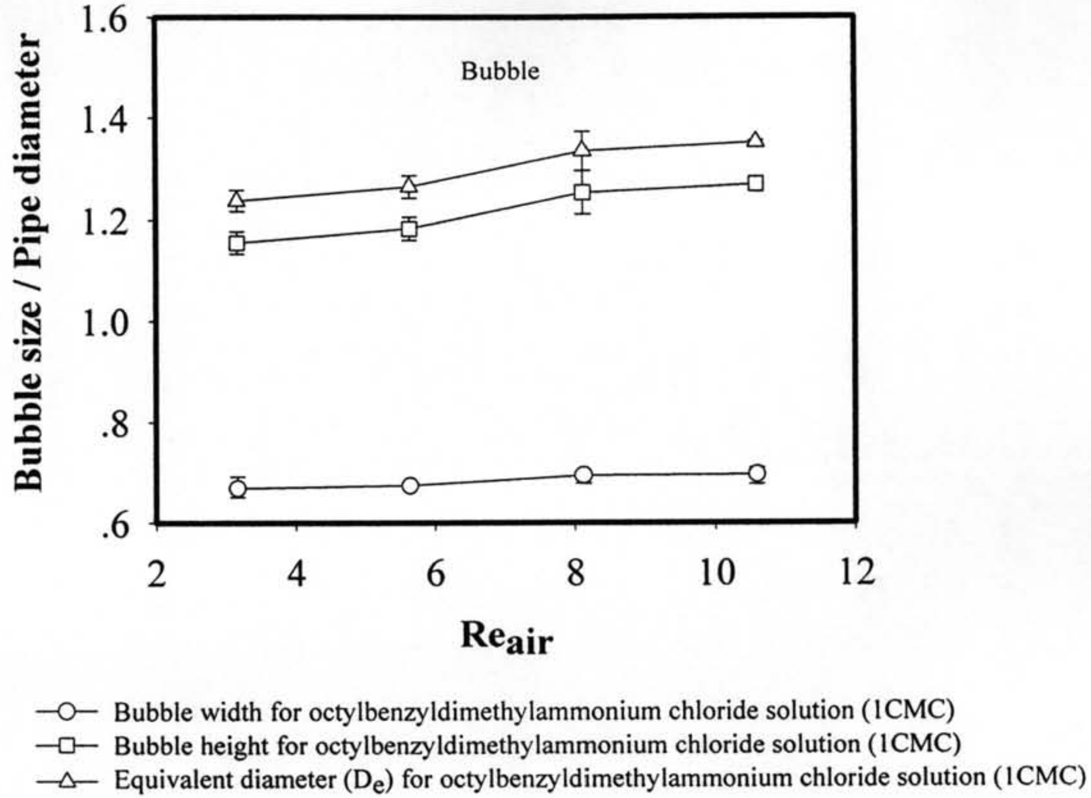


Figure H3 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) at $Re_{solution}$ = 1001 by using pipe diameter of 19 mm.

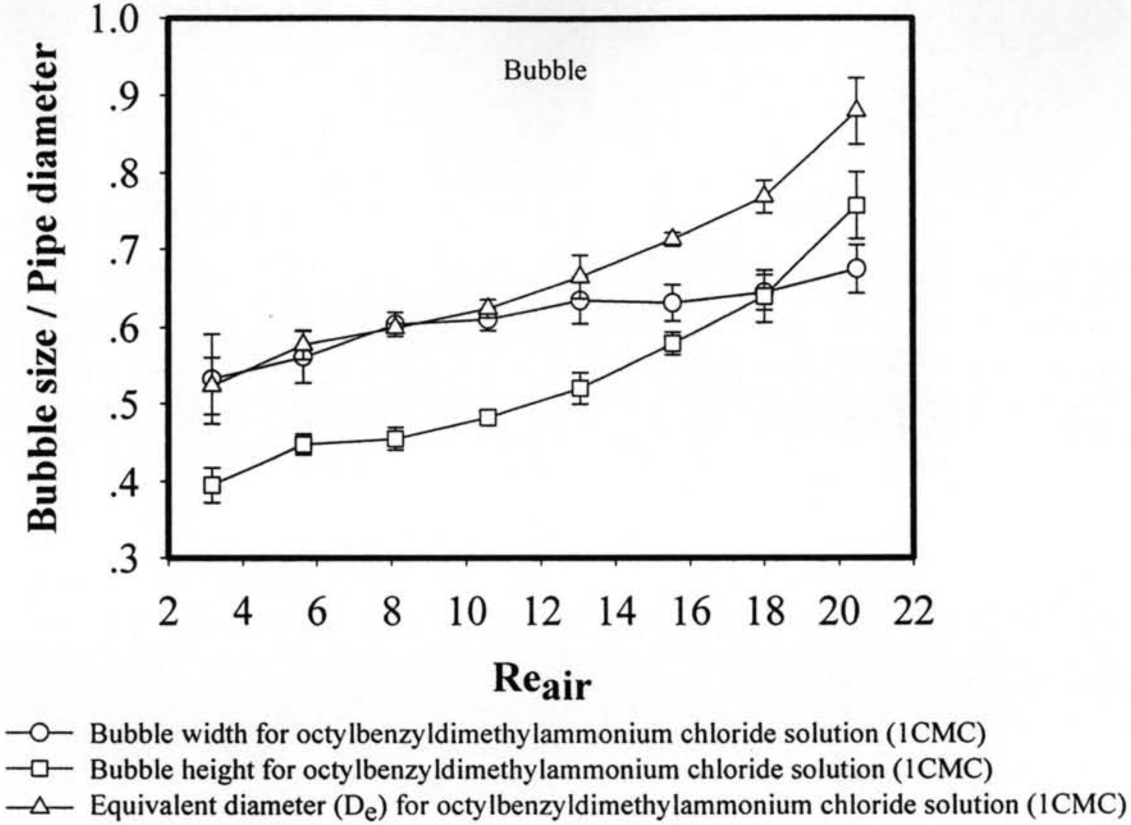


Figure H4 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) at $Re_{solution}$ = 2749 by using pipe diameter of 19 mm.

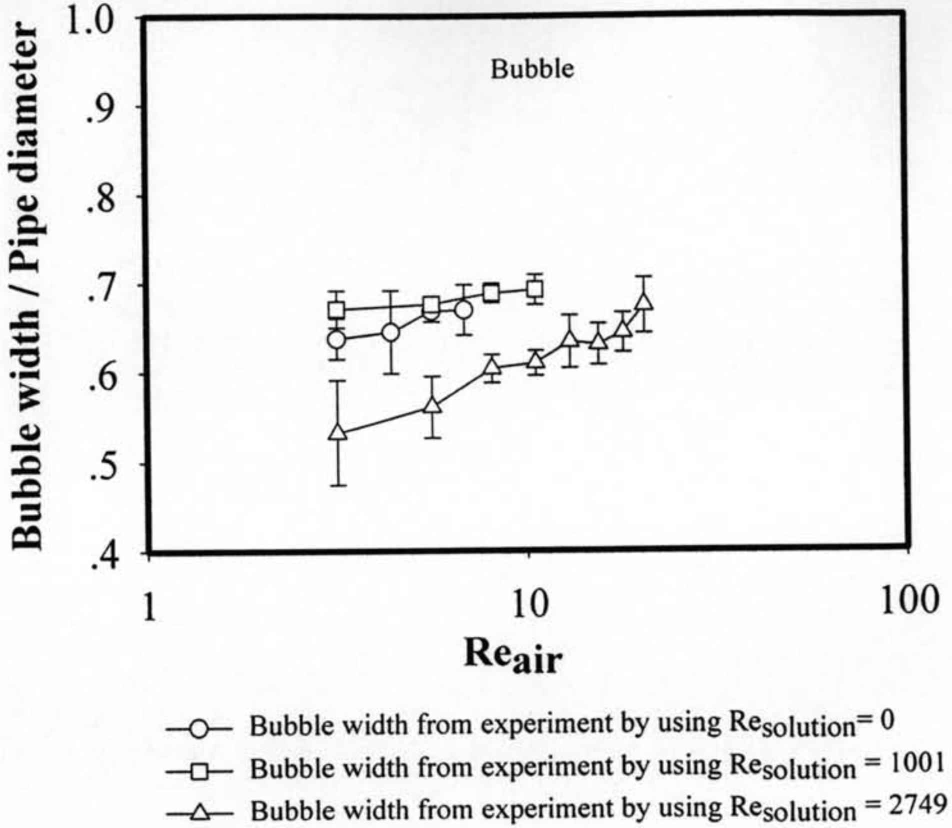


Figure H5 Bubble width from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

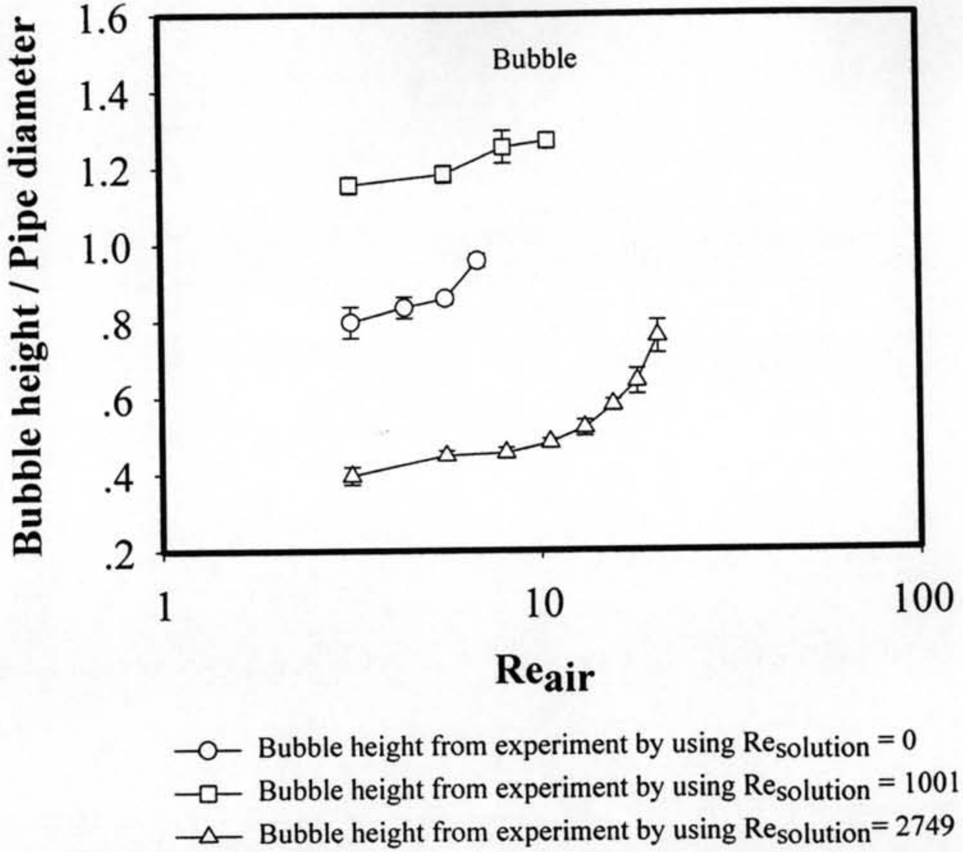


Figure H6 Bubble height from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table H2 Determination of slug height from octylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$ = 9.73×10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85×10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the slug height:

1. Make a movie of the slug flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the slug height by Scion Image software program.

$Re_{solution}$	Re_{air}	Length of Taylor bubble (L_{TB}), mm			Average length of Taylor bubble (L_{TB}), mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
0	20.49	31.3	29.7	33.9	31.6 ± 2.1	1.6	1.6	1.8	1.7 ± 0.11
0	22.95	39.3	38.6	37.1	38.3 ± 1.1	2.1	2.0	2.0	2.0 ± 0.06
0	28.08	43.8	47.5	43.1	44.8 ± 2.4	2.3	2.5	2.3	2.4 ± 0.12
0	33.21	54.9	54.2	53.5	54.2 ± 0.7	2.9	2.9	2.8	2.9 ± 0.04
0	38.33	53.8	55.3	56.1	55.1 ± 1.2	2.8	2.9	3.0	2.9 ± 0.06
0	43.46	61.8	58.8	62.5	61.0 ± 1.9	3.3	3.1	3.3	3.2 ± 0.10
0	48.59	62.9	60.0	64.3	62.4 ± 2.2	3.3	3.2	3.4	3.3 ± 0.11
0	58.85	72.1	72.9	77.9	74.3 ± 3.1	3.8	3.8	4.1	3.9 ± 0.16
0	69.10	79.0	79.8	84.7	81.2 ± 3.1	4.2	4.2	4.5	4.3 ± 0.16
0	79.36	88.0	89.0	92.0	89.7 ± 2.1	4.6	4.7	4.8	4.7 ± 0.11
0	89.62	93.3	97.5	95.4	95.4 ± 2.1	4.9	5.1	5.0	5.0 ± 0.11
0	99.87	116.5	113.0	110.0	113.2 ± 3.2	6.1	5.9	5.8	6.0 ± 0.17
1001	28.08	39.1	35.2	35.2	36.5 ± 2.3	2.1	1.9	1.9	1.9 ± 0.12
1001	33.21	41.2	41.9	40.4	41.2 ± 0.7	2.2	2.2	2.1	2.2 ± 0.04
1001	38.33	47.3	46.0	45.3	46.2 ± 1.0	2.5	2.4	2.4	2.4 ± 0.05
1001	43.46	50.0	49.3	52.1	50.5 ± 1.5	2.6	2.6	2.7	2.7 ± 0.08
1001	48.59	56.1	55.9	55.2	55.7 ± 0.5	3.0	2.9	2.9	2.9 ± 0.03
1001	58.85	59.1	59.9	59.6	59.5 ± 0.4	3.1	3.2	3.1	3.1 ± 0.02
1001	69.10	63.7	64.5	64.8	64.3 ± 0.6	3.4	3.4	3.4	3.4 ± 0.03
1001	79.36	66.4	70.4	67.6	68.1 ± 2.0	3.5	3.7	3.6	3.6 ± 0.11
1001	89.62	72.1	76.9	77.9	75.6 ± 3.1	3.8	4.0	4.1	4.0 ± 0.16
1001	99.87	84.8	86.5	87.5	86.3 ± 1.4	4.5	4.6	4.6	4.5 ± 0.07
1001	177	142.3	145.2	153.9	147.1 ± 6.0	7.5	7.6	8.1	7.7 ± 0.32
2749	43.46	34.9	36.4	34.1	35.1 ± 1.2	1.8	1.9	1.8	1.8 ± 0.06
2749	48.59	37.0	38.0	36.1	37.0 ± 0.9	1.9	2.0	1.9	1.9 ± 0.05
2749	58.85	41.0	43.0	41.0	41.7 ± 1.2	2.2	2.3	2.2	2.2 ± 0.06

$Re_{solution}$	Re_{air}	Length of Taylor bubble (L_{TB}), mm			Average length of Taylor bubble (L_{TB}), mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
2749	69.10	44.0	45.0	43.0	44.0 ± 1.0	2.3	2.4	2.3	2.3 ± 0.05
2749	79.36	48.0	49.0	48.0	48.3 ± 0.6	2.5	2.6	2.5	2.5 ± 0.03
2749	89.62	54.6	52.1	51.1	52.6 ± 1.8	2.9	2.7	2.7	2.8 ± 0.09
2749	99.87	54.2	56.3	55.2	55.2 ± 1.0	2.9	3.0	2.9	2.9 ± 0.05
2749	177	70.8	68.8	72.9	70.8 ± 2.1	3.7	3.6	3.8	3.7 ± 0.11
2749	296	137	140	139	138 ± 1.6	7.2	7.4	7.3	7.3 ± 0.08

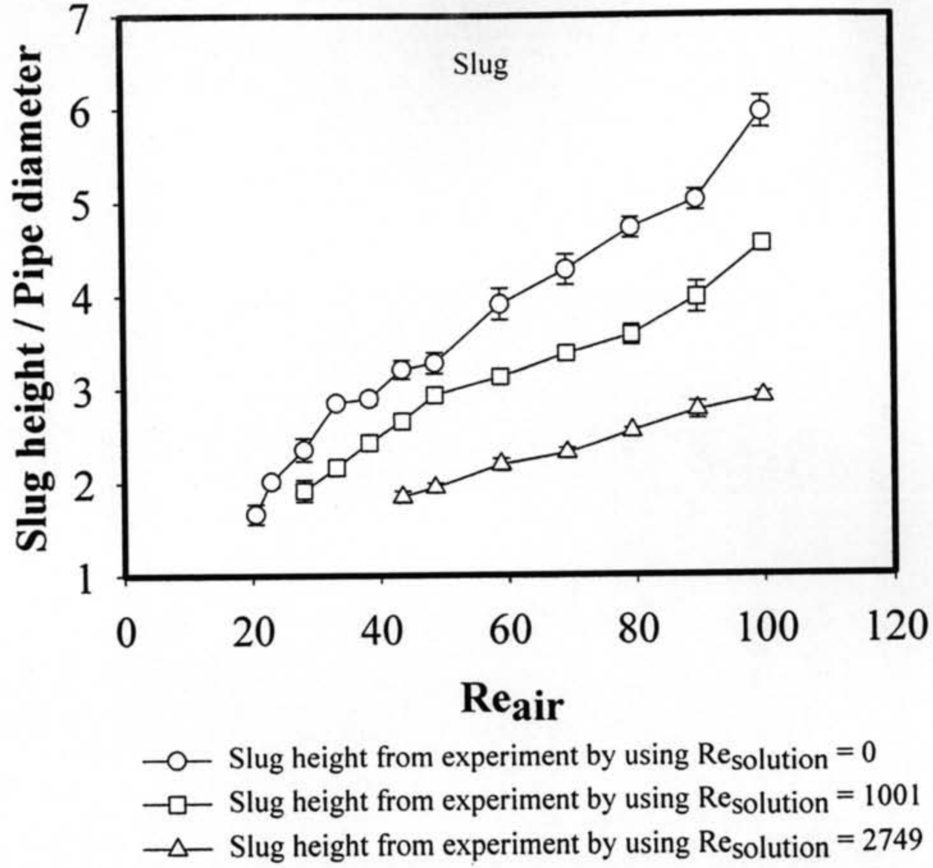


Figure H7 Slug height from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table H3 Determination of bubble and slug velocity for octylbenzyldimethylammonium chloride solution (1CMC) from Nicklin's theory and experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution} = 9.73 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Bubble velocity from theory, $$u_s = 1.2(\frac{Q_{qir} + Q_{liquid}}{A}) + 0.35\sqrt{gD} \qquad \text{(H2)}$$

Determination of bubble velocity from experiment by timing the bubble at known distance (0.8m)

$Re_{solution}$	Re_{air}	Time of bubble travel (sec)/0.8m					Average (sec/0.8 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
0	3.17	5.10	5.10	5.25	5.25	5.28	5.20 ± 0.09	0.16	0.16	0.15	0.15	0.15	0.15 ± 0.003	0.15
0	4.40	4.94	5.03	5.03	5.06	5.19	5.05 ± 0.09	0.16	0.16	0.16	0.16	0.15	0.16 ± 0.003	0.16
0	5.64	4.97	5.06	4.78	5.12	5.10	5.01 ± 0.14	0.16	0.16	0.17	0.16	0.16	0.16 ± 0.005	0.16
0	6.88	5.00	4.87	5.06	5.03	4.91	4.97 ± 0.08	0.16	0.16	0.16	0.16	0.16	0.16 ± 0.003	0.16
0	8.11	4.97	4.88	4.93	4.84	4.78	4.88 ± 0.07	0.16	0.16	0.16	0.17	0.17	0.16 ± 0.003	0.16
0	10.59	4.88	4.91	4.85	4.84	4.82	4.86 ± 0.04	0.16	0.16	0.16	0.17	0.17	0.16 ± 0.001	0.16
0	13.06	4.78	4.66	4.82	4.81	4.90	4.79 ± 0.09	0.17	0.17	0.17	0.17	0.16	0.17 ± 0.003	0.16
0	15.53	4.84	4.69	4.60	4.75	4.65	4.71 ± 0.09	0.17	0.17	0.17	0.17	0.17	0.17 ± 0.003	0.17
0	18.01	4.63	4.50	4.56	4.40	4.56	4.53 ± 0.09	0.17	0.18	0.18	0.18	0.18	0.18 ± 0.003	0.17
0	20.48	4.41	4.44	4.44	4.38	4.44	4.42 ± 0.03	0.18	0.18	0.18	0.18	0.18	0.18 ± 0.001	0.17
0	22.94	4.22	4.28	4.22	4.19	4.25	4.23 ± 0.03	0.19	0.19	0.19	0.19	0.19	0.19 ± 0.002	0.17
0	28.06	4.15	4.10	4.09	4.16	4.13	4.13 ± 0.03	0.19	0.20	0.20	0.19	0.19	0.19 ± 0.001	0.18
0	33.19	3.87	3.90	4.00	3.90	3.94	3.92 ± 0.05	0.21	0.21	0.20	0.21	0.20	0.20 ± 0.003	0.18
0	38.31	3.78	3.72	3.78	3.87	3.84	3.80 ± 0.06	0.21	0.22	0.21	0.21	0.21	0.21 ± 0.003	0.19
0	43.44	3.65	3.63	3.62	3.65	3.75	3.66 ± 0.05	0.22	0.22	0.22	0.22	0.21	0.22 ± 0.003	0.19
0	48.57	3.56	3.59	3.56	3.65	3.57	3.59 ± 0.04	0.22	0.22	0.22	0.22	0.22	0.22 ± 0.002	0.20
0	58.82	3.35	3.34	3.32	3.37	3.37	3.35 ± 0.02	0.24	0.24	0.24	0.24	0.24	0.24 ± 0.002	0.21
0	69.07	3.25	3.28	3.25	3.22	3.22	3.24 ± 0.03	0.25	0.24	0.25	0.25	0.25	0.25 ± 0.002	0.22
0	79.32	3.16	3.04	3.13	3.15	3.18	3.13 ± 0.05	0.25	0.26	0.26	0.25	0.25	0.26 ± 0.005	0.23
0	89.57	3.00	3.12	3.07	3.10	3.12	3.08 ± 0.05	0.27	0.26	0.26	0.26	0.26	0.26 ± 0.004	0.24
0	99.82	3.00	3.07	3.06	2.97	3.00	3.02 ± 0.04	0.27	0.26	0.26	0.27	0.27	0.26 ± 0.004	0.25
1001	3.17	3.66	3.66	3.63	3.63	3.65	3.65 ± 0.02	0.22	0.22	0.22	0.22	0.22	0.22 ± 0.001	0.22
1001	5.64	3.63	3.60	3.59	3.62	3.56	3.60 ± 0.03	0.22	0.22	0.22	0.22	0.22	0.22 ± 0.002	0.22
1001	8.12	3.57	3.56	3.50	3.59	3.59	3.56 ± 0.04	0.22	0.22	0.23	0.22	0.22	0.22 ± 0.002	0.22
1001	10.59	3.53	3.47	3.53	3.56	3.47	3.51 ± 0.04	0.23	0.23	0.23	0.22	0.23	0.23 ± 0.003	0.22

$Re_{solution}$	Re_{air}	Time of bubble travel (sec)/0.8m					Average (sec/0.8 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
1001	13.07	3.47	3.41	3.43	3.43	3.41	3.43 ± 0.02	0.23	0.23	0.23	0.23	0.23	0.23 ± 0.002	0.23
1001	15.54	3.40	3.47	3.40	3.37	3.37	3.40 ± 0.04	0.24	0.23	0.24	0.24	0.24	0.24 ± 0.003	0.23
1001	18.02	3.34	3.34	3.31	3.32	3.32	3.33 ± 0.01	0.24	0.24	0.24	0.24	0.24	0.24 ± 0.001	0.23
1001	20.49	3.25	3.28	3.32	3.29	3.32	3.29 ± 0.03	0.25	0.24	0.24	0.24	0.24	0.24 ± 0.002	0.23
1001	22.95	3.22	3.21	3.22	3.19	3.22	3.21 ± 0.01	0.25	0.25	0.25	0.25	0.25	0.25 ± 0.001	0.24
1001	28.08	3.10	3.12	3.15	3.15	3.13	3.13 ± 0.02	0.26	0.26	0.25	0.25	0.26	0.26 ± 0.002	0.24
1001	33.21	3.10	3.10	3.13	3.06	3.06	3.09 ± 0.03	0.26	0.26	0.26	0.26	0.26	0.26 ± 0.003	0.25
1001	38.33	3.03	3.03	2.97	3.03	2.96	3.00 ± 0.04	0.26	0.26	0.27	0.26	0.27	0.27 ± 0.003	0.25
1001	43.46	2.87	2.91	2.91	2.94	2.91	2.91 ± 0.02	0.28	0.27	0.27	0.27	0.27	0.28 ± 0.002	0.26
1001	48.59	2.84	2.85	2.84	2.79	2.78	2.82 ± 0.03	0.28	0.28	0.28	0.29	0.29	0.28 ± 0.003	0.26
1001	58.85	2.69	2.68	2.66	2.69	2.66	2.68 ± 0.02	0.30	0.30	0.30	0.30	0.30	0.30 ± 0.002	0.27
1001	69.10	2.65	2.66	2.62	2.66	2.66	2.65 ± 0.02	0.30	0.30	0.31	0.30	0.30	0.30 ± 0.002	0.28
1001	79.36	2.53	2.50	2.56	2.54	2.53	2.53 ± 0.02	0.32	0.32	0.31	0.31	0.32	0.32 ± 0.003	0.29
1001	89.62	2.50	2.44	2.50	2.44	2.50	2.48 ± 0.03	0.32	0.33	0.32	0.33	0.32	0.32 ± 0.004	0.30
1001	99.87	2.37	2.37	2.41	2.41	2.44	2.40 ± 0.03	0.34	0.34	0.33	0.33	0.33	0.33 ± 0.004	0.31
1001	177	2.03	2.00	1.97	2.06	2.09	2.03 ± 0.05	0.39	0.40	0.41	0.39	0.38	0.39 ± 0.009	0.39
2749	3.17	2.40	2.41	2.41	2.41	2.40	2.41 ± 0.01	0.33	0.33	0.33	0.33	0.33	0.33 ± 0.001	0.32
2749	5.64	2.35	2.38	2.37	2.38	2.34	2.36 ± 0.02	0.34	0.34	0.34	0.34	0.34	0.34 ± 0.003	0.33
2749	8.11	2.31	2.28	2.28	2.28	2.31	2.29 ± 0.02	0.35	0.35	0.35	0.35	0.35	0.35 ± 0.002	0.33
2749	10.59	2.29	2.28	2.31	2.29	2.25	2.28 ± 0.02	0.35	0.35	0.35	0.35	0.36	0.35 ± 0.003	0.33
2749	13.06	2.28	2.25	2.28	2.28	2.28	2.27 ± 0.01	0.35	0.36	0.35	0.35	0.35	0.35 ± 0.002	0.33
2749	15.53	2.28	2.22	2.22	2.31	2.28	2.26 ± 0.04	0.35	0.36	0.36	0.35	0.35	0.35 ± 0.006	0.34
2749	18.01	2.25	2.18	2.19	2.19	2.19	2.20 ± 0.03	0.36	0.37	0.37	0.37	0.37	0.36 ± 0.005	0.34
2749	20.48	2.22	2.19	2.19	2.18	2.18	2.19 ± 0.02	0.36	0.37	0.37	0.37	0.37	0.36 ± 0.003	0.34
2749	22.94	2.19	2.22	2.16	2.18	2.18	2.19 ± 0.02	0.37	0.36	0.37	0.37	0.37	0.37 ± 0.004	0.34
2749	28.06	2.16	2.13	2.19	2.15	2.19	2.16 ± 0.03	0.37	0.38	0.37	0.37	0.37	0.37 ± 0.004	0.35
2749	33.19	2.16	2.13	2.12	2.12	2.16	2.14 ± 0.02	0.37	0.38	0.38	0.38	0.37	0.37 ± 0.004	0.35

$Re_{solution}$	Re_{air}	Time of bubble travel (sec)/0.8m					Average (sec/0.8 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
2749	38.31	2.13	2.13	2.10	2.15	2.12	2.13 ± 0.02	0.38	0.38	0.38	0.37	0.38	0.38 ± 0.003	0.36
2749	43.44	2.10	2.09	2.15	2.12	2.12	2.12 ± 0.02	0.38	0.38	0.37	0.38	0.38	0.38 ± 0.004	0.36
2749	48.57	2.09	2.10	2.09	2.09	2.10	2.09 ± 0.01	0.38	0.38	0.38	0.38	0.38	0.38 ± 0.001	0.37
2749	58.82	2.03	2.00	2.00	2.00	2.00	2.01 ± 0.01	0.39	0.40	0.40	0.40	0.40	0.40 ± 0.003	0.38
2749	69.07	1.94	1.94	1.93	1.96	1.94	1.94 ± 0.01	0.41	0.41	0.41	0.41	0.41	0.41 ± 0.002	0.39
2749	79.32	1.93	1.88	1.94	1.87	1.89	1.90 ± 0.03	0.41	0.43	0.41	0.43	0.42	0.42 ± 0.007	0.40
2749	89.57	1.81	1.79	1.79	1.81	1.81	1.80 ± 0.01	0.44	0.45	0.45	0.44	0.44	0.44 ± 0.003	0.41
2749	99.82	1.78	1.79	1.78	1.81	1.78	1.79 ± 0.01	0.45	0.45	0.45	0.44	0.45	0.45 ± 0.003	0.42
2749	177	1.59	1.59	1.53	1.56	1.59	1.57 ± 0.03	0.50	0.50	0.52	0.51	0.50	0.51 ± 0.009	0.50
2749	296	1.31	1.3	1.32	1.31	1.3	1.31 ± 0.01	0.61	0.62	0.61	0.61	0.62	0.61 ± 0.004	0.61

$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
0	3.17	0.36	0.36	0.35	0.35	0.35	0.36 ± 0.006	0.36
0	4.40	0.38	0.37	0.37	0.37	0.36	0.37 ± 0.007	0.36
0	5.64	0.37	0.37	0.39	0.36	0.36	0.37 ± 0.011	0.36
0	6.88	0.37	0.38	0.37	0.37	0.38	0.37 ± 0.006	0.37
0	8.11	0.37	0.38	0.38	0.38	0.39	0.38 ± 0.006	0.37
0	10.59	0.38	0.38	0.38	0.38	0.38	0.38 ± 0.003	0.37
0	13.06	0.39	0.40	0.38	0.39	0.38	0.39 ± 0.007	0.38
0	15.53	0.38	0.40	0.40	0.39	0.40	0.39 ± 0.008	0.39
0	18.01	0.40	0.41	0.41	0.42	0.41	0.41 ± 0.008	0.39
0	20.48	0.42	0.42	0.42	0.42	0.42	0.42 ± 0.003	0.40
0	22.94	0.44	0.43	0.44	0.44	0.44	0.44 ± 0.004	0.40
0	28.06	0.45	0.45	0.45	0.45	0.45	0.45 ± 0.003	0.41
0	33.19	0.48	0.48	0.46	0.48	0.47	0.47 ± 0.006	0.43
0	38.31	0.49	0.50	0.49	0.48	0.48	0.49 ± 0.008	0.44
0	43.44	0.51	0.51	0.51	0.51	0.49	0.51 ± 0.007	0.45
0	48.57	0.52	0.52	0.52	0.51	0.52	0.52 ± 0.005	0.46
0	58.82	0.55	0.55	0.56	0.55	0.55	0.55 ± 0.004	0.48
0	69.07	0.57	0.56	0.57	0.58	0.58	0.57 ± 0.004	0.51
0	79.32	0.59	0.61	0.59	0.59	0.58	0.59 ± 0.010	0.53
0	89.57	0.62	0.59	0.60	0.60	0.59	0.60 ± 0.010	0.56
0	99.82	0.62	0.60	0.61	0.62	0.62	0.61 ± 0.009	0.58
1001	3.17	0.51	0.51	0.51	0.51	0.51	0.51 ± 0.002	0.50
1001	5.64	0.51	0.51	0.52	0.51	0.52	0.51 ± 0.004	0.51
1001	8.12	0.52	0.52	0.53	0.52	0.52	0.52 ± 0.005	0.51
1001	10.59	0.52	0.53	0.52	0.52	0.53	0.53 ± 0.006	0.52

$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
1001	13.07	0.53	0.54	0.54	0.54	0.54	0.54 ± 0.004	0.52
1001	15.54	0.55	0.53	0.55	0.55	0.55	0.54 ± 0.006	0.53
1001	18.02	0.55	0.55	0.56	0.56	0.56	0.56 ± 0.002	0.53
1001	20.49	0.57	0.56	0.56	0.56	0.56	0.56 ± 0.005	0.54
1001	22.95	0.58	0.58	0.58	0.58	0.58	0.58 ± 0.002	0.55
1001	28.08	0.60	0.59	0.59	0.59	0.59	0.59 ± 0.004	0.56
1001	33.21	0.60	0.60	0.59	0.61	0.61	0.60 ± 0.006	0.57
1001	38.33	0.61	0.61	0.62	0.61	0.63	0.62 ± 0.007	0.58
1001	43.46	0.65	0.64	0.64	0.63	0.64	0.64 ± 0.005	0.59
1001	48.59	0.65	0.65	0.65	0.66	0.67	0.66 ± 0.008	0.60
1001	58.85	0.69	0.69	0.70	0.69	0.70	0.69 ± 0.004	0.63
1001	69.10	0.70	0.70	0.71	0.70	0.70	0.70 ± 0.005	0.65
1001	79.36	0.73	0.74	0.72	0.73	0.73	0.73 ± 0.006	0.67
1001	89.62	0.74	0.76	0.74	0.76	0.74	0.75 ± 0.010	0.70
1001	99.87	0.78	0.78	0.77	0.77	0.76	0.77 ± 0.010	0.72
1001	177	0.91	0.93	0.94	0.90	0.89	0.91 ± 0.021	0.90
2749	3.17	0.77	0.77	0.77	0.77	0.77	0.77 ± 0.002	0.75
2749	5.64	0.79	0.78	0.78	0.78	0.79	0.78 ± 0.006	0.76
2749	8.11	0.80	0.81	0.81	0.81	0.80	0.81 ± 0.006	0.76
2749	10.59	0.81	0.81	0.80	0.81	0.82	0.81 ± 0.008	0.77
2749	13.06	0.81	0.82	0.81	0.81	0.81	0.81 ± 0.005	0.77
2749	15.53	0.81	0.83	0.83	0.80	0.81	0.82 ± 0.015	0.78
2749	18.01	0.82	0.85	0.85	0.85	0.85	0.84 ± 0.011	0.78
2749	20.48	0.83	0.85	0.85	0.85	0.85	0.85 ± 0.006	0.79
2749	22.94	0.85	0.83	0.86	0.85	0.85	0.85 ± 0.008	0.79
2749	28.06	0.86	0.87	0.85	0.86	0.85	0.86 ± 0.010	0.81

$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
2749	33.19	0.86	0.87	0.87	0.87	0.86	0.87 ± 0.008	0.82
2749	38.31	0.87	0.87	0.88	0.86	0.87	0.87 ± 0.007	0.83
2749	43.44	0.88	0.89	0.86	0.87	0.87	0.88 ± 0.009	0.84
2749	48.57	0.89	0.88	0.89	0.89	0.88	0.88 ± 0.002	0.85
2749	58.82	0.91	0.93	0.93	0.93	0.93	0.92 ± 0.006	0.88
2749	69.07	0.96	0.96	0.96	0.95	0.96	0.95 ± 0.005	0.90
2749	79.32	0.96	0.99	0.96	0.99	0.98	0.97 ± 0.016	0.92
2749	89.57	1.02	1.04	1.04	1.02	1.02	1.03 ± 0.006	0.95
2749	99.82	1.04	1.04	1.04	1.02	1.04	1.04 ± 0.008	0.97
2749	177	1.17	1.17	1.21	1.19	1.17	1.18 ± 0.020	1.15
2749	296	1.41	1.43	1.40	1.41	1.43	1.42 ± 0.009	1.42

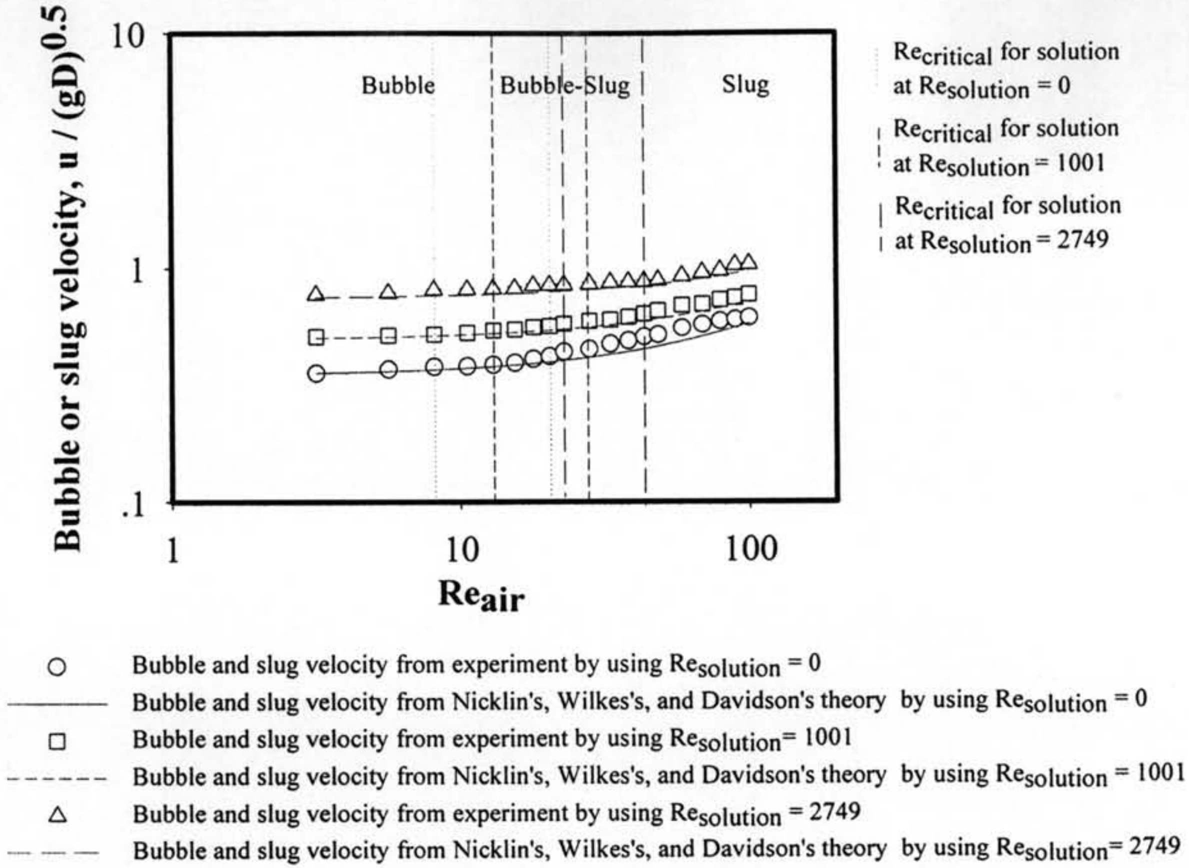


Figure H8 Comparison bubble and slug velocity from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) comparing with Nicklin's theory by using pipe diameter of 19 mm.

Table H4 Determination of the pressure gradient for the bubble flow regime from Nicklin's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$ = 9.73 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Superficial liquid velocity, $j_{liquid} = \dfrac{Q_{liquid}}{A}$ (H3)

Superficial air velocity, $j_{air} = \dfrac{Q_{air}}{A}$ (H4)

Reynolds number of liquid, $\mathrm{Re}_{liquid} = \dfrac{\rho j_{liquid} D}{\mu_{liquid}}$ (H5)

Reynolds number of air, $\mathrm{Re}_{air} = \dfrac{\rho j_{air} D}{\mu_{air}}$ (H6)

Bubble velocity rising in stagnant liquid, $u_b = 1.00\sqrt{g R_b}$ (H7)

where R_b is equivalent radius of the bubble which defined as the radius of a sphere that has the same volume as the bubble

Void fraction, $\varepsilon = \dfrac{Q_{air}}{Q_{air} + Q_{liquid} + u_b A}$ (H8)

Pressure gradient for bubble flow regime, $\dfrac{dp}{dz} = -\rho_l g(1-\varepsilon)$ (H9)

$Q_{solution}$ (ml/min)	Sup. solution velocity $j_{solution}$ (m/s)	$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Q_{air} (L/min)	Sup. Air velocity j_{air} (m/s)	Q_{air} (m^3/sec)	Re_{air}	Flow regime	U_b (m/s)	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
0	0	0	0	0.0444	0.0026	7.4E-07	3.17	bubble	0.2902	0.0089	9.7030
0	0	0	0	0.0792	0.0047	1.3E-06	5.64	bubble	0.3004	0.0153	9.6410
874	0.0514	1.46E-05	1001	0.0444	0.0026	7.4E-07	3.17	bubble	0.3397	0.0066	9.7254
874	0.0514	1.46E-05	1001	0.0792	0.0047	1.3E-06	5.64	bubble	0.3434	0.0117	9.6763
874	0.0514	1.46E-05	1001	0.1139	0.0067	1.90E-06	8.12	bubble	0.3527	0.0163	9.6308
874	0.0514	1.46E-05	1001	0.1486	0.0087	2.5E-06	10.59	bubble	0.3549	0.0211	9.5842
2399	0.1411	4E-05	2749	0.0444	0.0026	7.4E-07	3.1670	bubble	0.2209	0.0072	9.7202
2399	0.1411	4E-05	2749	0.0792	0.0047	1.3E-06	5.6418	bubble	0.2320	0.0123	9.6697
2399	0.1411	4E-05	2749	0.1139	0.0067	1.9E-06	8.1165	bubble	0.2363	0.0174	9.6197
2399	0.1411	4E-05	2749	0.1486	0.0087	2.5E-06	10.5912	bubble	0.2411	0.0224	9.5715
2399	0.1411	4E-05	2749	0.1833	0.0108	3.1E-06	13.0659	bubble	0.2488	0.0269	9.5269
2399	0.1411	4E-05	2749	0.2180	0.0128	3.6E-06	15.5407	bubble	0.2577	0.0312	9.4853
2399	0.1411	4E-05	2749	0.2528	0.0149	4.2E-06	18.0154	bubble	0.2676	0.0351	9.4468
2399	0.1411	4E-05	2749	0.2875	0.0169	4.8E-06	20.4901	bubble	0.2863	0.0381	9.4178
2399	0.1411	4E-05	2749	0.3220	0.0189	5.4E-06	22.9498	bubble	0.3001	0.0412	9.3874
2399	0.1411	4E-05	2749	0.3939	0.0232	6.6E-06	28.0780	bubble	0.3274	0.0471	9.3290

Table H5 Determination of the pressure gradient for the slug flow regime from Nicklin's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$ = 9.73 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Mean liquid velocity, $u_l = \dfrac{Q_{air} + Q_{liquid}}{A}$ (H10)

Reynolds number of the liquid slug, $\mathrm{Re}_{slug} = \dfrac{\rho_{liquid} u_l D}{\mu_{liquid}}$ (H11)

Fanning friction factor, $f_F = \dfrac{16}{\mathrm{Re}_{slug}}$ for laminar flow ($\mathrm{Re}_{slug} < 2000$) (H12)

$f_F = 0.079\,\mathrm{Re}_{slug}^{-1/4}$ for turbulent flow ($\mathrm{Re}_{slug} > 4000$) (H13)

Single-phase frictional pressure gradient for liquid only, $\left(\dfrac{dp}{dz}\right)_{sp} = \dfrac{2 f_F \rho_{liquid} u_l}{D}$ (H14)

Void fraction, $\varepsilon = \dfrac{Q_{air}}{1.2\left(Q_{air} + Q_{liquid}\right) + 0.35 A\sqrt{gD}}$ (H15)

Pressure gradient for slug flow regime, $\dfrac{dp}{dz} = (1-\varepsilon)\left[-\rho_{liquid} g + \left(\dfrac{dp}{dz}\right)_{sp}\right]$ (H16)

$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Qair (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
0	0	4.791E-06	20.49	slug	0.0169	329	0.0486	1.4583	0.0987	8.8258
0	0	5.367E-06	22.95	slug	0.0189	369	0.0434	1.6333	0.1089	8.7252
0	0	6.566E-06	28.08	slug	0.0232	452	0.0354	1.9983	0.1295	8.5242
0	0	7.765E-06	33.21	slug	0.0274	534	0.0300	2.3633	0.1489	8.3343
0	0	8.964E-06	38.33	slug	0.0316	616	0.0260	2.7282	0.1673	8.1546
0	0	1.016E-05	43.46	slug	0.0359	699	0.0229	3.0932	0.1847	7.9842
0	0	1.136E-05	48.59	slug	0.0401	781	0.0205	3.4582	0.2013	7.8226
0	0	1.376E-05	58.85	slug	0.0486	946	0.0169	4.1881	0.2319	7.5229
0	0	1.616E-05	69.10	slug	0.0570	1111	0.0144	4.9181	0.2598	7.2509
0	0	1.856E-05	79.36	slug	0.0655	1276	0.0125	5.6480	0.2851	7.0030
0	0	2.096E-05	89.62	slug	0.0739	1441	0.0111	6.3779	0.3083	6.7761
0	0	2.335E-05	99.87	slug	0.0824	1606	0.0100	7.1079	0.3297	6.5677
1.456E-05	1001	6.566E-06	28.08	Slug	0.0746	1453	0.0110	6.4303	0.0963	8.8533
1.456E-05	1001	7.765E-06	33.21	Slug	0.0788	1535	0.0104	6.7953	0.1115	8.7043
1.456E-05	1001	8.964E-06	38.33	Slug	0.0830	1618	0.0099	7.1603	0.1262	8.5614
1.456E-05	1001	1.016E-05	43.46	Slug	0.0873	1700	0.0094	7.5253	0.1402	8.4242
1.456E-05	1001	1.136E-05	48.59	Slug	0.0915	1783	0.0090	7.8902	0.1537	8.2923
1.456E-05	1001	1.376E-05	58.85	Slug	0.0999	1948	0.0082	8.6202	0.1792	8.0434
1.456E-05	1001	1.616E-05	69.10	Slug	0.1084	2113	0.0076	9.3501	0.2028	7.8124
1.456E-05	1001	1.856E-05	79.36	Slug	0.1169	2278	0.0070	10.0801	0.2248	7.5976
1.456E-05	1001	2.096E-05	89.62	Slug	0.1253	2443	0.0066	10.8100	0.2453	7.3973
1.456E-05	1001	2.335E-05	99.87	Slug	0.1338	2607	0.0061	11.5399	0.2644	7.2100
1.456E-05	1001	4.134E-05	176.80	Slug	0.1973	3844	0.0100	41.0159	0.3762	6.1332
1.456E-05	1001	6.922E-05	296.03	Slug-Churn	0.2957	5762	0.0091	83.2679	0.4829	5.1060
1.456E-05	1001	8.631E-05	369.11	Slug-Churn	0.3560	6937	0.0087	115.2243	0.5267	4.6881
1.456E-05	1001	0.0001205	515.27	Slug-Churn	0.4766	9287	0.0080	191.9995	0.5881	4.1118

$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Qair (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
1.456E-05	1001	0.0001718	734.50	Slug-Churn	0.6575	12813	0.0074	337.1844	0.6447	3.5980
3.998E-05	2749	1.016E-05	43.46	Slug	0.1769	3448	0.0103	33.9045	0.0987	8.8548
3.998E-05	2749	1.136E-05	48.59	Slug	0.1812	3531	0.0102	35.3362	0.1088	8.7566
3.998E-05	2749	1.376E-05	58.85	Slug	0.1896	3696	0.0101	38.2754	0.1282	8.5683
3.998E-05	2749	1.616E-05	69.10	Slug	0.1981	3860	0.0100	41.3147	0.1467	8.3898
3.998E-05	2749	1.856E-05	79.36	Slug	0.2066	4025	0.0099	44.4530	0.1641	8.2206
3.998E-05	2749	2.096E-05	89.62	Slug	0.2150	4190	0.0098	47.6892	0.1807	8.0599
3.998E-05	2749	2.335E-05	99.87	Slug	0.2235	4355	0.0097	51.0224	0.1966	7.9071
3.998E-05	2749	4.134E-05	176.80	Slug	0.2870	5592	0.0091	79.0248	0.2944	6.9634
3.998E-05	2749	6.922E-05	296.03	Slug	0.3853	7510	0.0085	132.3804	0.3982	5.9720
3.998E-05	2749	8.631E-05	369.11	Slug-Churn	0.4456	8685	0.0082	170.7338	0.4441	5.5377
3.998E-05	2749	0.0001205	515.27	Slug-Churn	0.5662	11035	0.0077	259.6264	0.5119	4.9055
3.998E-05	2749	0.0001718	734.50	Slug-Churn	0.7471	14561	0.0072	421.7471	0.5785	4.3045
3.998E-05	2749	0.0003399	1453.62	Slug-Churn	1.3405	26125	0.0062	1173.0783	0.6816	3.4906

Table H6 Determination of the pressure gradient for the slug flow regime from Sylvester's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{siolution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$ = 9.73 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

$$\beta = L_{TB}/L_{SU} \tag{H17}$$

where: L_{TB} is length of the Taylor bubble

L_{SU} is length of the slug unit

Friction factor associated with the Taylor bubble, $$f_{TB} = \frac{1}{\left[-2.0\log\left\{\frac{\left(1-\alpha_{TB}^{1/2}\right)}{7.4}\right\}\right]^2} \tag{H18}$$

Reynolds number of the liquid slug, $$\mathrm{Re}_{LS} = \frac{\rho_L U_{LLS} D}{\mu_L} \tag{H19}$$

where: velocity of the liquid in the liquid slug, $$U_{LLS} = U_{SG} + U_{SL} \tag{H20}$$

Friction factor associated with the liquid slug, $$f_{LS} = \frac{1}{\left[-2.0\log\left\{\frac{\varepsilon/D}{3.7}-\left(\frac{5.02}{\mathrm{Re}_{LS}}\right)\log\left(\frac{\varepsilon/D}{3.7}+\frac{13}{\mathrm{Re}_{LS}}\right)\right\}\right]^2} \tag{H21}$$

where: ε is the pipe roughness

Acceleration pressure drop, $$(\Delta P)_A = \rho_L(U_{LTB} + U_{TB})(1-\alpha_{TB})(U_{LTB} + U_{TB} + U_{LLS}) \tag{H22}$$

where: velocity of the liquid film around the Taylor bubble, $$U_{LTB} = 9.916\left[gD\left(1-\sqrt{\alpha_{TB}}\right)\right]^{1/2} \tag{H23}$$

velocity of the Taylor bubble, $U_{TB} = 1.2(U_{SG} + U_{SL}) + 0.35\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}$ (H24)

area average void fraction of the Taylor bubble, $\alpha_{TB} = \frac{\text{Average all area at Taylor bubble region}}{\text{Average area in Taylor bubble}}$ (H25)

Hydrostatic pressure drop, $(\Delta P)_H = \rho_L(1-\alpha_{LS})gL_{LS}$ (H26)

where: void fraction of the liquid slug, $\alpha_{LS} = \frac{U_{SG}}{0.425 + 2.65(U_{SG} + U_{SL})}$ (H27)

length of the liquid slug, L_{LS}

Frictional pressure drop of slug unit, $(\Delta P)_F = \frac{L_{LS}}{2D}\left[\frac{\rho_G \beta f_{TB} U_{TB}^2}{(1-\beta)[1-(1-\alpha_{TB}^{1/2}]} + U_{LLS}^2 \rho_L (1-\alpha_{LS}) f_{LS} (1-\beta)\right]$ (H28)

Total pressure drop in the slug unit, $(\Delta P)_T = (\Delta P)_A + (\Delta P)_H + (\Delta P)_F$ (H29)

$Re_{solution}$	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
0	20.49	slug	0.2085	0.0621	329	0.0897	250	1132	0.0635	1382.1	1.3821	9.1192
0	22.95	slug	0.1879	0.0619	369	0.0861	249	1558	0.1072	1806.7	1.8067	8.8541
0	28.08	slug	0.2263	0.0619	452	0.0801	250	1428	0.1304	1678.2	1.6782	8.4791
0	33.21	slug	0.2779	0.0617	534	0.0756	250	1302	0.1469	1552.6	1.5526	7.9655
0	38.33	slug	0.2411	0.0600	616	0.0719	225	1591	0.2369	1816.3	1.8163	7.9544
0	43.46	slug	0.2778	0.0601	699	0.0688	228	1446	0.2526	1674.5	1.6745	7.6233
0	48.59	slug	0.2802	0.0595	781	0.0663	222	1450	0.3033	1672.6	1.6726	7.5132
0	58.85	slug	0.3298	0.0599	946	0.0622	233	1348	0.3618	1581.8	1.5818	7.0229
0	69.10	slug	0.3544	0.0575	1111	0.0590	200	1305	0.4406	1505.1	1.5051	6.5702
0	79.36	slug	0.4256	0.0569	1276	0.0564	196	1055	0.4018	1251.3	1.2513	5.9397
0	89.62	slug	0.4425	0.0556	1441	0.0542	181	1036	0.4694	1218.1	1.2181	5.6520
0	99.87	slug	0.4431	0.0511	1606	0.0524	128	1214	0.6572	1342.6	1.3426	5.2569
1001	28.08	slug	0.1972	0.0532	1453	0.0541	149	1399	0.9094	1549.3	1.5493	8.3792
1001	33.21	slug	0.1716	0.0513	1535	0.0531	129	1863	1.3696	1993.2	1.9932	8.3031
1001	38.33	slug	0.2048	0.0532	1618	0.0523	153	1669	1.2876	1823.9	1.8239	8.0900
1001	43.46	slug	0.1999	0.0531	1700	0.0515	153	1869	1.5773	2024.1	2.0241	8.0184
1001	48.59	slug	0.2426	0.0558	1783	0.0507	193	1600	1.3861	1793.8	1.7938	7.8145
1001	58.85	slug	0.2217	0.0533	1948	0.0493	162	1901	1.9634	2065.4	2.0654	7.6954
1001	69.10	slug	0.2852	0.0537	2113	0.0481	171	1452	1.5832	1624.5	1.6245	7.2021
1001	79.36	slug	0.3049	0.0534	2278	0.0470	171	1385	1.6683	1557.2	1.5572	6.9708
1001	89.62	slug	0.2757	0.0467	2443	0.0460	97	1756	2.4770	1855.1	1.8551	6.7616
1001	99.87	slug	0.2527	0.0373	2607	0.0451	35	2235	3.6302	2273.5	2.2735	6.6570
1001	176.80	slug	0.4215	0.0381	3844	0.0403	48	1673	4.0956	1724.3	1.7243	4.9403
2749	43.46	slug	0.3188	0.0577	3448	0.0416	271	705	1.6848	977.7	0.9777	8.8800
2749	48.59	slug	0.2928	0.0579	3531	0.0413	276	837	2.1603	1115.0	1.1150	8.8180
2749	58.85	slug	0.2671	0.0574	3696	0.0407	271	1061	3.0666	1335.2	1.3352	8.5592

$Re_{solution}$	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
2749	69.10	slug	0.2629	0.0581	3860	0.0402	292	1135	3.5556	1430.1	1.4301	8.5466
2749	79.36	slug	0.2783	0.0578	4025	0.0398	290	1144	3.7724	1437.9	1.4379	8.2798
2749	89.62	slug	0.2406	0.0532	4190	0.0393	211	1504	5.5823	1721.0	1.7210	7.8755
2749	99.87	slug	0.2611	0.0491	4355	0.0389	155	1406	5.4251	1566.2	1.5662	7.4067
2749	176.80	slug	0.3626	0.0465	5592	0.0362	144	1220	6.2545	1370.4	1.3704	6.1478
2749	296.03	slug	0.5290	0.0513	7510	0.0335	263	1003	6.3832	1272.7	1.2727	4.8621

Table H7 Determination of the pressure gradient for the annular and mist flow regime from Wallis's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution} = 9.73 \times 10^{-4}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Fanning friction factor, $f_F = \dfrac{16}{\text{Re}}$ for laminar flow (Re < 2000) (H30)

$f_F = 0.079\,\text{Re}^{-1/4}$ for turbulent flow (Re > 4000) (H31)

Pressure gradient for air, $\left(\dfrac{dp}{dz}\right)_{air} = \dfrac{2 f_F \rho_{air} j_{air}}{D}$ (H32)

Pressure gradient for liquid, $\left(\dfrac{dp}{dz}\right)_{liquid} = \dfrac{2 f_F \rho_{liquid} j_{liquid}}{D}$ (H33)

Martinelli parameter, X

from $\left(1+X^{2/3.61}\right)^{3.61}\left(\dfrac{dp}{dz}\right)_{air} - \rho_{air} g = \dfrac{\left(1+X^{2/3.61}\right)^{3.61}}{X^2}\left(\dfrac{dp}{dz}\right)_{liquid} - [\dfrac{1}{(1+0.0904X^{0.548})^{2.82}}\rho_{air} + (1-\dfrac{1}{(1+0.0904X^{0.548})^{2.82}})\rho_{liquid}]g$ (H34)

Void fraction, $\varepsilon = \dfrac{1}{\left(1+0.0904\,X^{0.548}\right)^{2.82}}$ (H35)

Gas two-phase flow multiplier, $\phi_g = \left(1+X^{2/3.61}\right)^{3.61/2}$ (H36)

Pressure gradient for two-phase flow, $\left(\frac{dp}{dz}\right) = \phi_g^2 \left(\frac{dp}{dz}\right)_{air} - \rho_{air} g$ (H37)

$Q_{solution}$ (ml/min)	$Re_{solution}$	Q_{air} (L/min)	Re_{air}	Flow regime	f_F of air	f_F of solution	$(-dp/dz)_{air}$ (Pa/m)	$(-dp/dz)_{solution}$ (Pa/m)	Martinelli parameter (X)	Void fraction (ε)	Φ_g^2	Pressure gradient $(-dp/dz)_{tp}$ (kPa/m)
874	1001	400	28510	Annular	0.0061	0.0160	418	4.4321	0.1794	0.9069	3.2490	1.3694
874	1001	500	35637	Annular	0.0057	0.0160	618	4.4321	0.1144	0.9262	2.5849	1.6080
874	1001	600	42765	Annular	0.0055	0.0160	850	4.4321	0.0877	0.9358	2.3006	1.9663
874	1001	700	49892	Annular	0.0053	0.0160	1113	4.4321	0.0724	0.9419	2.1326	2.3847
874	1001	800	57020	mist	0.0051	0.0160	1406	4.4321	0.0622	0.9464	2.0177	2.8479
874	1001	900	64147	mist	0.0050	0.0160	1728	4.4321	0.0548	0.9498	1.9324	3.3498
2399	2749	400	28510	Annular	0.0061	0.0058	418	12.1672	0.2842	0.8824	4.3025	1.8097
2399	2749	500	35637	Annular	0.0057	0.0058	618	12.1672	0.1897	0.9042	3.3528	2.0822
2399	2749	600	42765	Annular	0.0055	0.0058	850	12.1672	0.1463	0.9162	2.9137	2.4873
2399	2749	700	49892	Annular	0.0053	0.0058	1113	12.1672	0.1209	0.9241	2.6518	2.9625
2399	2749	800	57020	mist	0.0051	0.0058	1406	12.1672	0.1038	0.9298	2.4735	3.4886
2399	2749	900	64147	mist	0.0050	0.0058	1728	12.1672	0.0915	0.9343	2.3420	4.0573
2399	2749	1000	71275	mist	0.0048	0.0058	2077	12.1672	0.0821	0.9380	2.2398	4.6642

Table H8 Determination of the pressure gradient from experiment for octylbenzyldimethylammonium chloride solution (1CMC)

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$ = 9.73 × 10^{-4} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m;

cross-sectional area of pipe, A = 0.00028 m^2; pressure taps difference = 0.4 m

Procedure to determine of pressure gradient from experiment:

1. Read the highest and lowest difference level from manometer.
2. Put the value of difference level in $-\frac{dp}{dz} = \frac{\rho_w g(100 - level_{water,L}) - (100 - level_{water,R})}{100x0.4x1000}$ (H38)

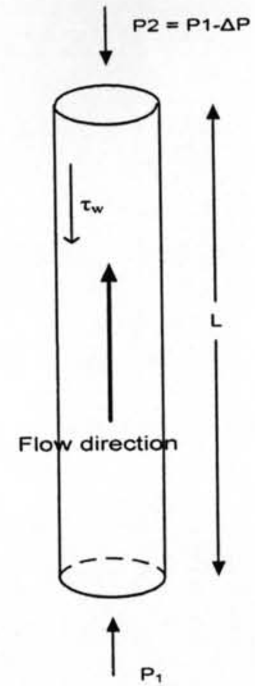


Figure H9 Pressure drop in a vertical pipe.

Upward flow in a vertical pipe is depicted in Fig. H9. A steady-state momentum balance in the direction of flow on the fluid in the pipe gives:

$$(P_1 - P_2)\frac{\pi D^2}{4} - \tau_w \pi D L - \frac{\pi D^2}{4}\rho L g = 0 \quad \text{(H39)}$$

$$(P_1 - P_2)\frac{D}{4} - \tau_w L - \frac{D}{4}\rho L g = 0 \quad \text{(H40)}$$

$$(P_1 - P_2)\frac{D}{4} - \rho L g\frac{D}{4} = \tau_w L \quad \text{(H41)}$$

$$(\frac{P_1 - P_2}{L})\frac{D}{4} - \rho g\frac{D}{4} = \tau_w \quad \text{(H42)}$$

We define the pressure drop: $\Delta P = P_1 - P_2$. Equation (H42) can be written as:

$$\frac{D}{4}[(\frac{\Delta P}{L})_d - \rho g] = \tau_w \quad \text{(H43)}$$

Elimination of the gravity term from Equation (H43) gives:

$$\frac{D}{4}(\frac{\Delta P}{L})_d = \tau_{w,d} \quad \text{(H44)}$$

From the definition of friction factor (f_F):

$$f_F = \frac{8\tau_{w,d}}{\rho_w \bar{u}_{liq}^2} \qquad \text{(H45)}$$

Rearrangement of Equation (H45) gives:

$$f_F = \frac{8\frac{D}{4}(\frac{\Delta P}{L})_d}{\rho_w \bar{u}_{liq}^2} \qquad \text{(H46)}$$

or

$$f_F = \frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^2} \qquad \text{(H47)}$$

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
0	3.17	Bubble	84.3	84.3	84.3	84.3	84.3	45.3	45.3	45.3	45.3	45.3
0	5.64	Bubble	82.3	82.3	82.3	82.3	82.3	44	44	44	44	44
0	8.12	Bubble-Slug	81	81	81	81	81	43	43	43	43	43
0	10.59	Bubble-Slug	80.5	80.5	80.5	80.5	80.5	42.8	42.8	42.8	42.8	42.8
0	13.07	Bubble-Slug	76.7	76.6	76.7	76.7	76.6	39.3	39.3	39.4	39.2	39.2
0	15.54	Bubble-Slug	73.5	73.8	73.5	73.5	73.4	37.8	37.5	37.3	37.5	37.4
0	18.02	Bubble-Slug	70.2	70.2	70	70.8	70.4	35.2	35.1	35	33.8	33.5
0	20.49	Slug	65.6	65.5	65.6	65.5	65.6	30.6	30.5	30.6	30.5	30.5
0	22.95	Slug	64.5	64.8	65	64.8	64.8	31.6	31.3	30.9	31.2	31.1
0	28.08	Slug	62.5	62.3	62	61.8	61	29.2	29	29	28	28.8
0	33.21	Slug	60.3	60.3	60.5	59.3	59.6	27	26.9	26.8	26	25.3
0	38.33	Slug	55.8	55.5	55.8	54.5	53.5	23	22.8	23	21.3	21
0	43.46	Slug	87.8	87.7	87.7	87.8	87.8	56.2	56.2	56.3	56.3	56.3
0	48.59	Slug	87.7	87.6	87.6	87.6	87.7	56.1	56	56	56.1	56.1
0	58.85	Slug	87.6	87.6	87.6	83.8	83.5	56	55.9	56	57.8	57.5
0	69.10	Slug	72.5	72.8	71.5	72	70.5	44.3	43.8	44.3	42.9	43
0	79.36	Slug	56.5	56.8	56	56	55.8	32.3	32	31.8	31.2	31.2
0	89.62	Slug	49.5	49.7	49.8	49.8	49.7	28.3	28.8	28.6	28.6	28.8
0	99.87	Slug	33.3	33.1	32.5	32.8	30	13.2	12.8	11.8	10.8	9
1001	3.17	Bubble	66.5	66.5	66.5	66.5	66.5	27.6	27.6	27.6	27.6	27.6
1001	5.64	Bubble	65	65	65	65	65	26.5	26.5	26.5	26.5	26.5
1001	8.12	Bubble	63	63	63	63	63	24.9	24.9	24.9	24.9	24.9
1001	10.59	Bubble	62.6	62.6	62.6	62.6	62.6	24.9	24.9	24.9	24.9	24.9
1001	13.07	Bubble-Slug	61.6	61.6	61.6	61.6	61.6	24.7	24.7	24.7	24.7	24.7
1001	15.54	Bubble-Slug	62.7	61.8	61	60.5	61	24.6	24.8	25.6	25.6	25.3
1001	18.02	Bubble-Slug	61.6	61.6	61	60.5	61.5	24.3	24.5	24.8	25.5	24.2

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
1001	20.49	Bubble-Slug	60.4	60	60.5	60.5	60.5	24.5	24.2	24.2	24.3	24.2
1001	22.95	Bubble-Slug	59.6	59	59	59.4	59	24.3	24.3	24	23.9	24.5
1001	28.08	Slug	58	58.5	57.5	58.8	57	24.8	23.8	24.8	23.8	24
1001	33.21	Slug	55.9	55.8	55.5	55.8	55.2	23.6	23.4	22.6	22.8	23.5
1001	38.33	Slug	52.8	52.8	52	52.4	52	19.8	19.5	20.2	18.3	18
1001	43.46	Slug	87.5	87.2	87.5	87.9	87.6	55	54.8	54.8	54.5	54
1001	48.59	Slug	85	84.8	85	84	84.2	53.8	52.5	51.2	52.5	52.2
1001	58.85	Slug	80.5	80.2	80.5	79.8	79.5	49.2	49	48.8	48	48.2
1001	69.10	Slug	73.5	73	73.1	72.8	72	44.2	44	43	43.3	42.5
1001	79.36	Slug	66.2	66	65	65	65	38	37.2	38.2	38	37.8
1001	89.62	Slug	56.5	56.8	56.2	56.7	56.9	32.5	32	31.8	31.4	31.5
1001	99.87	Slug	52.2	52	51.5	52	51.8	27.2	27	26.8	26	26.2
1001	177	Slug	37.5	36	36.2	36.2	36.5	19.2	19	19	18.5	17.2
1001	296	Slug-Churn	80.2	80	79.5	79	79.3	67.2	66.8	66.6	67	66.5
1001	369	Slug-Churn	74.8	74.8	74.9	74.8	74.8	64.6	64.5	64	64.1	64.2
1001	515	Slug-Churn	56.5	56.5	56.3	56	56	48	47.8	47.8	48	47.8
1001	735	Slug-Churn	55	55	55	55	55	48	48	48	48	48
1001	1454	Churn	77.3	77.5	77.5	77.5	77.5	71.5	71.5	71.5	71.5	71.5
1001	2474	Churn	76.7	76.7	76.7	76.7	76.7	70	70	70	70	70
1001	3495	Churn	76	76	76	76	76	69.5	69.5	69.5	69.5	69.5
1001	4516	Churn	75.8	75.8	75.8	75.8	75.8	69.4	69.4	69.4	69.4	69.4
1001	5537	Churn	79.5	79.5	79.5	79.5	79.5	73.8	73.8	73.8	73.8	73.8
1001	14255	Churn	76.1	76.1	76.1	76.1	76.1	71	71	71	71	71
1001	21382	Churn	74.5	74.5	74.5	74.5	74.5	66.8	66.8	66.8	66.8	66.8
1001	28510	Annular	72	72	72	72	72	61.6	61.6	61.6	61.6	61.6
1001	35637	Annular	72	72	72	72	72	55.5	55.5	55.5	55.5	55.5
1001	42765	Annular	84.5	84.5	84.5	84.5	84.5	58.2	58.2	58.2	58.2	58.2

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
1001	49892	Annular	85	85	85	85	85	53	53	53	53	53
1001	57020	Mist	85.8	85.8	85.8	85.8	85.8	49.8	49.8	49.8	49.8	49.8
2749	3.17	Bubble	87.8	87.8	87.8	87.8	87.8	49	49	49	49	49
2749	5.64	Bubble	87.8	87.8	87.8	87.8	87.8	49.1	49.1	49.1	49.1	49.1
2749	8.12	Bubble	87.7	87.7	87.7	87.7	87.7	49.1	49.1	49.1	49.1	49.1
2749	10.59	Bubble	87	87	87	87	87	48.9	48.9	48.9	48.9	48.9
2749	13.07	Bubble	86.7	86.7	86.7	86.7	86.7	48.7	48.7	48.7	48.7	48.7
2749	15.54	Bubble	86.4	86.4	86.4	86.4	86.4	48.6	48.6	48.6	48.6	48.6
2749	18.02	Bubble	86	86	86	86	86	48.3	48.3	48.3	48.3	48.3
2749	20.49	Bubble	85.6	85.7	85.6	85.6	85.8	48.1	48	48.1	48.2	48.1
2749	22.95	Bubble	85.1	85.2	85.2	85.1	85.1	48	48	47.9	47.9	47.9
2749	28.08	Bubble	82.5	82.7	82.6	82.5	82.6	46	46.3	46	46.1	46.1
2749	33.21	Bubble-Slug	81.5	81.4	80.8	80.8	80.5	44.5	44.9	45	45	45
2749	38.33	Bubble-Slug	78.9	79.2	79.5	79.6	79.8	45.1	44.9	44.3	44.5	44.1
2749	43.46	Slug	78.5	78.5	78.5	78.5	78.5	43.1	43.2	43.1	43.1	43
2749	48.59	Slug	77	77	77	76.8	76.8	42.1	42.4	42	42.1	42
2749	58.85	Slug	75.6	75.8	75.8	75.2	75	41	41.1	40.8	41	41.2
2749	69.10	Slug	72.8	72.6	72.8	71.5	72.5	39.1	39.1	38.5	40	38.8
2749	79.36	Slug	69.9	69.9	70	70	70	38.2	38	37.8	37.8	37.9
2749	89.62	Slug	67.8	67.6	67.5	67	66.5	35.6	35.4	35.1	35.1	34
2749	99.87	Slug	62.4	62.3	62.5	62.6	62.6	32.1	32.1	32.3	31.1	31.5
2749	177	Slug	56	55.3	55	54.3	54.1	30.8	31	30.8	30.9	30.7
2749	296	Slug	80.3	80.5	80.5	80.5	80.5	62.1	62	61.8	61.8	61.5
2749	369	Slug-Churn	76.6	76.8	76.9	76.9	76.9	60.4	60	60	60	60
2749	515	Slug-Churn	74.9	74.9	75	75	75.4	61.8	61.8	61.8	61.8	61.3
2749	735	Slug-Churn	73.7	73.5	73.5	73.5	73.5	62.5	62.9	62.6	62.5	62.4
2749	1454	Slug-Churn	38.6	38.6	38.6	38.6	38.6	30	30	30	30	30

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2749	2474	Churn	39	39	39	39	39	29.3	29.3	29.3	29.3	29.3
2749	3495	Churn	38.9	38.9	38.9	38.9	38.9	29	29	29	29	29
2749	4516	Churn	39	39	39	39	39	28.9	28.9	28.9	28.9	28.9
2749	5537	Churn	60	60	60	60	60	51	51	51	51	51
2749	14255	Churn	55.9	55.9	55.9	55.9	55.9	44.3	44.3	44.3	44.3	44.3
2749	21382	Churn	53.5	53.5	53.5	53.5	53.5	37.2	37.2	37.2	37.2	37.2
2749	28510	Annular	54.5	54.5	54.5	54.5	54.5	32	32	32	32	32
2749	35637	Annular	55.5	55.5	55.5	55.5	55.5	27.7	27.7	27.7	27.7	27.7
2749	42765	Annular	57.2	57.2	57.2	57.2	57.2	25	25	25	25	25
2749	49892	Annular	55	55	55	55	55	20	20	20	20	20
2749	57020	Mist	52	52	52	52	52	15.1	15.1	15.1	15.1	15.1

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
0	3.17	Bubble	84.3	84.3	84.3	84.3	84.3	45.3	45.3	45.3	45.3	45.3
0	5.64	Bubble	82.3	82.3	82.3	82.3	82.3	44	44	44	44	44
0	8.12	Bubble-Slug	81	81	81	81	81	43	43	43	43	43
0	10.59	Bubble-Slug	80.5	80.5	80.5	80.5	80.5	42.8	42.8	42.8	42.8	42.8
0	13.07	Bubble-Slug	76.6	76.8	76.7	76.7	76.8	39.1	39.2	38.8	39.2	39
0	15.54	Bubble-Slug	73.5	73.3	74.8	74.5	74.4	37.2	37.2	36.8	36.8	36.9
0	18.02	Bubble-Slug	69.5	69.8	69	69.6	69.2	34.8	34.8	34.8	34.8	34
0	20.49	Slug	65	64.8	64.6	64.5	65	31.3	31.8	31.8	31.5	31.5
0	22.95	Slug	64	64	63.5	63.6	63.5	30.4	30.4	30.2	29.8	30
0	28.08	Slug	60.8	61.5	61	60.5	60.6	28.3	27.8	27.5	28	27.8
0	33.21	Slug	58	58	57	57.5	57.5	26	25.8	26.5	25.5	25
0	38.33	Slug	51	51	51	51	50	20.3	20.2	20.3	20.3	19.2
0	43.46	Slug	85.2	85.3	85.2	85.1	85.3	56	56	56	56	56
0	48.59	Slug	83.7	83.6	83.5	83.7	83.5	56.7	56.5	56.6	56.7	56.5
0	58.85	Slug	82.8	82	81.9	81.9	82	57.3	56.3	56	55.9	55.6
0	69.10	Slug	67	67	66.2	66	65.5	41.5	41	41.3	41	40
0	79.36	Slug	53	53.5	53	52.8	51.5	31	31.2	30.5	29.2	29.5
0	89.62	Slug	53.1	53.3	53.1	53.1	53.2	29.6	29.8	30.3	30.5	30.5
0	99.87	Slug	29.8	28	28.5	26.5	26.3	8.8	9	8.8	9.5	9
1001	3.17	Bubble	66.5	66.5	66.5	66.5	66.5	27.6	27.6	27.6	27.6	27.6
1001	5.64	Bubble	65	65	65	65	65	26.5	26.5	26.5	26.5	26.5
1001	8.12	Bubble	63	63	63	63	63	24.9	24.9	24.9	24.9	24.9
1001	10.59	Bubble	63	63	63	63	63	24.5	24.5	24.5	24.5	24.5
1001	13.07	Bubble-Slug	61.3	61.3	61.3	61.3	61.3	24.7	24.7	24.7	24.7	24.7
1001	15.54	Bubble-Slug	62.6	60.9	61	61	61	24.5	25.3	25.2	25	25
1001	18.02	Bubble-Slug	60.5	60.6	60.9	60	61	25.4	25	24.9	25.5	23.8

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
1001	20.49	Bubble-Slug	60	60.5	59.6	59.7	59.5	24.8	23.9	24.8	24.3	24.5
1001	22.95	Bubble-Slug	58.7	58.6	58.5	59.2	59	24.3	24.5	24.5	23.3	23.6
1001	28.08	Slug	58	58	58.2	57.5	57.8	23	22.8	22.5	23.8	23
1001	33.21	Slug	55.2	55	55.3	55.4	55.1	20.2	20.1	20.3	20.2	20
1001	38.33	Slug	51.2	51.2	50.8	50.8	50.3	18.5	17.9	17.2	17.5	17
1001	43.46	Slug	88	87.9	87.6	87.5	87.3	54.8	54.6	54.9	54.8	54.3
1001	48.59	Slug	84	83.3	83.2	83	82	51.8	52	52	51.8	51
1001	58.85	Slug	78	77.8	78	78	77	47.8	47	46.8	46	46.8
1001	69.10	Slug	71	71.3	71	71	70.5	42.8	42.5	42	42	41.8
1001	79.36	Slug	64.5	64.5	64	64.2	63.5	38	37.6	37.6	36.8	35
1001	89.62	Slug	58	58.2	57	57	57	31	30	30	30	29.5
1001	99.87	Slug	51.2	51	50	50	49.5	25.5	25.1	24.8	24.8	24.5
1001	177	Slug	34	34	33	34	33	16.8	16.5	16.8	16	16.2
1001	296	Slug-Churn	79	79	79	79	79	66.3	66.4	66.5	66.5	66.5
1001	369	Slug-Churn	72	72.2	72.3	72.9	72.7	61	61.1	60	61	61.8
1001	515	Slug-Churn	56	56	56	55.8	55.8	47.8	47.9	47.9	48	48
1001	735	Slug-Churn	54.8	54.8	54.8	54.8	54.8	48.2	48.2	48.2	48.2	48.2
1001	1454	Churn	76.5	76.5	76.5	76.5	76.5	71.3	71.3	71.3	71.3	71.3
1001	2474	Churn	76.7	76.7	76.7	76.7	76.7	70	70	70	70	70
1001	3495	Churn	76	76	76	76	76	69.5	69.5	69.5	69.5	69.5
1001	4516	Churn	75.8	75.8	75.8	75.8	75.8	69.4	69.4	69.4	69.4	69.4
1001	5537	Churn	79	79	79	79	79	74.3	74.3	74.3	74.3	74.3
1001	14255	Churn	75.5	75.5	75.5	75.5	75.5	71	71	71	71	71
1001	21382	Churn	74	74	74	74	74	66.6	66.6	66.6	66.6	66.6
1001	28510	Annular	71.6	71.6	71.6	71.6	71.6	61.5	61.5	61.5	61.5	61.5
1001	35637	Annular	71.8	71.8	71.8	71.8	71.8	55.6	55.6	55.6	55.6	55.6
1001	42765	Annular	84.5	84.5	84.5	84.5	84.5	58.2	58.2	58.2	58.2	58.2

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
1001	49892	Annular	85	85	85	85	85	53	53	53	53	53
1001	57020	Mist	85.8	85.8	85.8	85.8	85.8	49.8	49.8	49.8	49.8	49.8
2749	3.17	Bubble	87.8	87.8	87.8	87.8	87.8	49	49	49	49	49
2749	5.64	Bubble	87.8	87.8	87.8	87.8	87.8	49.1	49.1	49.1	49.1	49.1
2749	8.12	Bubble	87.7	87.7	87.7	87.7	87.7	49.1	49.1	49.1	49.1	49.1
2749	10.59	Bubble	87	87	87	87	87	49	49	49	49	49
2749	13.07	Bubble	86.7	86.7	86.7	86.7	86.7	48.7	48.7	48.7	48.7	48.7
2749	15.54	Bubble	86.4	86.4	86.4	86.4	86.4	48.6	48.6	48.6	48.6	48.6
2749	18.02	Bubble	86	86	86	86	86	48.3	48.3	48.3	48.3	48.3
2749	20.49	Bubble	85.6	85.6	85.4	85.6	85.6	48.3	48.3	48.2	48.2	48.2
2749	22.95	Bubble	83.5	83.6	83.5	83.6	83.5	48.1	48	48	48	48
2749	28.08	Bubble	81.5	81.3	81.5	81.6	81.5	46.4	46.6	46.8	46.1	45.9
2749	33.21	Bubble-Slug	80	80	80	80	80	45	44.9	45	45	44.9
2749	38.33	Bubble-Slug	79	78.8	79.2	79.8	78.8	44	44.6	43.5	43	43.6
2749	43.46	Slug	77.5	77.6	77.7	77.5	77.8	43.6	43.5	43.3	44	43
2749	48.59	Slug	76.1	76.1	76	76	76	42.3	42.2	42.1	42	42
2749	58.85	Slug	74.6	74.3	74.3	74.5	73.8	40.8	40.5	40.3	40	40.2
2749	69.10	Slug	71.8	72	71.8	70.9	71	38.8	39.1	39.1	39	38.8
2749	79.36	Slug	68.7	68.7	68.6	69.3	69	37.5	37.6	37.4	37	37
2749	89.62	Slug	65.6	65.2	65.3	65	65.2	33.8	34	33.9	33.4	33
2749	99.87	Slug	61.8	61	60.8	60.5	60.8	31.1	30.2	30.5	30.2	30
2749	177	Slug	54	53.8	53.8	53.8	53.8	30	30	30	30	30
2749	296	Slug	80.6	80.6	80.6	80.6	80.5	61.2	61	60.9	60.5	60.8
2749	369	Slug-Churn	76.7	76.7	76.8	76.8	76.9	60.1	60.2	60	59.9	60
2749	515	Slug-Churn	75.1	75.1	75.3	75.3	75	61.3	61.4	61.3	61.4	61.3
2749	735	Slug-Churn	73.3	73.3	73.3	72.8	72.8	62	62.1	62.2	62.5	62.3
2749	1454	Slug-Churn	39.3	39.4	39.2	39.3	39.2	30	30	30	30	30

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2749	2474	Churn	38.9	38.9	38.9	38.9	38.9	29.3	29.3	29.3	29.3	29.3
2749	3495	Churn	38.9	38.9	38.9	38.9	38.9	29	29	29	29	29
2749	4516	Churn	39	39	39	39	39	28.9	28.9	28.9	28.9	28.9
2749	5537	Churn	58.8	58.8	58.8	58.8	58.8	50.5	50.5	50.5	50.5	50.5
2749	14255	Churn	55.4	55.4	55.4	55.4	55.4	44.3	44.3	44.3	44.3	44.3
2749	21382	Churn	53.4	53.4	53.4	53.4	53.4	37.2	37.2	37.2	37.2	37.2
2749	28510	Annular	54.5	54.5	54.5	54.5	54.5	32	32	32	32	32
2749	35637	Annular	55.5	55.5	55.5	55.5	55.5	27.7	27.7	27.7	27.7	27.7
2749	42765	Annular	57.2	57.2	57.2	57.2	57.2	25	25	25	25	25
2749	49892	Annular	55	55	55	55	55	20	20	20	20	20
2749	57020	Mist	52	52	52	52	52	15.1	15.1	15.1	15.1	15.1

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
0	3.17	Bubble	9.5456	9.5456	9.5456	9.5456	9.5456	9.5456	9.5456	9.5456	9.5456	9.5456	9.5456 ± 0.00
0	5.64	Bubble	9.3743	9.3743	9.3743	9.3743	9.3743	9.3743	9.3743	9.3743	9.3743	9.3743	9.3743 ± 0.00
0	8.12	Bubble-Slug	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009 ± 0.00
0	10.59	Bubble-Slug	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274 ± 0.00
0	13.07	Bubble-Slug	9.1540	9.1295	9.1295	9.1785	9.1540	9.1785	9.2030	9.2764	9.1785	9.2519	9.1834 ± 0.05
0	15.54	Bubble-Slug	8.7379	8.8848	8.8603	8.8113	8.8113	8.8848	8.8358	9.3009	9.2274	9.1785	8.9533 ± 0.20
0	18.02	Bubble-Slug	8.5666	8.5911	8.5666	9.0561	9.0316	8.4932	8.5666	8.3708	8.5176	8.6155	8.6376 ± 0.22
0	20.49	Slug	8.5666	8.5666	8.5666	8.5666	8.5911	8.2484	8.0771	8.0281	8.0771	8.1994	8.3487 ± 0.24
0	22.95	Slug	8.0526	8.1994	8.3463	8.2239	8.2484	8.2239	8.2239	8.1505	8.2729	8.1994	8.2141 ± 0.08
0	28.08	Slug	8.1505	8.1505	8.0771	8.2729	7.8813	7.9547	8.2484	8.1994	7.9547	8.0281	8.0917 ± 0.13
0	33.21	Slug	8.1505	8.1750	8.2484	8.1505	8.3953	7.8323	7.8813	7.4652	7.8323	7.9547	8.0085 ± 0.27
0	38.33	Slug	8.0281	8.0036	8.0281	8.1260	7.9547	7.5141	7.5386	7.5141	7.5141	7.5386	7.7760 ± 0.27
0	43.46	Slug	7.7344	7.7099	7.6854	7.7099	7.7099	7.1470	7.1715	7.1470	7.1225	7.1715	7.4309 ± 0.29
0	48.59	Slug	7.7344	7.7344	7.7344	7.7099	7.7344	6.6085	6.6330	6.5840	6.6085	6.6085	7.1690 ± 0.59
0	58.85	Slug	7.7344	7.7589	7.7344	6.3637	6.3637	6.2414	6.2903	6.3393	6.3637	6.4617	6.7652 ± 0.68
0	69.10	Slug	6.9022	7.0980	6.6575	7.1225	6.7309	6.2414	6.3637	6.0945	6.1190	6.2414	6.5571 ± 0.40
0	79.36	Slug	5.9232	6.0700	5.9232	6.0700	6.0211	5.3847	5.4581	5.5071	5.7763	5.3847	5.7518 ± 0.29
0	89.62	Slug	5.1889	5.1155	5.1889	5.1889	5.1155	5.7518	5.7518	5.5805	5.5316	5.5560	5.3969 ± 0.26
0	99.87	Slug	4.9197	4.9686	5.0665	5.3847	5.1399	5.1399	4.6504	4.8218	4.1609	4.2343	4.8487 ± 0.40
1001	3.17	Bubble	9.5211	9.5211	9.5211	9.5211	9.5211	9.5211	9.5211	9.5211	9.5211	9.5211	9.5211 ± 0.00
1001	5.64	Bubble	9.4232	9.4232	9.4232	9.4232	9.4232	9.4232	9.4232	9.4232	9.4232	9.4232	9.4232 ± 0.00
1001	8.12	Bubble	9.3253	9.3253	9.3253	9.3253	9.3253	9.3253	9.3253	9.3253	9.3253	9.3253	9.3253 ± 0.00
1001	10.59	Bubble	9.2274	9.2274	9.2274	9.2274	9.2274	9.4232	9.4232	9.4232	9.4232	9.4232	9.3253 ± 0.10
1001	13.07	Bubble-Slug	9.0316	9.0316	9.0316	9.0316	9.0316	8.9582	8.9582	8.9582	8.9582	8.9582	8.9949 ± 0.04
1001	15.54	Bubble-Slug	9.3253	9.0561	8.6645	8.5421	8.7379	9.3253	8.7134	8.7624	8.8113	8.8113	8.8750 ± 0.27
1001	18.02	Bubble-Slug	9.1295	9.0806	8.8603	8.5666	9.1295	8.5911	8.7134	8.8113	8.4442	9.1051	8.8432 ± 0.26

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
1001	20.49	Bubble-Slug	8.7869	8.7624	8.8848	8.8603	8.8848	8.6155	8.9582	8.5176	8.6645	8.5666	8.7502 ± 0.15
1001	22.95	Bubble-Slug	8.6400	8.4932	8.5666	8.6890	8.4442	8.4197	8.3463	8.3218	8.7869	8.6645	8.5372 ± 0.16
1001	28.08	Slug	8.1260	8.4932	8.0036	8.5666	8.0771	8.5666	8.6155	8.7379	8.2484	8.5176	8.3953 ± 0.26
1001	33.21	Slug	7.9057	7.9302	8.0526	8.0771	7.7589	8.5666	8.5421	8.5666	8.6155	8.5911	8.2606 ± 0.34
1001	38.33	Slug	8.0771	8.1505	7.7834	8.3463	8.3218	8.0036	8.1505	8.2239	8.1505	8.1505	8.1358 ± 0.16
1001	43.46	Slug	7.9547	7.9302	8.0036	8.1750	8.2239	8.1260	8.1505	8.0036	8.0036	8.0771	8.0648 ± 0.10
1001	48.59	Slug	7.6365	7.9057	8.2729	7.7099	7.8323	7.8813	7.6610	7.6365	7.6365	7.5875	7.7760 ± 0.21
1001	58.85	Slug	7.6610	7.6365	7.7589	7.7834	7.6610	7.3917	7.5386	7.6365	7.8323	7.3917	7.6292 ± 0.15
1001	69.10	Slug	7.1715	7.0980	7.3673	7.2204	7.2204	6.9022	7.0491	7.0980	7.0980	7.0246	7.1249 ± 0.13
1001	79.36	Slug	6.9022	7.0491	6.5596	6.6085	6.6575	6.4861	6.5840	6.4617	6.7064	6.9756	6.6991 ± 0.21
1001	89.62	Slug	5.8742	6.0700	5.9721	6.1924	6.2169	6.6085	6.9022	6.6085	6.6085	6.7309	6.3784 ± 0.35
1001	99.87	Slug	6.1190	6.1190	6.0456	6.3637	6.2658	6.2903	6.3393	6.1679	6.1679	6.1190	6.1998 ± 0.11
1001	177	Slug	4.4791	4.1609	4.2099	4.3322	4.7239	4.2099	4.2833	3.9651	4.4057	4.1120	4.2882 ± 0.21
1001	296	Slug-Churn	3.1819	3.2308	3.1574	2.9371	3.1329	3.1084	3.0840	3.0595	3.0595	3.0595	3.1011 ± 0.08
1001	369	Slug-Churn	2.4965	2.5210	2.6679	2.6189	2.5945	2.6924	2.7168	3.0105	2.9126	2.6679	2.6899 ± 0.16
1001	515	Slug-Churn	2.0805	2.1294	2.0805	1.9581	2.0070	2.0070	1.9826	1.9826	1.9091	1.9091	2.0046 ± 0.07
1001	735	Slug-Churn	1.7133	1.7133	1.7133	1.7133	1.7133	1.6154	1.6154	1.6154	1.6154	1.6154	1.6644 ± 0.05
1001	1454	Churn	1.4196	1.4686	1.4686	1.4686	1.4686	1.2727	1.2727	1.2727	1.2727	1.2727	1.3658 ± 0.10
1001	2474	Churn	1.6399	1.6399	1.6399	1.6399	1.6399	1.6399	1.6399	1.6399	1.6399	1.6399	1.6399 ± 0.00
1001	3495	Churn	1.5909	1.5909	1.5909	1.5909	1.5909	1.5909	1.5909	1.5909	1.5909	1.5909	1.5909 ± 0.00
1001	4516	Churn	1.5665	1.5665	1.5665	1.5665	1.5665	1.5665	1.5665	1.5665	1.5665	1.5665	1.5665 ± 0.00
1001	5537	Churn	1.3951	1.3951	1.3951	1.3951	1.3951	1.1504	1.1504	1.1504	1.1504	1.1504	1.2727 ± 0.13
1001	14255	Churn	1.2483	1.2483	1.2483	1.2483	1.2483	1.1014	1.1014	1.1014	1.1014	1.1014	1.1748 ± 0.08
1001	21382	Churn	1.8846	1.8846	1.8846	1.8846	1.8846	1.8112	1.8112	1.8112	1.8112	1.8112	1.8479 ± 0.04
1001	28510	Annular	2.5455	2.5455	2.5455	2.5455	2.5455	2.4721	2.4721	2.4721	2.4721	2.4721	2.5088 ± 0.04
1001	35637	Annular	4.0385	4.0385	4.0385	4.0385	4.0385	3.9651	3.9651	3.9651	3.9651	3.9651	4.0018 ± 0.04
1001	42765	Annular	6.4372	6.4372	6.4372	6.4372	6.4372	6.4372	6.4372	6.4372	6.4372	6.4372	6.4372 ± 0.00

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
1001	49892	Annular	7.8323	7.8323	7.8323	7.8323	7.8323	7.8323	7.8323	7.8323	7.8323	7.8323	7.8323 ± 0.00
1001	57020	Mist	8.8113	8.8113	8.8113	8.8113	8.8113	8.8113	8.8113	8.8113	8.8113	8.8113	8.8113 ± 0.00
2749	3.17	Bubble	9.4967	9.4967	9.4967	9.4967	9.4967	9.4967	9.4967	9.4967	9.4967	9.4967	9.4967 ± 0.00
2749	5.64	Bubble	9.4722	9.4722	9.4722	9.4722	9.4722	9.4722	9.4722	9.4722	9.4722	9.4722	9.4722 ± 0.00
2749	8.12	Bubble	9.4477	9.4477	9.4477	9.4477	9.4477	9.4477	9.4477	9.4477	9.4477	9.4477	9.4477 ± 0.00
2749	10.59	Bubble	9.3253	9.3253	9.3253	9.3253	9.3253	9.3009	9.3009	9.3009	9.3009	9.3009	9.3131 ± 0.01
2749	13.07	Bubble	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009	9.3009 ± 0.00
2749	15.54	Bubble	9.2519	9.2519	9.2519	9.2519	9.2519	9.2519	9.2519	9.2519	9.2519	9.2519	9.2519 ± 0.00
2749	18.02	Bubble	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274	9.2274 ± 0.00
2749	20.49	Bubble	9.1785	9.2274	9.1785	9.1540	9.2274	9.1295	9.1295	9.1051	9.1540	9.1540	9.1638 ± 0.04
2749	22.95	Bubble	9.0806	9.1051	9.1295	9.1051	9.1051	8.6645	8.7134	8.6890	8.7134	8.6890	8.8995 ± 0.22
2749	28.08	Bubble	8.9337	8.9092	8.9582	8.9092	8.9337	8.5911	8.4932	8.4932	8.6890	8.7134	8.7624 ± 0.19
2749	33.21	Bubble-Slug	9.0561	8.9337	8.7624	8.7624	8.6890	8.5666	8.5911	8.5666	8.5666	8.5911	8.7085 ± 0.17
2749	38.33	Bubble-Slug	8.2729	8.3953	8.6155	8.5911	8.7379	8.5666	8.3708	8.7379	9.0071	8.6155	8.5911 ± 0.21
2749	43.46	Slug	8.6645	8.6400	8.6645	8.6645	8.6890	8.2973	8.3463	8.4197	8.1994	8.5176	8.5103 ± 0.18
2749	48.59	Slug	8.5421	8.4687	8.5666	8.4932	8.5176	8.2729	8.2973	8.2973	8.3218	8.3218	8.4099 ± 0.12
2749	58.85	Slug	8.4687	8.4932	8.5666	8.3708	8.2729	8.2729	8.2729	8.3218	8.4442	8.2239	8.3708 ± 0.12
2749	69.10	Slug	8.2484	8.1994	8.3953	7.7099	8.2484	8.0771	8.0526	8.0036	7.8078	7.8813	8.0624 ± 0.22
2749	79.36	Slug	7.7589	7.8078	7.8813	7.8813	7.8568	7.6365	7.6120	7.6365	7.9057	7.8323	7.7809 ± 0.11
2749	89.62	Slug	7.8813	7.8813	7.9302	7.8078	7.9547	7.7834	7.6365	7.6854	7.7344	7.8813	7.8176 ± 0.11
2749	99.87	Slug	7.4162	7.3917	7.3917	7.7099	7.6120	7.5141	7.5386	7.4162	7.4162	7.5386	7.4945 ± 0.11
2749	177	Slug	6.1679	5.9477	5.9232	5.7274	5.7274	5.8742	5.8253	5.8253	5.8253	5.8253	5.8669 ± 0.13
2749	296	Slug	4.4546	4.5281	4.5770	4.5770	4.6504	4.7483	4.7973	4.8218	4.9197	4.8218	4.6896 ± 0.15
2749	369	Slug-Churn	3.9651	4.1120	4.1364	4.1364	4.1364	4.0630	4.0385	4.1120	4.1364	4.1364	4.0973 ± 0.06
2749	515	Slug-Churn	3.2063	3.2063	3.2308	3.2308	3.4511	3.3777	3.3532	3.4266	3.4022	3.3532	3.3238 ± 0.10
2749	735	Slug-Churn	2.7413	2.5945	2.6679	2.6924	2.7168	2.7658	2.7413	2.7168	2.5210	2.5700	2.6728 ± 0.08
2749	1454	Slug-Churn	2.1049	2.1049	2.1049	2.1049	2.1049	2.2763	2.3007	2.2518	2.2763	2.2518	2.1881 ± 0.09

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2749	2474	Churn	2.3742	2.3742	2.3742	2.3742	2.3742	2.3497	2.3497	2.3497	2.3497	2.3497	2.3619 ± 0.01
2749	3495	Churn	2.4231	2.4231	2.4231	2.4231	2.4231	2.4231	2.4231	2.4231	2.4231	2.4231	2.4231 ± 0.00
2749	4516	Churn	2.4721	2.4721	2.4721	2.4721	2.4721	2.4721	2.4721	2.4721	2.4721	2.4721	2.4721 ± 0.00
2749	5537	Churn	2.2028	2.2028	2.2028	2.2028	2.2028	2.0315	2.0315	2.0315	2.0315	2.0315	2.1172 ± 0.09
2749	14255	Churn	2.8392	2.8392	2.8392	2.8392	2.8392	2.7168	2.7168	2.7168	2.7168	2.7168	2.7780 ± 0.06
2749	21382	Churn	3.9896	3.9896	3.9896	3.9896	3.9896	3.9651	3.9651	3.9651	3.9651	3.9651	3.9773 ± 0.01
2749	28510	Annular	5.5071	5.5071	5.5071	5.5071	5.5071	5.5071	5.5071	5.5071	5.5071	5.5071	5.5071 ± 0.00
2749	35637	Annular	6.8043	6.8043	6.8043	6.8043	6.8043	6.8043	6.8043	6.8043	6.8043	6.8043	6.8043 ± 0.00
2749	42765	Annular	7.8813	7.8813	7.8813	7.8813	7.8813	7.8813	7.8813	7.8813	7.8813	7.8813	7.8813 ± 0.00
2749	49892	Annular	8.5666	8.5666	8.5666	8.5666	8.5666	8.5666	8.5666	8.5666	8.5666	8.5666	8.5666 ± 0.00
2749	57020	Mist	9.0316	9.0316	9.0316	9.0316	9.0316	9.0316	9.0316	9.0316	9.0316	9.0316	9.0316 ± 0.00

Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
			1	2	3	4	5	6	7	8	9	10	
1001	3.17	Bubble	3.88227	3.88227	3.8822726	3.882273	3.8822726	3.882273	3.882273	3.882273	3.882273	3.882273	3.882273 ± 9E-16
1001	5.64	Bubble	5.29401	5.29401	5.2940081	5.294008	5.2940081	5.294008	5.294008	5.294008	5.294008	5.294008	5.294008 ± 9E-16
1001	8.12	Bubble	6.70574	6.70574	6.7057436	6.705744	6.7057436	6.705744	6.705744	6.705744	6.705744	6.705744	6.705744 ± 9E-16
1001	10.59	Bubble	8.11748	8.11748	8.1174791	8.117479	8.1174791	5.294008	5.294008	5.294008	5.294008	5.294008	6.705744 ± 1.4881
1001	13.07	Bubble-Slug	10.941	10.941	10.94095	10.94095	10.94095	11.99975	11.99975	11.99975	11.99975	11.99975	11.47035 ± 0.558
1001	15.54	Bubble-Slug	6.70574	10.588	16.234958	17.99963	15.176157	6.705744	15.52909	14.82322	14.11735	14.11735	13.19973 ± 3.9025
1001	18.02	Bubble-Slug	9.52921	10.2351	13.411487	17.64669	9.5292146	17.29376	15.52909	14.11735	19.41136	9.882148	13.65854 ± 3.7427
1001	20.49	Bubble-Slug	14.4703	14.8232	13.058553	13.41149	13.058553	16.94083	11.99975	18.35256	16.23496	17.64669	14.99969 ± 2.1836
1001	22.95	Bubble-Slug	16.5879	18.7055	17.646694	15.88202	19.411363	19.7643	20.8231	21.17603	14.47029	16.23496	18.07021 ± 2.2556
1001	28.08	Slug	23.9995	18.7055	25.764173	17.64669	24.705371	17.64669	16.94083	15.17616	22.23483	18.35256	20.11723 ± 3.7165
1001	33.21	Slug	27.1759	26.823	25.058305	24.70537	29.293511	17.64669	17.99963	17.64669	16.94083	17.29376	22.05837 ± 4.9613
1001	38.33	Slug	24.7054	23.6466	28.940578	20.8231	21.176032	25.76417	23.64657	22.58777	23.64657	23.64657	23.85833 ± 2.3185
1001	43.46	Slug	26.47	26.823	25.764173	23.29364	22.587768	23.9995	23.64657	25.76417	25.76417	24.70537	24.88184 ± 1.4432
1001	48.59	Slug	31.0582	27.1759	21.8819	29.99938	28.23471	27.52884	30.70525	31.05818	31.05818	31.76405	29.04646 ± 2.9996
1001	58.85	Slug	30.7052	31.0582	29.293511	28.94058	30.705247	34.58752	32.46992	31.05818	28.23471	34.58752	31.16406 ± 2.1759
1001	69.10	Slug	37.7639	38.8227	34.940453	37.05806	37.058057	41.6462	39.52859	38.82273	38.82273	39.88153	38.4345 ± 1.8411
1001	79.36	Slug	41.6462	39.5286	46.587271	45.8814	45.175536	47.64607	46.23434	47.99901	44.46967	40.5874	44.57555 ± 2.9811
1001	89.62	Slug	56.4694	53.6459	55.057684	51.88128	51.528345	45.8814	41.6462	45.8814	45.8814	44.11673	49.19898 ± 5.115
1001	99.87	Slug	52.9401	52.9401	53.998882	49.41074	50.822478	50.46954	49.76368	52.23421	52.23421	52.94008	51.7754 ± 1.5523
1001	177	Slug	76.5867	81.1748	80.468923	78.70425	73.057312	80.46892	79.41012	83.99826	77.64545	81.88066	79.33953 ± 3.0624
1001	296	Slug-Churn	95.2921	94.5863	95.645079	98.82148	95.998013	96.35095	96.70388	97.05681	97.05681	97.05681	96.45683 ± 1.177
1001	369	Slug-Churn	105.174	104.821	102.70376	103.4096	103.76256	102.3508	101.9979	97.76268	99.17442	102.7038	102.3861 ± 2.326
1001	˙515	Slug-Churn	111.174	110.468	111.17417	112.9388	112.23297	112.233	112.5859	112.5859	113.6447	113.6447	112.2683 ± 1.0581
1001	735	Slug-Churn	116.468	116.468	116.46818	116.4682	116.46818	117.8799	117.8799	117.8799	117.8799	117.8799	117.174 ± 0.744
1001	1454	Churn	120.703	119.998	119.99752	119.9975	119.99752	122.821	122.821	122.821	122.821	122.821	121.4798 ± 1.4293
1001	2474	Churn	117.527	117.527	117.52698	117.527	117.52698	117.527	117.527	117.527	117.527	117.527	117.527 ± 0

Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^2}$										Average dimensionless pressure gradient
			1	2	3	4	5	6	7	8	9	10	
1001	3495	Churn	118.233	118.233	118.23285	118.2328	118.23285	118.2328	118.2328	118.2328	118.2328	118.2328	118.2328 ± 0
1001	4516	Churn	118.586	118.586	118.58578	118.5858	118.58578	118.5858	118.5858	118.5858	118.5858	118.5858	118.5858 ± 1E-14
1001	5537	Churn	121.056	121.056	121.05632	121.0563	121.05632	124.5857	124.5857	124.5857	124.5857	124.5857	122.821 ± 1.8601
1001	14255	Churn	123.174	123.174	123.17392	123.1739	123.17392	125.2915	125.2915	125.2915	125.2915	125.2915	124.2327 ± 1.1161
1001	21382	Churn	113.998	113.998	113.99764	113.9976	113.99764	115.0564	115.0564	115.0564	115.0564	115.0564	114.527 ± 0.558
1001	28510	Annular	104.468	104.468	104.46843	104.4684	104.46843	105.5272	105.5272	105.5272	105.5272	105.5272	104.9978 ± 0.558
1001	35637	Annular	82.9395	82.9395	82.93946	82.93946	82.93946	83.99826	83.99826	83.99826	83.99826	83.99826	83.46886 ± 0.558
1001	42765	Annular	48.3519	48.3519	48.351941	48.35194	48.351941	48.35194	48.35194	48.35194	48.35194	48.35194	48.35194 ± 7E-15
1001	49892	Annular	28.2347	28.2347	28.23471	28.23471	28.23471	28.23471	28.23471	28.23471	28.23471	28.23471	28.23471 ± 0
1001	57020	Mist	14.1174	14.1174	14.117355	14.11735	14.117355	14.11735	14.11735	14.11735	14.11735	14.11735	14.11735 ± 0
2749	3.17	Bubble	0.56196	0.56196	0.5619618	0.561962	0.5619618	0.561962	0.561962	0.561962	0.561962	0.561962	0.561962 ± 1E-16
2749	5.64	Bubble	0.60879	0.60879	0.608792	0.608792	0.608792	0.608792	0.608792	0.608792	0.608792	0.608792	0.608792 ± 0
2749	8.12	Bubble	0.65562	0.65562	0.6556221	0.655622	0.6556221	0.655622	0.655622	0.655622	0.655622	0.655622	0.655622 ± 1E-16
2749	10.59	Bubble	0.88977	0.88977	0.8897729	0.889773	0.8897729	0.936603	0.936603	0.936603	0.936603	0.936603	0.913188 ± 0.0247
2749	13.07	Bubble	0.9366	0.9366	0.936603	0.936603	0.936603	0.936603	0.936603	0.936603	0.936603	0.936603	0.936603 ± 0
2749	15.54	Bubble	1.03026	1.03026	1.0302633	1.030263	1.0302633	1.030263	1.030263	1.030263	1.030263	1.030263	1.030263 ± 2E-16
2749	18.02	Bubble	1.07709	1.07709	1.0770935	1.077093	1.0770935	1.077093	1.077093	1.077093	1.077093	1.077093	1.077093 ± 0
2749	20.49	Bubble	1.17075	1.07709	1.1707538	1.217584	1.0770935	1.264414	1.264414	1.311244	1.217584	1.217584	1.198852 ± 0.0771
2749	22.95	Bubble	1.35807	1.31124	1.2644141	1.311244	1.3112443	2.154187	2.060527	2.107357	2.060527	2.107357	1.704618 ± 0.4161
2749	28.08	Bubble	1.63906	1.68589	1.5922252	1.685885	1.6390553	2.294677	2.481998	2.481998	2.107357	2.060527	1.966866 ± 0.3621
2749	33.21	Bubble-Slug	1.4049	1.63906	1.9668664	1.966866	2.1073568	2.341508	2.294677	2.341508	2.341508	2.294677	2.069893 ± 0.3288
2749	38.33	Bubble-Slug	2.90347	2.66932	2.2478473	2.294677	2.0136965	2.341508	2.716149	2.013697	1.498565	2.247847	2.294677 ± 0.4065
2749	43.46	Slug	2.15419	2.20102	2.154187	2.154187	2.1073568	2.856639	2.762979	2.622489	3.04396	2.435168	2.449217 ± 0.3477
2749	48.59	Slug	2.38834	2.52883	2.3415076	2.481998	2.4351679	2.903469	2.856639	2.856639	2.809809	2.809809	2.641221 ± 0.2243
2749	58.85	Slug	2.52883	2.482	2.3415076	2.716149	2.9034694	2.903469	2.903469	2.809809	2.575658	2.99713	2.716149 ± 0.2219
2749	69.10	Slug	2.9503	3.04396	2.6693187	3.980563	2.9502996	3.278111	3.324941	3.418601	3.793242	3.652752	3.306209 ± 0.4155

Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^2}$										Average dimensionless pressure gradient
			1	2	3	4	5	6	7	8	9	10	
2749	79.36	Slug	3.8869	3.79324	3.6527519	3.652752	3.699582	4.121053	4.167884	4.121053	3.605922	3.746412	3.844755 ± 0.2168
2749	89.62	Slug	3.65275	3.65275	3.5590916	3.793242	3.5122614	3.840072	4.121053	4.027393	3.933733	3.652752	3.77451 ± 0.2038
2749	99.87	Slug	4.54252	4.58935	4.5893549	3.980563	4.1678835	4.355204	4.308374	4.542525	4.542525	4.308374	4.392668 ± 0.2057
2749	177	Slug	6.93086	7.35233	7.399164	7.773805	7.7738052	7.492824	7.586485	7.586485	7.586485	7.586485	7.506873 ± 0.2439
2749	296	Slug	10.209	10.0685	9.9748224	9.974822	9.8343319	9.647011	9.553351	9.506521	9.3192	9.506521	9.759404 ± 0.293
2749	369	Slug-Churn	11.1456	10.8646	10.817765	10.81777	10.817765	10.95826	11.00509	10.8646	10.81777	10.81777	10.89269 ± 0.1108
2749	515	Slug-Churn	12.5973	12.5973	12.550481	12.55048	12.129009	12.2695	12.31633	12.17584	12.22267	12.31633	12.37253 ± 0.1831
2749	735	Slug-Churn	13.4871	13.7681	13.627574	13.58074	13.533914	13.44025	13.48708	13.53391	13.90856	13.81489	13.61821 ± 0.1589
2749	1454	Slug-Churn	14.7047	14.7047	14.704668	14.70467	14.704668	14.37686	14.33003	14.42369	14.37686	14.42369	14.54545 ± 0.1699
2749	2474	Churn	14.1895	14.1895	14.189536	14.18954	14.189536	14.23637	14.23637	14.23637	14.23637	14.23637	14.21295 ± 0.0247
2749	3495	Churn	14.0959	14.0959	14.095876	14.09588	14.095876	14.09588	14.09588	14.09588	14.09588	14.09588	14.09588 ± 0
2749	4516	Churn	14.0022	14.0022	14.002215	14.00222	14.002215	14.00222	14.00222	14.00222	14.00222	14.00222	14.00222 ± 4E-15
2749	5537	Churn	14.5173	14.5173	14.517347	14.51735	14.517347	14.84516	14.84516	14.84516	14.84516	14.84516	14.68125 ± 0.1728
2749	14255	Churn	13.2998	13.2998	13.299763	13.29976	13.299763	13.53391	13.53391	13.53391	13.53391	13.53391	13.41684 ± 0.1234
2749	21382	Churn	11.0987	11.0987	11.098746	11.09875	11.098746	11.14558	11.14558	11.14558	11.14558	11.14558	11.12216 ± 0.0247
2749	28510	Annular	8.19528	8.19528	8.1952766	8.195277	8.1952766	8.195277	8.195277	8.195277	8.195277	8.195277	8.195277 ± 2E-15
2749	35637	Annular	5.71328	5.71328	5.7132785	5.713279	5.7132785	5.713279	5.713279	5.713279	5.713279	5.713279	5.713279 ± 9E-16
2749	42765	Annular	3.65275	3.65275	3.6527519	3.652752	3.6527519	3.652752	3.652752	3.652752	3.652752	3.652752	3.652752 ± 5E-16
2749	49892	Annular	2.34151	2.34151	2.3415076	2.341508	2.3415076	2.341508	2.341508	2.341508	2.341508	2.341508	2.341508 ± 5E-16
2749	57020	Mist	1.45173	1.45173	1.4517347	1.451735	1.4517347	1.451735	1.451735	1.451735	1.451735	1.451735	1.451735 ± 2E-16

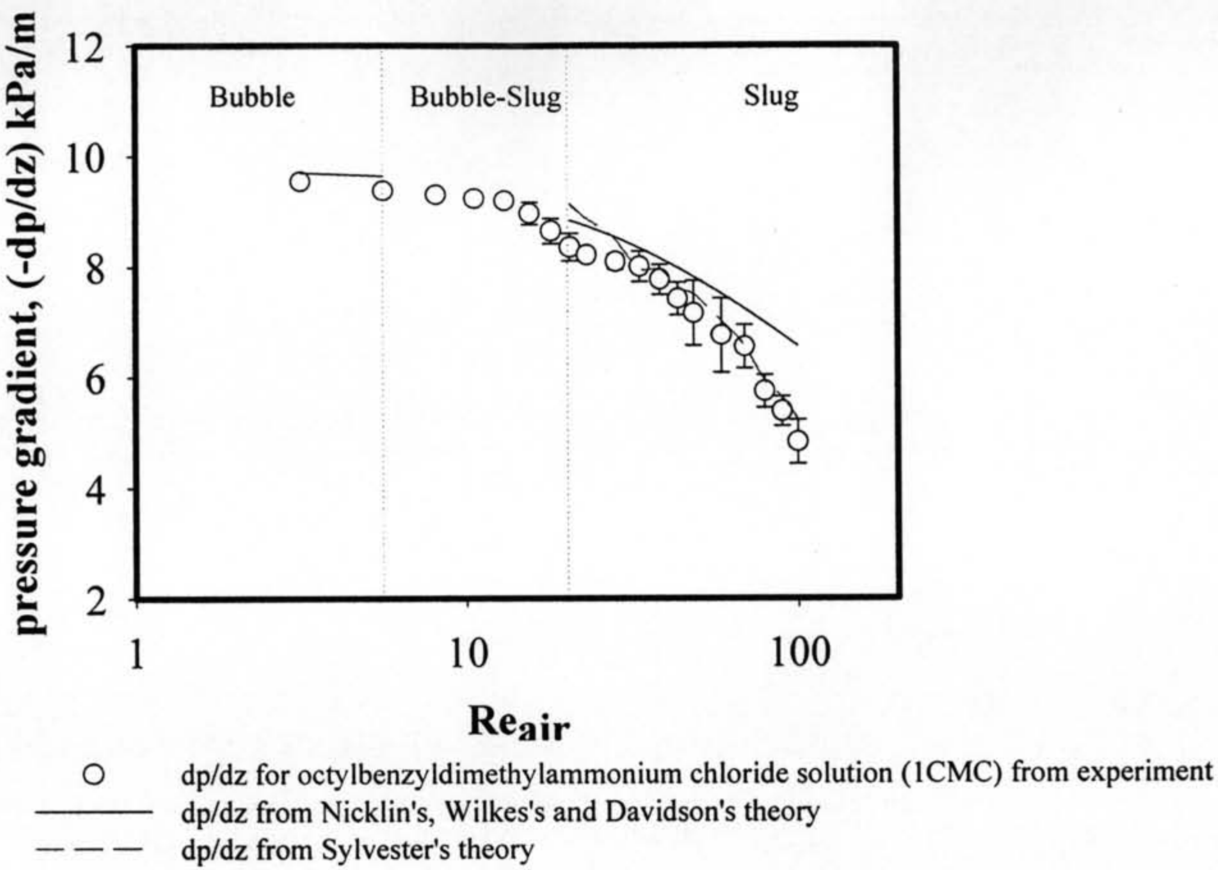


Figure H10 Comparison between Nicklin's theory, Sylvester's theory and experimental pressure gradient vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) at $Re_{solution} = 0$ by using pipe diameter 19 mm.

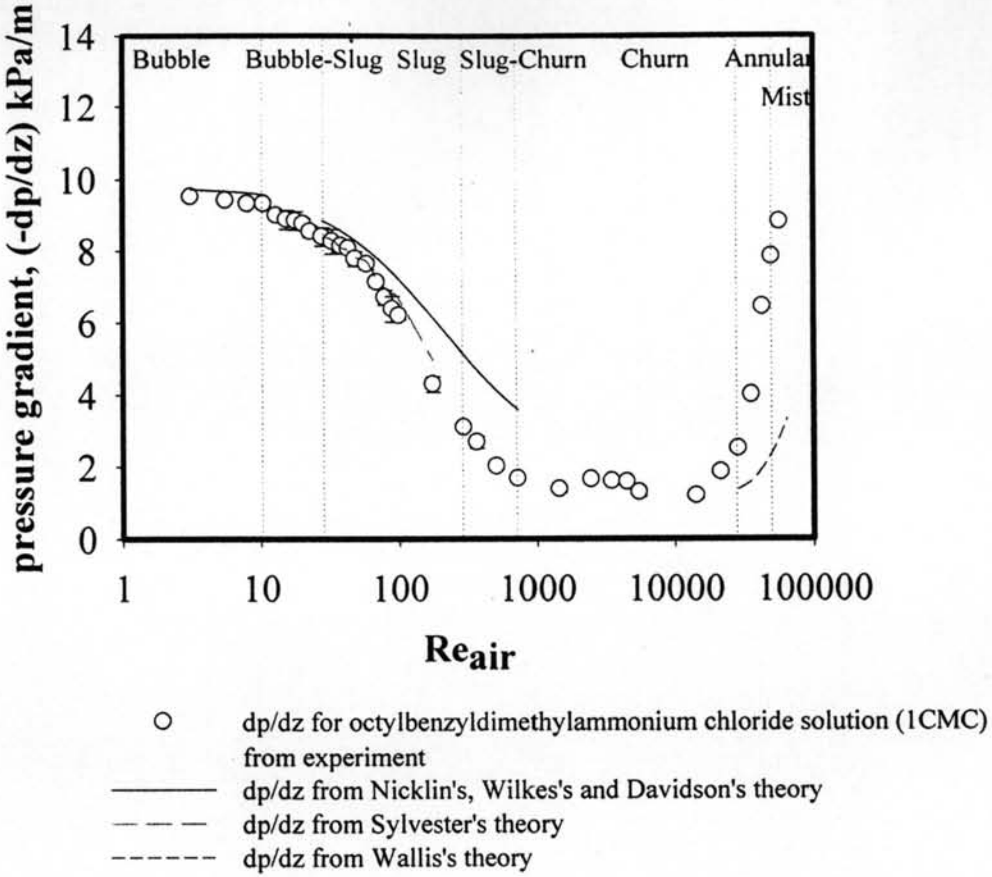
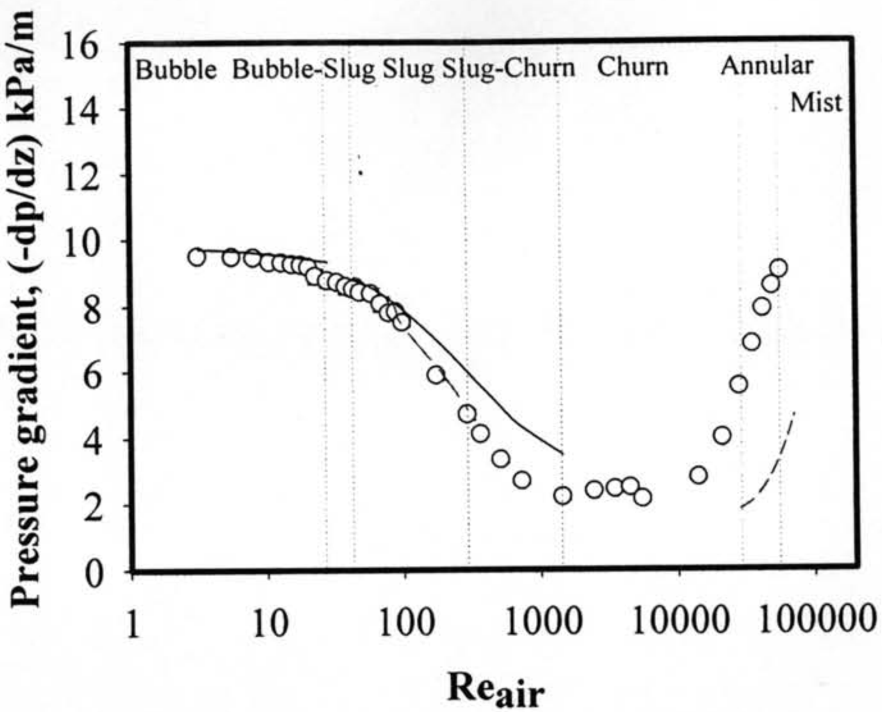


Figure H11 Comparison between Nicklin's theory, Sylvester's theory, Wallis's theory and experimental pressure gradient vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) at $Re_{solution}$ = 1001 by using pipe diameter of 19 mm.



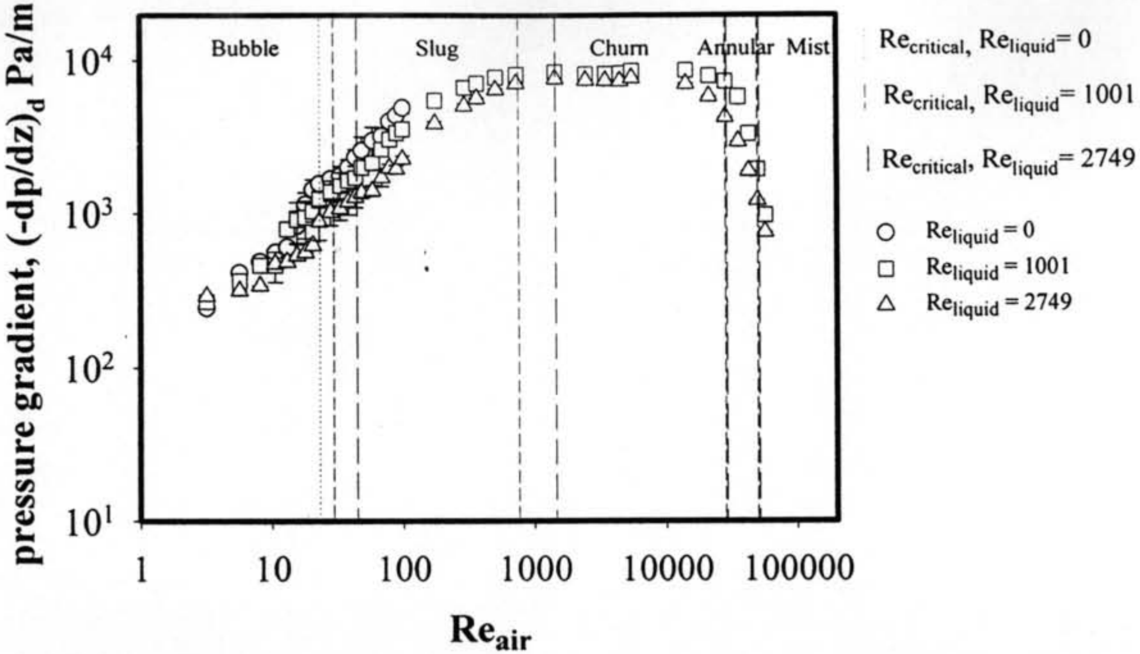
○ dp/dz for octylbenzyldimethylammonium chloride solution (1CMC) from experiment

——— dp/dz from Nicklin's, Wilkes's and Davidson's theory

— — — dp/dz from Sylvester's theory

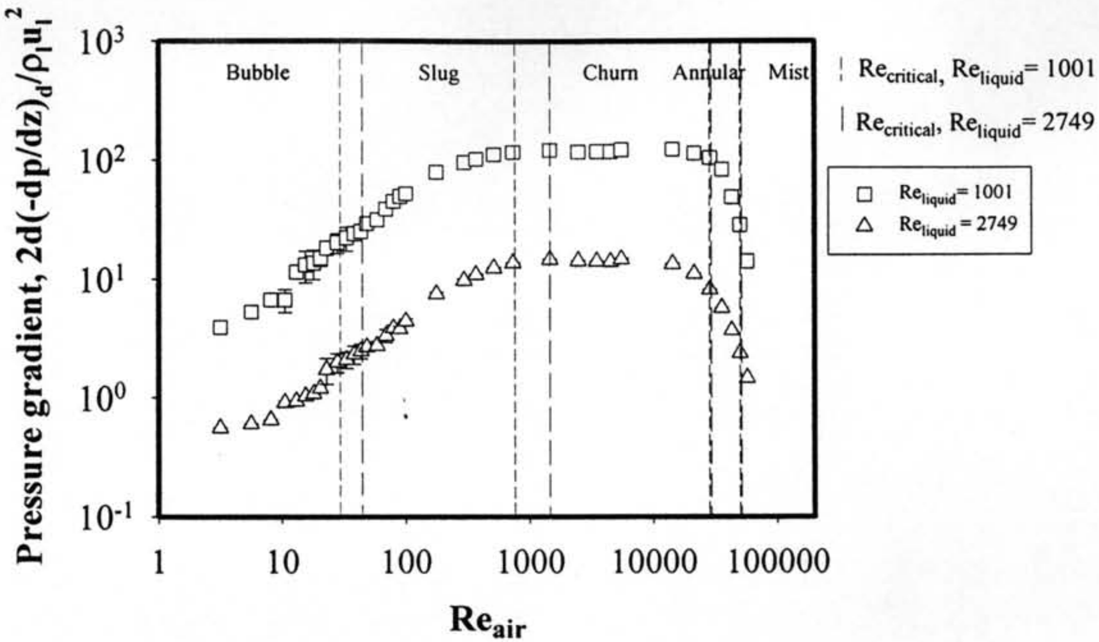
------ dp/dz from Wallis's theory

Figure H12 Comparison between Nicklin's theory, Sylvester's theory, Wallis's theory and experimental pressure gradient vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) at $Re_{solution}$ = 2749 by using pipe diameter of 19 mm.



$(-dp/dz)_d$: Dynamic pressure gradient for octylbenzyldimethyl ammonium chloride surfactant (1CMC)

Figure H13 Comparison dynamic pressure gradient from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.



$(-dp/dz)_d$: Dynamic pressure gradient for octylbenzyldimethyl ammonium chloride surfactant (1CMC)

ρ_l : Liquid density

u_l : Mean liquid velocity, (Liquid flow rate / Cross section area)

d : Pipe diameter

Figure H14 Comparison dimensionless pressure gradient from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table H9 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes of octylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm

Pipe diameter (mm)	$Re_{solution}$	Re_{air}(critical) for each flow regime					
		Bubble-slug	Slug	Slug-churn	Churn	Annular	Mist
19	0	8.12	20.49	-	-	-	-
	1001	13.07	28.08	296	1454	28510	57020
	2749	33.21	43.46	369	2474	28510	57020

Appendix I Octylbenzyldimethylammonium Chloride Surfactant (2CMC) – Air Flow for the Pipe Diameter of 19 mm

Table I1 Determination of bubble size from octylbenzyldimethylammonium chloride solution (2CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the bubble size:

1. Make a movie of the bubble flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the bubble size by Scion Image software program.

Equivalent diameter (D_e) of the bubble is defined as the diameter of a sphere that has the same volume as the bubble.

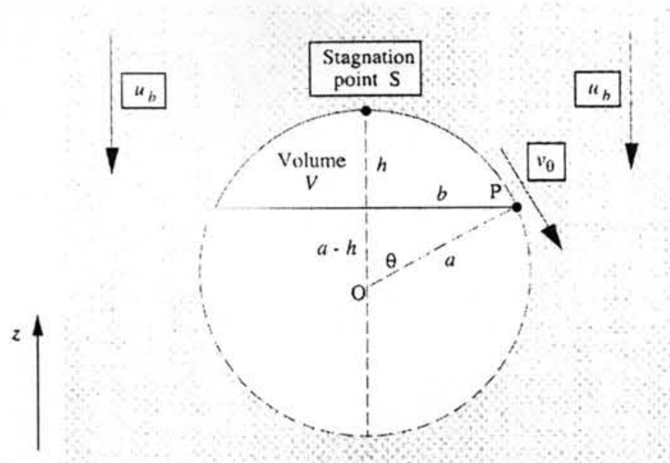


Figure I1 Flow around a spherical cap bubble (Wilkes, 1999).

$$\text{Equivalent diameter } (D_e) = \sqrt[3]{3.94h\left[\frac{h^2+b^2}{2h}\right]^2 - 1.94b^2\left[\left(\frac{h^2+b^2}{2h}\right)-h\right]} \qquad \text{(I1)}$$

$Re_{solution}$	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble width, W_b (mm)			Average bubble width (mm)	Equivalent diameter, D_e (mm)			Average equivalent diameter, De (mm)
		1	2	3		1	2	3		1	2	3	
2731	3.17	8.6	8.8	8.0	8.5 ± 0.4	10.6	9.7	10.5	10.3 ± 0.5	11.0	10.8	10.5	10.8 ± 0.3
2731	5.64	8.7	9.7	9.2	9.2 ± 0.5	10.5	10.9	10.6	10.7 ± 0.2	11.1	12.0	11.5	11.5 ± 0.5
2731	8.12	9.3	9.5	9.8	9.6 ± 0.3	10.8	10.4	11.5	10.9 ± 0.6	11.7	11.7	12.4	11.9 ± 0.4
2731	10.59	10.2	9.7	9.7	9.9 ± 0.3	10.4	11.5	10.9	10.9 ± 0.6	12.3	12.2	12.0	12.2 ± 0.1
2731	13.07	10.4	10.3	10.5	10.4 ± 0.1	11.5	10.4	11.2	11.0 ± 0.6	12.8	12.3	12.8	12.7 ± 0.3
2731	15.54	11.1	11.7	11.6	11.5 ± 0.3	11.3	11.2	11.7	11.4 ± 0.3	13.4	13.8	13.9	13.7 ± 0.3
2731	18.02	12.4	12.5	12.7	12.5 ± 0.2	11.4	11.6	12.6	11.8 ± 0.6	14.5	14.6	15.2	14.8 ± 0.4
2731	20.49	13.2	13.1	13.4	13.2 ± 0.2	12.1	12.3	12.4	12.2 ± 0.2	15.4	15.4	15.8	15.5 ± 0.2
2731	22.95	14.7	15.2	15.6	15.2 ± 0.4	12.1	12.7	12.4	12.4 ± 0.3	16.8	17.4	17.6	17.3 ± 0.5
2731	28.08	17.8	17.4	17.4	17.5 ± 0.3	13.0	13.5	12.5	13.0 ± 0.5	19.8	19.6	19.3	19.6 ± 0.3
2731	33.21	19.4	19.7	19.3	19.5 ± 0.2	13.8	13.6	12.9	13.5 ± 0.5	21.5	21.7	21.2	21.4 ± 0.2

$Re_{solution}$	Re_{air}	Bubble height / Pipe diameter			Average, R_h/D	Bubble width / Pipe diameter			Average, W_b/D	Equivalent diameter / Pipe diameter			Average equivalent diameter, De/D
		1	2	3		1	2	3		1	2	3	
2731	3.17	0.45	0.46	0.42	0.45 ± 0.02	0.56	0.51	0.55	0.54 ± 0.03	0.58	0.57	0.55	0.57 ± 0.01
2731	5.64	0.46	0.51	0.48	0.48 ± 0.03	0.55	0.57	0.56	0.56 ± 0.01	0.58	0.63	0.61	0.61 ± 0.02
2731	8.12	0.49	0.50	0.52	0.50 ± 0.01	0.57	0.55	0.61	0.57 ± 0.03	0.62	0.62	0.65	0.63 ± 0.02
2731	10.59	0.54	0.51	0.51	0.52 ± 0.02	0.55	0.60	0.58	0.58 ± 0.03	0.65	0.64	0.63	0.64 ± 0.01
2731	13.07	0.55	0.54	0.55	0.55 ± 0.01	0.61	0.55	0.59	0.58 ± 0.03	0.68	0.65	0.67	0.67 ± 0.01
2731	15.54	0.59	0.61	0.61	0.60 ± 0.02	0.60	0.59	0.62	0.60 ± 0.01	0.71	0.73	0.73	0.72 ± 0.01
2731	18.02	0.65	0.66	0.67	0.66 ± 0.01	0.60	0.61	0.66	0.62 ± 0.03	0.76	0.77	0.80	0.78 ± 0.02
2731	20.49	0.69	0.69	0.71	0.70 ± 0.01	0.64	0.65	0.65	0.64 ± 0.01	0.81	0.81	0.83	0.82 ± 0.01
2731	22.95	0.77	0.80	0.82	0.80 ± 0.02	0.64	0.67	0.65	0.65 ± 0.02	0.88	0.92	0.93	0.91 ± 0.02
2731	28.08	0.94	0.91	0.92	0.92 ± 0.01	0.68	0.71	0.66	0.68 ± 0.03	1.04	1.03	1.02	1.03 ± 0.01
2731	33.21	1.02	1.03	1.02	1.02 ± 0.01	0.73	0.72	0.68	0.71 ± 0.02	1.13	1.14	1.11	1.13 ± 0.01

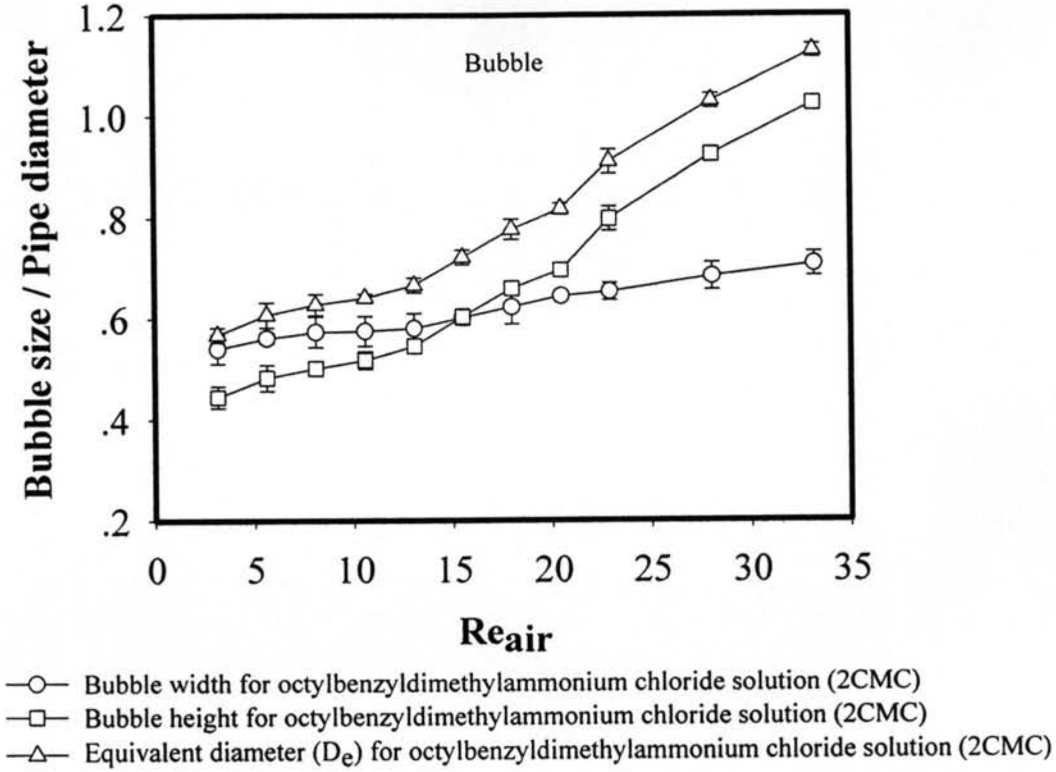


Figure I2 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (2CMC) at $Re_{solution}$ = 2731 by using pipe diameter of 19 mm.

Table I2 Determination of slug height from octylbenzyldimethylammonium chloride solution (2CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the slug height:

1. Make a movie of the slug flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the slug height by Scion Image software program.

$Re_{solution}$	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
2731	43.46	37.3	37.2	37.8	37.5 ± 0.3	2.0	2.0	2.0	2.0 ± 0.02
2731	48.59	40.7	40.6	41.5	40.9 ± 0.5	2.1	2.1	2.2	2.2 ± 0.03
2731	58.85	43.5	43.0	44.1	43.5 ± 0.6	2.3	2.3	2.3	2.3 ± 0.03
2731	69.10	48.3	49.7	48.0	48.6 ± 0.9	2.5	2.6	2.5	2.6 ± 0.05
2731	79.36	51.1	52.0	52.0	51.7 ± 0.5	2.7	2.7	2.7	2.7 ± 0.03
2731	89.62	55.5	55.0	56.0	55.5 ± 0.5	2.9	2.9	2.9	2.9 ± 0.03
2731	99.87	60.5	59.4	59.3	59.7 ± 0.7	3.2	3.1	3.1	3.1 ± 0.04
2731	177	84.7	85.0	84.8	84.8 ± 0.2	4.5	4.5	4.5	4.5 ± 0.01
2731	296	143	144	141	142.6 ± 1.2	7.5	7.6	7.4	7.5 ± 0.06

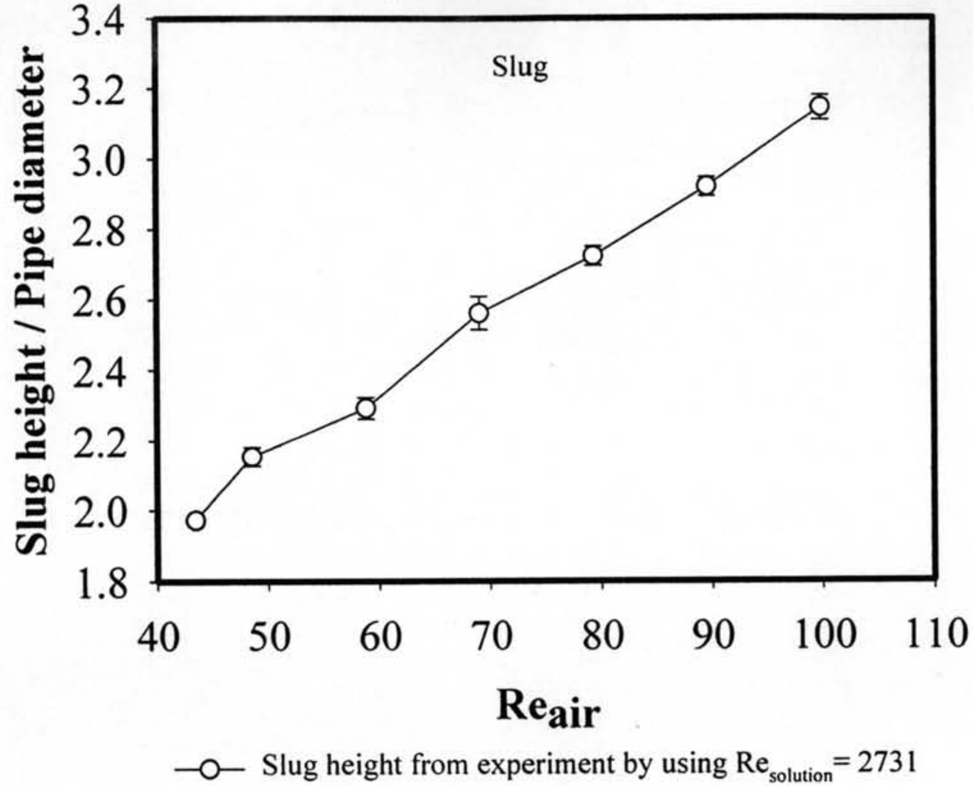


Figure I3 Slug height from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (2CMC) by using pipe diameter of 19 mm.

Table I3 Determination of bubble and slug velocity for octylbenzyldimethylammonium chloride solution (2CMC) from Nicklin's theory and experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

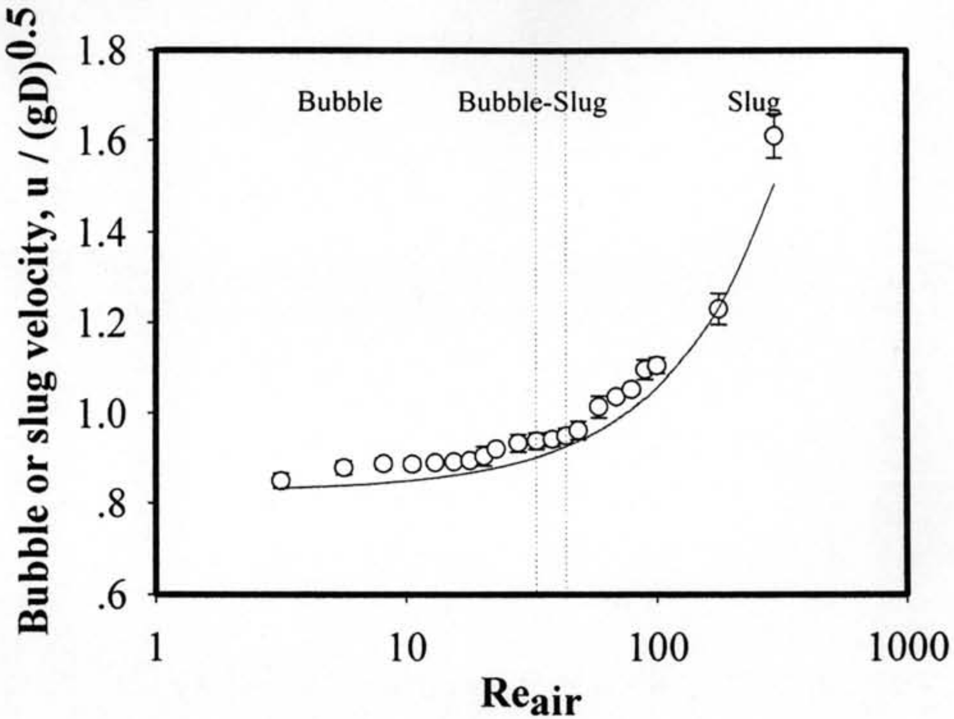
temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Bubble velocity from theory, $u_s = 1.2(\frac{Q_{qir} + Q_{liquid}}{A}) + 0.35\sqrt{gD}$ (I2)

Determination of bubble velocity from experiment by timing the bubble at known distance (0.8m)

$Re_{solution}$	Re_{air}	Time of bubble travel (sec)/0.8m					Average (sec/0.8 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
2731	3.17	2.19	2.22	2.16	2.22	2.12	2.18 ± 0.04	0.37	0.36	0.37	0.36	0.38	0.37 ± 0.007	0.36
2731	5.64	2.12	2.09	2.06	2.12	2.16	2.11 ± 0.04	0.38	0.38	0.39	0.38	0.37	0.38 ± 0.007	0.36
2731	8.11	2.09	2.06	2.10	2.06	2.13	2.09 ± 0.03	0.38	0.39	0.38	0.39	0.38	0.38 ± 0.005	0.36
2731	10.59	2.06	2.06	2.10	2.13	2.10	2.09 ± 0.03	0.39	0.39	0.38	0.38	0.38	0.38 ± 0.005	0.37
2731	13.06	2.09	2.10	2.06	2.10	2.06	2.08 ± 0.02	0.38	0.38	0.39	0.38	0.39	0.38 ± 0.004	0.37
2731	15.53	2.06	2.09	2.06	2.09	2.09	2.08 ± 0.02	0.39	0.38	0.39	0.38	0.38	0.39 ± 0.003	0.37
2731	18.01	2.07	2.10	2.06	2.06	2.07	2.07 ± 0.02	0.39	0.38	0.39	0.39	0.39	0.39 ± 0.003	0.37
2731	20.48	2.00	2.00	2.09	2.10	2.06	2.05 ± 0.05	0.40	0.40	0.38	0.38	0.39	0.39 ± 0.009	0.38
2731	22.94	2.00	2.04	2.03	2.00	2.00	2.01 ± 0.02	0.40	0.39	0.39	0.40	0.40	0.40 ± 0.004	0.38
2731	28.06	1.96	1.97	1.94	2.03	2.03	1.99 ± 0.04	0.41	0.41	0.41	0.39	0.39	0.40 ± 0.008	0.38
2731	33.19	1.94	2.03	1.94	2.00	1.97	1.98 ± 0.04	0.41	0.39	0.41	0.40	0.41	0.40 ± 0.008	0.39
2731	38.31	2.00	2.00	1.94	1.97	1.93	1.97 ± 0.03	0.40	0.40	0.41	0.41	0.41	0.41 ± 0.007	0.39
2731	43.44	1.94	1.94	1.91	2.00	1.97	1.95 ± 0.03	0.41	0.41	0.42	0.40	0.41	0.41 ± 0.007	0.40
2731	48.57	1.97	1.91	1.97	1.91	1.88	1.93 ± 0.04	0.41	0.42	0.41	0.42	0.43	0.42 ± 0.009	0.40
2731	58.82	1.79	1.78	1.85	1.88	1.85	1.83 ± 0.04	0.45	0.45	0.43	0.43	0.43	0.44 ± 0.010	0.41
2731	69.07	1.78	1.79	1.81	1.79	1.78	1.79 ± 0.01	0.45	0.45	0.44	0.45	0.45	0.45 ± 0.003	0.42
2731	79.32	1.75	1.78	1.75	1.75	1.78	1.76 ± 0.02	0.46	0.45	0.46	0.46	0.45	0.45 ± 0.004	0.44
2731	89.57	1.68	1.66	1.69	1.68	1.75	1.69 ± 0.03	0.48	0.48	0.47	0.48	0.46	0.47 ± 0.009	0.45
2731	99.82	1.66	1.69	1.66	1.72	1.66	1.68 ± 0.03	0.48	0.47	0.48	0.47	0.48	0.48 ± 0.008	0.46
2731	177	1.50	1.47	1.53	1.47	1.57	1.51 ± 0.04	0.53	0.54	0.52	0.54	0.51	0.53 ± 0.015	0.53
2731	296	1.19	1.19	1.13	1.13	1.12	1.15 ± 0.03	0.67	0.67	0.71	0.71	0.71	0.69 ± 0.021	0.65

$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
2731	3.17	0.85	0.83	0.86	0.83	0.87	0.85 ± 0.017	0.83
2731	5.64	0.87	0.89	0.90	0.87	0.86	0.88 ± 0.016	0.84
2731	8.11	0.89	0.90	0.88	0.90	0.87	0.89 ± 0.012	0.84
2731	10.59	0.90	0.90	0.88	0.87	0.88	0.89 ± 0.013	0.85
2731	13.06	0.89	0.88	0.90	0.88	0.90	0.89 ± 0.009	0.86
2731	15.53	0.90	0.89	0.90	0.89	0.89	0.89 ± 0.007	0.86
2731	18.01	0.90	0.88	0.90	0.90	0.90	0.89 ± 0.007	0.87
2731	20.48	0.93	0.93	0.89	0.88	0.90	0.90 ± 0.021	0.87
2731	22.94	0.93	0.91	0.91	0.93	0.93	0.92 ± 0.009	0.88
2731	28.06	0.95	0.94	0.96	0.91	0.91	0.93 ± 0.019	0.89
2731	33.19	0.96	0.91	0.96	0.93	0.94	0.94 ± 0.018	0.90
2731	38.31	0.93	0.93	0.96	0.94	0.96	0.94 ± 0.016	0.91
2731	43.44	0.96	0.96	0.97	0.93	0.94	0.95 ± 0.017	0.93
2731	48.57	0.94	0.97	0.94	0.97	0.99	0.96 ± 0.020	0.94
2731	58.82	1.04	1.04	1.00	0.99	1.00	1.01 ± 0.024	0.96
2731	69.07	1.04	1.04	1.02	1.04	1.04	1.04 ± 0.007	0.98
2731	79.32	1.06	1.04	1.06	1.06	1.04	1.05 ± 0.010	1.01
2731	89.57	1.10	1.12	1.10	1.10	1.06	1.10 ± 0.022	1.03
2731	99.82	1.12	1.10	1.12	1.08	1.12	1.10 ± 0.017	1.05
2731	177	1.24	1.26	1.21	1.26	1.18	1.23 ± 0.034	1.23
2731	296	1.56	1.56	1.64	1.64	1.65	1.61 ± 0.048	1.50



○ Bubble and slug velocity from experiment by using $Re_{solution}$= 2731

—— Bubble and slug velocity from Nicklin's, Wilkes's, and Davidson's theory by using $Re_{solution}$= 2731

Figure I4 Comparison bubble and slug velocity from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (2CMC) comparing with Nicklin's theory by using pipe diameter of 19 mm.

Table I4 Determination of the pressure gradient for the bubble flow regime from Nicklin's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution} = 1.189 \times 10^{-3}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Superficial liquid velocity, $j_{liquid} = \dfrac{Q_{liquid}}{A}$ (I3)

Superficial air velocity, $j_{air} = \dfrac{Q_{air}}{A}$ (I4)

Reynolds number of liquid, $\mathrm{Re}_{liquid} = \dfrac{\rho\, j_{liquid} D}{\mu_{liquid}}$ (I5)

Reynolds number of air, $\mathrm{Re}_{air} = \dfrac{\rho\, j_{air} D}{\mu_{air}}$ (I6)

Bubble velocity rising in stagnant liquid, $u_b = 1.00\sqrt{g R_b}$ (I7)

where R_b is equivalent radius of the bubble which defined as the radius of a sphere that has the same volume as the bubble

Void fraction, $\varepsilon = \dfrac{Q_{air}}{Q_{air} + Q_{liquid} + u_b A}$ (I8)

Pressure gradient for bubble flow regime, $\dfrac{dp}{dz} = -\rho_l g(1-\varepsilon)$ (I9)

$Q_{solution}$ (ml/min)	Sup. solution velocity $j_{solution}$ (m/s)	$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Q_{air} (L/min)	Sup. Air velocity j_{air} (m/s)	Q_{air} (m^3/sec)	Re_{air}	Flow regime	U_b (m/s)	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
2911	0.1712	4.85E-05	2731	0.0444	0.0026	7.4E-07	3.17	Bubble	0.2301	0.0065	9.7300
2911	0.1712	4.85E-05	2731	0.0792	0.0047	1.3E-06	5.64	Bubble	0.2379	0.0113	9.6831
2911	0.1712	4.85E-05	2731	0.1139	0.0067	1.9E-06	8.12	Bubble	0.2418	0.0160	9.6370
2911	0.1712	4.85E-05	2731	0.1486	0.0087	2.5E-06	10.59	Bubble	0.2445	0.0206	9.5917
2911	0.1712	4.85E-05	2731	0.1833	0.0108	3.1E-06	13.07	Bubble	0.2492	0.0250	9.5484
2911	0.1712	4.85E-05	2731	0.2180	0.0128	3.6E-06	15.54	Bubble	0.2594	0.0289	9.5101
2911	0.1712	4.85E-05	2731	0.2528	0.0149	4.2E-06	18.02	Bubble	0.2692	0.0327	9.4735
2911	0.1712	4.85E-05	2731	0.2875	0.0169	4.8E-06	20.49	Bubble	0.2759	0.0364	9.4365
2911	0.1712	4.85E-05	2731	0.3220	0.0189	5.4E-06	22.95	Bubble	0.2910	0.0394	9.4079
2911	0.1712	4.85E-05	2731	0.3939	0.0232	6.6E-06	28.08	Bubble	0.3097	0.0460	9.3432
2911	0.1712	4.85E-05	2731	0.4659	0.0274	7.8E-06	33.21	Bubble	0.3243	0.0524	9.2801

Table I5 Determination of the pressure gradient for the slug flow regime from Nicklin's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Mean liquid velocity, $u_l = \dfrac{Q_{air} + Q_{liquid}}{A}$ (I10)

Reynolds number of the liquid slug, $\text{Re}_{slug} = \dfrac{\rho_{liquid} u_l D}{\mu_{liquid}}$ (I11)

Fanning friction factor, $f_F = \dfrac{16}{\text{Re}_{slug}}$ for laminar flow ($\text{Re}_{slug} < 2000$) (I12)

$f_F = 0.079\,\text{Re}_{slug}^{-1/4}$ for turbulent flow ($\text{Re}_{slug} > 4000$) (I13)

Single-phase frictional pressure gradient for liquid only, $\left(\dfrac{dp}{dz}\right)_{sp} = \dfrac{2 f_F \rho_{liquid} u_l}{D}$ (I14)

Void fraction, $\varepsilon = \dfrac{Q_{air}}{1.2(Q_{air} + Q_{liquid}) + 0.35 A\sqrt{gD}}$ (I15)

Pressure gradient for slug flow regime, $\dfrac{dp}{dz} = (1-\varepsilon)\left[-\rho_{liquid}\, g + \left(\dfrac{dp}{dz}\right)_{sp}\right]$ (I16)

$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Q_{air} (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
4.851E-05	2731	1.016E-05	43.46	Slug	0.2070	3303	0.0104	46.9430	0.0898	8.9570
4.851E-05	2731	1.136E-05	48.59	Slug	0.2113	3370	0.0104	48.6348	0.0991	8.8667
4.851E-05	2731	1.376E-05	58.85	Slug	0.2197	3505	0.0103	52.0951	0.1171	8.6929
4.851E-05	2731	1.616E-05	69.10	Slug	0.2282	3640	0.0102	55.6569	0.1342	8.5274
4.851E-05	2731	1.856E-05	79.36	Slug	0.2367	3775	0.0101	59.3192	0.1505	8.3698
4.851E-05	2731	2.096E-05	89.62	Slug	0.2451	3910	0.0100	63.0810	0.1661	8.2195
4.851E-05	2731	2.335E-05	99.87	Slug	0.2536	4045	0.0099	66.9415	0.1810	8.0760
4.851E-05	2731	4.134E-05	177	Slug	0.3171	5058	0.0094	98.9622	0.2744	7.1775
4.851E-05	2731	6.922E-05	296	Slug	0.4155	6628	0.0088	158.8083	0.3760	6.2101
4.851E-05	2731	8.631E-05	369	Slug-Churn	0.4758	7590	0.0085	201.3160	0.4218	5.7785
4.851E-05	2731	0.0001205	515	Slug-Churn	0.5964	9513	0.0080	298.9459	0.4905	5.1415
4.851E-05	2731	0.0001718	735	Slug-Churn	0.7773	12399	0.0075	475.2771	0.5592	4.5263
4.851E-05	2731	0.0003399	1454	Slug-Churn	1.3706	21865	0.0065	1282.5530	0.6679	3.6783

Table I6 Determination of the pressure gradient for the slug flow regime from Sylvester's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

$\beta = L_{TB}/L_{SU}$ (I17)

where: L_{TB} is length of the Taylor bubble

L_{SU} is length of the slug unit

Friction factor associated with the Taylor bubble, $f_{TB} = \dfrac{1}{\left[-2.0\log\left\{\dfrac{\left(1-\alpha_{TB}^{1/2}\right)}{7.4}\right\}\right]^2}$ (I18)

Reynolds number of the liquid slug, $\mathrm{Re}_{LS} = \dfrac{\rho_L U_{LLS} D}{\mu_L}$ (I19)

where: velocity of the liquid in the liquid slug, $U_{LLS} = U_{SG} + U_{SL}$ (I20)

Friction factor associated with the liquid slug, $f_{LS} = \dfrac{1}{\left[-2.0\log\left\{\dfrac{\varepsilon/D}{3.7} - \left(\dfrac{5.02}{\mathrm{Re}_{LS}}\right)\log\left(\dfrac{\varepsilon/D}{3.7} + \dfrac{13}{\mathrm{Re}_{LS}}\right)\right\}\right]^2}$ (I21)

where: ε is the pipe roughness

Acceleration pressure drop, $(\Delta P)_A = \rho_L(U_{LTB} + U_{TB})(1-\alpha_{TB})(U_{LTB} + U_{TB} + U_{LLS})$ (I22)

where: velocity of the liquid film around the Taylor bubble, $U_{LTB} = 9.916\left[gD\left(1-\sqrt{\alpha_{TB}}\right)\right]^{1/2}$ (I23) velocity of the Taylor bubble, $U_{TB} = 1.2(U_{SG} + U_{SL}) + 0.35\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}$ (I24)

area average void fraction of the Taylor bubble, $\alpha_{TB} = \frac{\text{Average all area at Taylor bubble region}}{\text{Average area in Taylor bubble}}$ (I25)

Hydrostatic pressure drop, $(\Delta P)_H = \rho_L(1-\alpha_{LS})gL_{LS}$ (I26)

where: void fraction of the liquid slug, $\alpha_{LS} = \frac{U_{SG}}{0.425 + 2.65(U_{SG} + U_{SL})}$ (I27)

length of the liquid slug, L_{LS}

Frictional pressure drop of slug unit, $(\Delta P)_F = \frac{L_{LS}}{2D}\left[\frac{\rho_G \beta f_{TB} U_{TB}^2}{(1-\beta)[1-(1-\alpha_{TB}^{1/2}]} + U_{LLS}^2 \rho_L (1-\alpha_{LS}) f_{LS} (1-\beta)\right]$ (I28)

Total pressure drop in the slug unit, $(\Delta P)_T = (\Delta P)_A + (\Delta P)_H + (\Delta P)_F$ (I29)

$Re_{solution}$	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
2731	43.46	Slug	0.2571	0.0539	3303	0.0421	220	1021	3.6819	1245.0	1.2450	8.5457
2731	48.59	Slug	0.2239	0.0538	3370	0.0418	220	1333	5.1956	1558.5	1.5585	8.5242
2731	58.85	Slug	0.2443	0.0535	3505	0.0414	220	1255	5.0945	1480.1	1.4801	8.3075
2731	69.10	Slug	0.2248	0.0535	3640	0.0409	224	1551	6.8900	1782.1	1.7821	8.2369
2731	79.36	Slug	0.2262	0.0537	3775	0.0405	231	1625	7.6676	1863.4	1.8634	8.1489
2731	89.62	Slug	0.2584	0.0536	3910	0.0401	233	1452	6.9754	1692.3	1.6923	7.8826
2731	99.87	Slug	0.3254	0.0555	4045	0.0397	274	1121	5.2014	1400.4	1.4004	7.6327
2731	177	Slug	0.3128	0.0468	5058	0.0373	159	1614	11.1839	1783.9	1.7839	6.5799
2731	296	Slug	0.3909	0.0465	6628	0.0346	190	1827	17.9216	2035.3	2.0353	5.5806

Table I7 Determination of the pressure gradient for the annular and mist flow regime from Wallis's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Fanning friction factor, $f_F = \dfrac{16}{\text{Re}}$ for laminar flow (Re < 2000) (I30)

$f_F = 0.079\,\text{Re}^{-1/4}$ for turbulent flow (Re > 4000) (I31)

Pressure gradient for air, $\left(\dfrac{dp}{dz}\right)_{air} = \dfrac{2 f_F \rho_{air} j_{air}}{D}$ (I32)

Pressure gradient for liquid, $\left(\dfrac{dp}{dz}\right)_{liquid} = \dfrac{2 f_F \rho_{liquid} j_{liquid}}{D}$ (I33)

Martinelli parameter, X

from $\left(1+X^{2/3.61}\right)^{3.61}\left(\dfrac{dp}{dz}\right)_{air} - \rho_{air} g = \dfrac{\left(1+X^{2/3.61}\right)^{3.61}}{X^2}\left(\dfrac{dp}{dz}\right)_{liquid} - [\dfrac{1}{(1+0.0904X^{0.548})^{2.82}}\rho_{air} + (1-\dfrac{1}{(1+0.0904X^{0.548})^{2.82}})\rho_{liquid}]g$ (I34)

Void fraction, $\varepsilon = \dfrac{1}{\left(1+0.0904\,X^{0.548}\right)^{2.82}}$ (I35)

Gas two-phase flow multiplier, $\phi_g = \left(1+X^{2/3.61}\right)^{3.61/2}$ (I36)

Pressure gradient for two-phase flow, $\left(\frac{dp}{dz}\right) = \phi_g^2 \left(\frac{dp}{dz}\right)_{air} - \rho_{air} g$ (I37)

$Q_{solution}$ (ml/min)	$Re_{solution}$	Q_{air} (L/min)	Re_{air}	Flow regime	f_F of air	f_F of solution	$(-dp/dz)_{air}$ (Pa/m)	$(-dp/dz)_{solution}$ (Pa/m)	Martinelli parameter (X)	Void fraction (ε)	Φ_g^2	Pressue gradient $(-dp/dz)_{tp}$ (kPa/m)
2911	2731	400	28510	Annular	0.0061	0.0059	418	18.0419	0.3370	0.8719	4.8362	2.0327
2911	2731	500	35637	Annular	0.0057	0.0059	618	18.0419	0.2295	0.8944	3.7531	2.3294
2911	2731	600	42765	Annular	0.0055	0.0059	850	18.0419	0.1780	0.9073	3.2353	2.7605
2911	2731	700	49892	Annular	0.0053	0.0059	1113	18.0419	0.1473	0.9159	2.9239	3.2653
2911	2731	800	57020	Mist	0.0051	0.0059	1406	18.0419	0.1266	0.9222	2.7115	3.8232
2911	2731	900	64147	Mist	0.0050	0.0059	1728	18.0419	0.1116	0.9272	2.5551	4.4255
2911	2731	1000	71275	Mist	0.0048	0.0059	2077	18.0419	0.1001	0.9312	2.4338	5.0673

Table I8 Determination of the pressure gradient from experiment for octylbenzyldimethylammonium chloride solution (2CMC)

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m;

cross-sectional area of pipe, A = 0.00028 m^2; pressure taps difference = 0.4 m

Procedure to determine of pressure gradient from experiment:

1. Read the highest and lowest difference level from manometer.
2. Put the value of difference level in $-\frac{dp}{dz}=\frac{\rho_l g(100-level_{liquid,L})-(100-level_{liquid,R})}{100x0.4x1000}$ (I38)

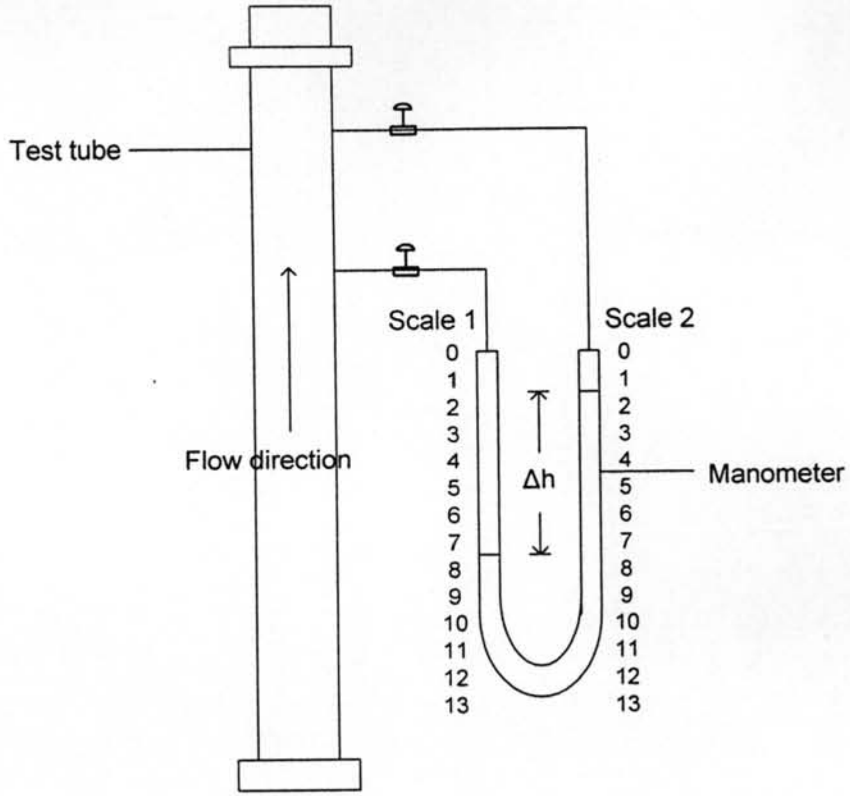


Figure I5 Appearance scale and water level in manometer.

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2731	3.17	Bubble	82.3	82.3	82.3	82.3	82.3	43.6	43.6	43.6	43.6	43.6
2731	5.64	Bubble	82.1	82.1	82.1	82.1	82.1	43.6	43.6	43.6	43.6	43.6
2731	8.12	Bubble	81.8	81.8	81.8	81.8	81.8	43.3	43.3	43.3	43.3	43.3
2731	10.59	Bubble	79.5	79.1	79.4	79	78.5	42.7	41.6	41.2	40.6	40.3
2731	13.07	Bubble	74.2	73.5	73.5	73	73.1	36.3	36.6	36.5	36.8	36.4
2731	15.54	Bubble	70	70	70.1	69.9	69.5	33.1	32.8	32.4	32.3	32
2731	18.02	Bubble	67.5	67.3	67.2	66.3	65.7	29.6	29.4	29.1	29.8	29.6
2731	20.49	Bubble	63.5	63	62.6	63	63	27.1	27	27	26.5	26.2
2731	22.95	Bubble	60.2	59.6	60	60	59.3	23.4	23.6	23.4	23	23.3
2731	28.08	Bubble	55.5	55	54.5	54.5	54	18.6	18.5	18.6	18.3	18.3
2731	33.21	Bubble	46	46	46	46.5	46	11.7	11.4	11.5	10.2	9.6
2731	38.33	Bubble-Slug	72.3	71.5	71	71.3	70.6	36.5	36.3	36.3	36.2	36.5
2731	43.46	Slug	69	68.5	68	68.1	68.5	34.5	34.9	35	34.8	34.3
2731	48.59	Slug	66.5	66.5	66	65.5	65.5	32.8	32.5	32.5	32.4	32.3
2731	58.85	Slug	61.3	60	60.3	60.1	60	27.6	27.3	26.6	26.5	26.6
2731	69.10	Slug	54.9	54.5	54.4	54	54.3	22.8	23	22.6	22.6	22.3
2731	79.36	Slug	51	51.2	50.6	50.3	50	20	19	18.6	18.2	18.3
2731	89.62	Slug	46	46	46	44.5	44.3	15	14.5	14	13.5	13.5
2731	99.87	Slug	73.5	73.5	73.2	72.9	72.7	44.2	43.6	43.5	43.3	42.7
2731	177	Slug	62.5	60.5	59.5	59.8	59	37.6	35.5	35.5	34	33.5
2731	296	Slug	57.3	54.5	51	50.3	49	38.5	36	33.5	31.6	29.1
2731	369	Slug-Churn	70.5	70	70.5	69.2	68	54.6	54.3	54.2	53.5	52.6
2731	515	Slug-Churn	45.5	45	45	45	45	31.3	31.3	31.2	31	30.9
2731	735	Slug-Churn	34.5	34.5	34.5	34.5	34.3	23.6	23.5	23.4	23.3	23.3
2731	1454	Slug-Churn	82	81.8	81.5	81.5	81.4	73	73	73.3	73.2	73
2731	2474	Churn	72.5	72.6	72.5	72	72.3	61.8	61.3	61.3	61.4	61.3

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2731	3495	Churn	71.5	71.5	71.5	71.5	71.5	59.7	59.7	59.7	59.7	59.7
2731	4516	Churn	70.3	65.5	65	65	65	58	54.3	53.5	53.5	53.3
2731	5537	Churn	78.3	77	77	76.5	75	67	66.5	66.5	66.3	66
2731	14255	Churn	69.5	68.5	68	67.2	66	56.5	55.8	55.3	54.8	54.3
2731	21382	Churn	62	62.2	62.2	62.2	62.2	45	44.6	44.6	44.6	44.6
2731	28510	Annular	62	62	62	62	62	38.8	38.8	38.8	38.8	38.8
2731	35637	Annular	64.5	64.1	64.1	64.1	64.1	36.2	36.6	36.6	36.6	36.6
2731	42765	Annular	66.6	66.6	66.6	66.6	66.6	34.6	34.6	34.6	34.6	34.6
2731	49892	Annular	87	86.5	87	87	86.5	52	51.4	52	52	51.5
2731	57020	Mist	89.5	88	87.5	88	88	51.1	51.1	51.1	51.1	51.1

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2731	3.17	Bubble	82.3	82.3	82.3	82.3	82.3	43.6	43.6	43.6	43.6	43.6
2731	5.64	Bubble	82.1	82.1	82.1	82.1	82.1	43.6	43.6	43.6	43.6	43.6
2731	8.12	Bubble	81.1	81.1	81.1	81.1	81.1	43.3	43.3	43.3	43.3	43.3
2731	10.59	Bubble	77.8	77.9	77.7	77.5	77.5	40.3	40	39.8	39.6	39.5
2731	13.07	Bubble	73.2	73.2	73.5	73	73.3	36.3	36	35.5	35.6	34.9
2731	15.54	Bubble	69.7	69.5	69	68.9	69	31.8	31.6	32	32	31.7
2731	18.02	Bubble	66.4	65.7	65	65.5	65.3	28.6	29	29.4	28.5	27.9
2731	20.49	Bubble	63	62.2	62	61.5	61.4	25.5	26.1	25.6	26	25.4
2731	22.95	Bubble	58.9	59	58.5	58.4	58.5	23.5	23	23.3	22.9	22.5
2731	28.08	Bubble	53.5	53.5	53	52.6	53	18.5	18.3	18.2	18.3	17.6
2731	33.21	Bubble	45.8	46	45.5	44.5	44.5	9.6	9.1	9.5	10.3	10.1
2731	38.33	Bubble-Slug	70.9	71	70.5	71	71	35.8	35.6	35.9	35.2	34.9
2731	43.46	Slug	68.5	68.1	67.7	68	68	34	34.3	34	33.8	33.4
2731	48.59	Slug	65.4	65	65.6	64.9	64.5	31.3	31.2	30.5	30.8	30.5
2731	58.85	Slug	60	59.4	58.3	58	57.9	26	25.6	25.5	25.1	24
2731	69.10	Slug	54.9	54	54	54	53.6	22	21.6	21	21.2	20.3
2731	79.36	Slug	49.6	49.6	49	49	48.8	18.4	17.9	17.6	17.4	17.3
2731	89.62	Slug	43.3	43.3	42.8	42.2	41.5	12.3	12	11.8	11.3	10.5
2731	99.87	Slug	72.3	71.5	71.1	70.2	70.3	41.6	41.5	40.3	39.8	39.6
2731	177	Slug	56.5	56.5	54	53.8	53.8	31.8	30.5	28.6	28	27.8
2731	296	Slug	46.3	44.3	43.5	42.6	38	26.5	26	25	24	19.5
2731	369	Slug-Churn	65	65.2	64.3	57	59	50.3	49	48	41.6	44
2731	515	Slug-Churn	45.6	45	45	45	44.6	30	30.5	30.5	30.4	30.3
2731	735	Slug-Churn	34.5	34.3	34.2	34	33.9	23	23.2	23	23	23
2731	1454	Slug-Churn	81.5	81.5	81.1	77	73.5	72.5	72.4	72.5	71	65
2731	2474	Churn	72	71.8	71.8	71.6	71.6	61.3	61.3	61	61	61

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2731	3495	Churn	71.3	71.3	71.3	71.3	71.3	59.6	59.6	59.6	59.6	59.6
2731	4516	Churn	70.6	70.6	70.6	70.6	70.6	58.2	58.2	58.2	58.2	58.2
2731	5537	Churn	78.3	77	77	76.5	75	65	65	64.3	64	62.8
2731	14255	Churn	65.9	66.3	66	65.5	65.4	54	53	53	52.4	52.3
2731	21382	Churn	62	62	62	62	62	44.3	44.3	44.5	44.5	44.5
2731	28510	Annular	62	62	62	62	62	38.8	38.8	38.8	38.8	38.8
2731	35637	Annular	64.1	64.1	64.1	64.1	64.1	36.6	36.6	36.6	36.6	36.6
2731	42765	Annular	66.6	66.6	66.6	66.6	66.6	34.6	34.6	34.6	34.6	34.6
2731	49892	Annular	87	87	87	87	87	52	52	52	52	52
2731	57020	Mist	88	88	88.3	88	88	51.1	51.1	51.1	51.1	51.1

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2731	3.17	Bubble	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750 ± 0.00
2731	5.64	Bubble	9.4261	9.4261	9.4261	9.4261	9.4261	9.4261	9.4261	9.4261	9.4261	9.4261	9.4261 ± 0.00
2731	8.12	Bubble	9.4261	9.4261	9.4261	9.4261	9.4261	9.2547	9.2547	9.2547	9.2547	9.2547	9.3404 ± 0.09
2731	10.59	Bubble	9.0099	9.1812	9.3526	9.4016	9.3526	9.1812	9.2792	9.2792	9.2792	9.3037	9.2620 ± 0.11
2731	13.07	Bubble	9.2792	9.0343	9.0588	8.8630	8.9854	9.0343	9.1078	9.3037	9.1568	9.4016	9.1225 ± 0.16
2731	15.54	Bubble	9.0343	9.1078	9.2302	9.2057	9.1812	9.2792	9.2792	9.0588	9.0343	9.1323	9.1543 ± 0.09
2731	18.02	Bubble	9.2792	9.2792	9.3281	8.9364	8.8385	9.2547	8.9854	8.7161	9.0588	9.1568	9.0833 ± 0.21
2731	20.49	Bubble	8.9119	8.8140	8.7161	8.9364	9.0099	9.1812	8.8385	8.9119	8.6916	8.8140	8.8825 ± 0.14
2731	22.95	Bubble	9.0099	8.8140	8.9609	9.0588	8.8140	8.6671	8.8140	8.6181	8.6916	8.8140	8.8262 ± 0.15
2731	28.08	Bubble	9.0343	8.9364	8.7895	8.8630	8.7405	8.5692	8.6181	8.5202	8.3978	8.6671	8.7136 ± 0.20
2731	33.21	Bubble	8.3978	8.4712	8.4467	8.8874	8.9119	8.8630	9.0343	8.8140	8.3733	8.4223	8.6622 ± 0.26
2731	38.33	Bubble-Slug	8.7650	8.6181	8.4957	8.5936	8.3488	8.5936	8.6671	8.4712	8.7650	8.8385	8.6157 ± 0.15
2731	43.46	Slug	8.4467	8.2264	8.0795	8.1529	8.3733	8.4467	8.2754	8.2509	8.3733	8.4712	8.3096 ± 0.13
2731	48.59	Slug	8.2509	8.3243	8.2019	8.1040	8.1285	8.3488	8.2754	8.5936	8.3488	8.3243	8.2900 ± 0.14
2731	58.85	Slug	8.2509	8.0060	8.2509	8.2264	8.1774	8.3243	8.2754	8.0305	8.0550	8.2998	8.1897 ± 0.12
2731	69.10	Slug	7.8591	7.7122	7.7857	7.6878	7.8347	8.0550	7.9326	8.0795	8.0305	8.1529	7.9130 ± 0.16
2731	79.36	Slug	7.5898	7.8836	7.8347	7.8591	7.7612	7.6388	7.7612	7.6878	7.7367	7.7122	7.7465 ± 0.09
2731	89.62	Slug	7.5898	7.7122	7.8347	7.5898	7.5409	7.5898	7.6633	7.5898	7.5653	7.5898	7.6266 ± 0.09
2731	99.87	Slug	7.1736	7.3205	7.2715	7.2471	7.3450	7.5164	7.3450	7.5409	7.4429	7.5164	7.3719 ± 0.13
2731	177	Slug	6.0963	6.1208	5.8760	6.3167	6.2432	6.0474	6.3657	6.2188	6.3167	6.3657	6.1967 ± 0.16
2731	296	Slug	4.6029	4.5294	4.2846	4.5784	4.8722	4.8477	4.4804	4.5294	4.5539	4.5294	4.5808 ± 0.17
2731	369	Slug-Churn	3.8928	3.8439	3.9908	3.8439	3.7704	3.5990	3.9663	3.9908	3.7704	3.6725	3.8341 ± 0.13
2731	515	Slug-Churn	3.4766	3.3542	3.3787	3.4277	3.4521	3.8194	3.5501	3.5501	3.5746	3.5011	3.5085 ± 0.13
2731	735	Slug-Churn	2.6687	2.6932	2.7176	2.7421	2.6932	2.8156	2.7176	2.7421	2.6932	2.6687	2.7152 ± 0.04
2731	1454	Slug-Churn	2.2035	2.1545	2.0076	2.0321	2.0566	2.2035	2.2280	2.1056	1.4690	2.0811	2.0541 ± 0.22
2731	2474	Churn	2.6197	2.7666	2.7421	2.5952	2.6932	2.6197	2.5707	2.6442	2.5952	2.5952	2.6442 ± 0.07

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2731	3495	Churn	2.8890	2.8890	2.8890	2.8890	2.8890	2.8645	2.8645	2.8645	2.8645	2.8645	2.8768 ± 0.01
2731	4516	Churn	3.0114	2.7421	2.8156	2.8156	2.8645	3.0359	3.0359	3.0359	3.0359	3.0359	2.9429 ± 0.12
2731	5537	Churn	2.7666	2.5707	2.5707	2.4973	2.2035	3.2563	2.9380	3.1094	3.0604	2.9870	2.7960 ± 0.33
2731	14255	Churn	3.1828	3.1094	3.1094	3.0359	2.8645	2.9135	3.2563	3.1828	3.2073	3.2073	3.1069 ± 0.13
2731	21382	Churn	4.1622	4.3091	4.3091	4.3091	4.3091	4.3335	4.3335	4.2846	4.2846	4.2846	4.2919 ± 0.05
2731	28510	Annular	5.6801	5.6801	5.6801	5.6801	5.6801	5.6801	5.6801	5.6801	5.6801	5.6801	5.6801 ± 0.00
2731	35637	Annular	6.9288	6.7329	6.7329	6.7329	6.7329	6.7329	6.7329	6.7329	6.7329	6.7329	6.7525 ± 0.06
2731	42765	Annular	7.8347	7.8347	7.8347	7.8347	7.8347	7.8347	7.8347	7.8347	7.8347	7.8347	7.8347 ± 0.00
2731	49892	Annular	8.5692	8.5936	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692	8.5716 ± 0.01
2731	57020	Mist	9.4016	9.0343	8.9119	9.0343	9.0343	9.0343	9.0343	9.1078	9.0343	9.0343	9.0662 ± 0.13

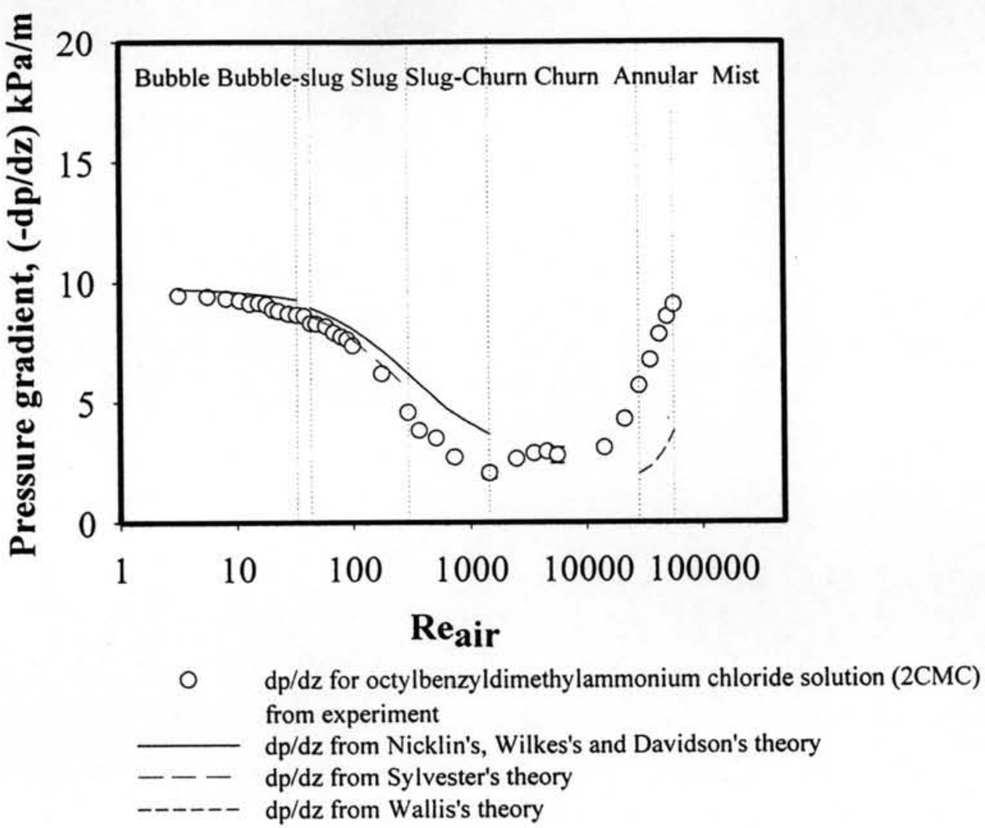


Figure I6 Comparison between Nicklin's theory, Sylvester's theory and experimental pressure gradient vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (2CMC) at $Re_{solution} = 2731$ by using pipe diameter 19 mm.

Table I9 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes of octylbenzyldimethylammonium chloride solution (2CMC) by using pipe diameter of 19 mm

Pipe diameter (mm)	$Re_{solution}$	Re_{air}(critical) for each flow regime					
		Bubble-Slug	Slug	Slug-Churn	Churn	Annular	Mist
19	2731	38.33	43.46	369	2474	28510	57020

Appendix J Octylbenzyldimethylammonium Chloride Surfactant (3CMC) – Air Flow for the Pipe Diameter of 19 mm

Table J1 Determination of bubble size from octylbenzyldimethylammonium chloride solution (3CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.317 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the bubble size:

1. Make a movie of the bubble flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the bubble size by Scion Image software program.

Equivalent diameter (D_e) of the bubble is defined as the diameter of a sphere that has the same volume as the bubble.

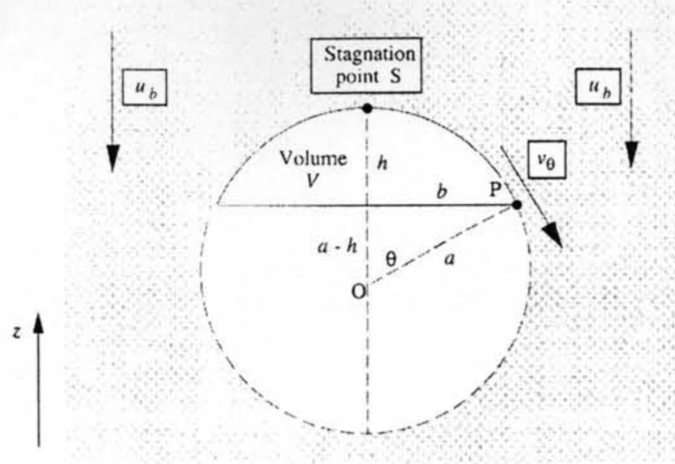


Figure J1 Flow around a spherical cap bubble (Wilkes, 1999).

$$\text{Equivalent diameter } (D_e) = \sqrt[3]{3.94h\left[\frac{h^2+b^2}{2h}\right]^2 - 1.94b^2\left[\left(\frac{h^2+b^2}{2h}\right) - h\right]} \quad \text{(J1)}$$

$Re_{solution}$	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble width, W_b (mm)			Average bubble width (mm)	Equivalent diameter, D_e (mm)			Average equivalent diameter, De (mm)
		1	2	3		1	2	3		1	2	3	
2735	3.17	10.0	9.9	10.3	10.0 ± 0.2	11.8	10.9	10.9	11.2 ± 0.5	12.6	12.2	12.6	12.5 ± 0.2
2735	5.64	9.7	10.7	10.0	10.1 ± 0.5	11.2	11.5	11.1	11.3 ± 0.2	12.1	13.1	12.4	12.5 ± 0.5
2735	8.12	10.3	10.6	10.3	10.4 ± 0.2	11.3	11.5	11.6	11.5 ± 0.1	12.7	13.0	12.8	12.8 ± 0.2
2735	10.59	10.4	10.3	10.7	10.5 ± 0.2	11.2	11.9	11.7	11.6 ± 0.3	12.8	12.9	13.2	13.0 ± 0.2
2735	13.07	11.4	11.4	11.4	11.4 ± 0.0	11.6	11.3	12.1	11.7 ± 0.4	13.7	13.7	13.9	13.8 ± 0.1
2735	15.54	12.1	12.4	12.7	12.4 ± 0.3	12.2	11.6	11.6	11.8 ± 0.4	14.6	14.6	14.9	14.7 ± 0.2
2735	18.02	13.2	12.7	13.5	13.1 ± 0.4	12.1	11.6	11.9	11.9 ± 0.3	15.5	14.8	15.7	15.3 ± 0.4
2735	20.49	14.7	14.1	14.3	14.4 ± 0.3	12.6	11.8	12.8	12.4 ± 0.5	16.9	16.1	16.7	16.6 ± 0.4
2735	22.95	15.4	15.3	15.6	15.4 ± 0.1	12.7	12.3	12.7	12.6 ± 0.2	17.5	17.4	17.7	17.6 ± 0.2
2735	28.08	17.2	16.9	16.6	16.9 ± 0.3	13.1	12.4	12.4	12.6 ± 0.4	19.3	18.8	18.6	18.9 ± 0.4
2735	33.21	18.5	18.8	18.8	18.7 ± 0.2	12.5	12.4	12.8	12.6 ± 0.2	20.3	20.6	20.7	20.5 ± 0.2

$Re_{solution}$	Re_{air}	Bubble height / Pipe diameter			Average, R_h/D	Bubble width / Pipe diameter			Average, W_b/D	Equivalent diameter / Pipe diameter			Average equivalent diameter, De/D
		1	2	3		1	2	3		1	2	3	
2735	3.17	0.53	0.52	0.54	0.53 ± 0.01	0.62	0.57	0.57	0.59 ± 0.03	0.66	0.64	0.66	0.66 ± 0.01
2735	5.64	0.51	0.56	0.53	0.53 ± 0.03	0.59	0.61	0.58	0.59 ± 0.01	0.64	0.69	0.65	0.66 ± 0.03
2735	8.12	0.54	0.56	0.54	0.55 ± 0.01	0.60	0.61	0.61	0.60 ± 0.01	0.67	0.68	0.67	0.67 ± 0.01
2735	10.59	0.55	0.54	0.56	0.55 ± 0.01	0.59	0.63	0.62	0.61 ± 0.02	0.67	0.68	0.70	0.68 ± 0.01
2735	13.07	0.60	0.60	0.60	0.60 ± 0.00	0.61	0.60	0.64	0.62 ± 0.02	0.72	0.72	0.73	0.72 ± 0.01
2735	15.54	0.64	0.65	0.67	0.65 ± 0.02	0.64	0.61	0.61	0.62 ± 0.02	0.77	0.77	0.78	0.77 ± 0.01
2735	18.02	0.70	0.67	0.71	0.69 ± 0.02	0.64	0.61	0.63	0.63 ± 0.01	0.82	0.78	0.82	0.81 ± 0.02
2735	20.49	0.77	0.74	0.75	0.76 ± 0.02	0.66	0.62	0.68	0.65 ± 0.03	0.89	0.85	0.88	0.87 ± 0.02
2735	22.95	0.81	0.81	0.82	0.81 ± 0.01	0.67	0.65	0.67	0.66 ± 0.01	0.92	0.92	0.93	0.92 ± 0.01
2735	28.08	0.90	0.89	0.87	0.89 ± 0.01	0.69	0.65	0.65	0.66 ± 0.02	1.01	0.99	0.98	0.99 ± 0.02
2735	33.21	0.98	0.99	0.99	0.99 ± 0.01	0.66	0.65	0.68	0.66 ± 0.01	1.07	1.08	1.09	1.08 ± 0.01

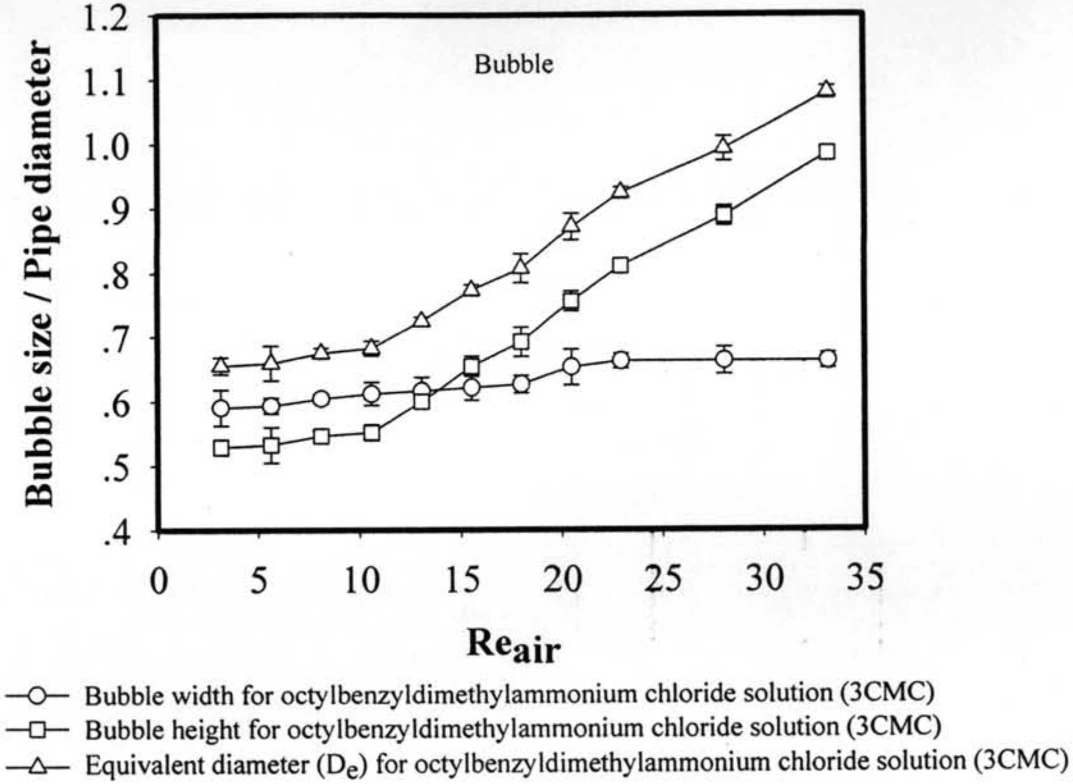


Figure J2 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (3CMC) at $Re_{solution} = 2735$ by using pipe diameter of 19 mm.

Table J2 Determination of slug height from octylbenzyldimethylammonium chloride solution (3CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.317 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the slug height:

1. Make a movie of the slug flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the slug height by Scion Image software program.

$Re_{solution}$	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
2735	43.46	38.0	37.6	37.1	37.6 ± 0.5	2.0	2.0	2.0	2.0 ± 0.02
2735	48.59	43.0	43.5	42.9	43.1 ± 0.3	2.3	2.3	2.3	2.3 ± 0.02
2735	58.85	49.4	49.0	49.1	49.2 ± 0.2	2.6	2.6	2.6	2.6 ± 0.01
2735	69.10	52.3	53.6	53.0	53.0 ± 0.6	2.8	2.8	2.8	2.8 ± 0.03
2735	79.36	56.2	56.1	55.9	56.1 ± 0.2	3.0	3.0	2.9	3.0 ± 0.01
2735	89.62	58.3	58.3	58.2	58.3 ± 0.1	3.1	3.1	3.1	3.1 ± 0.00
2735	99.87	63.0	61.9	62.9	62.6 ± 0.6	3.3	3.3	3.3	3.3 ± 0.03
2735	177	90.5	89.2	89.2	89.7 ± 0.7	4.8	4.7	4.7	4.7 ± 0.04
2735	296	145	146	146	145.7 ± 0.7	7.6	7.7	7.7	7.7 ± 0.04

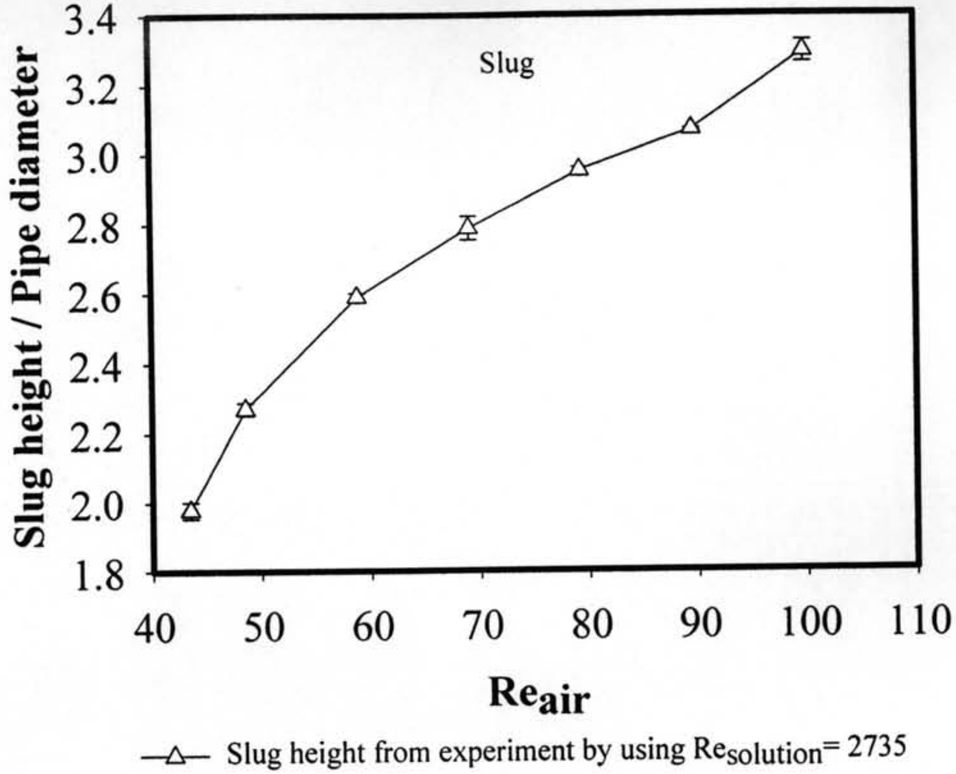


Figure J3 Slug height from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (3CMC) by using pipe diameter of 19 mm.

Table J3 Determination of bubble and slug velocity for octylbenzyldimethylammonium chloride solution (3CMC) from Nicklin's theory and experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution} = 1.317 \times 10^{-3}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

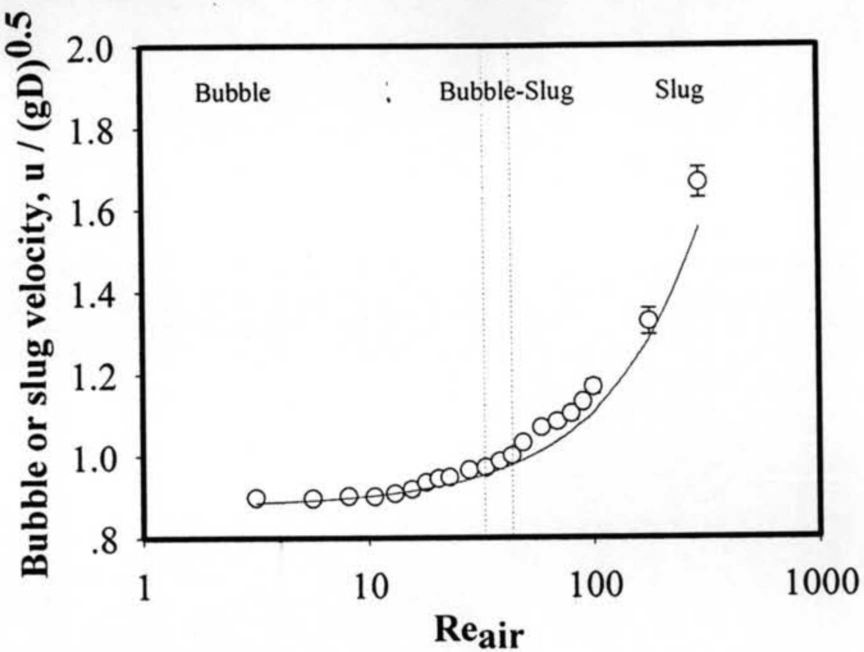
temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Bubble velocity from theory, $u_s = 1.2(\frac{Q_{qir} + Q_{liquid}}{A}) + 0.35\sqrt{gD}$ (J2)

Determination of bubble velocity from experiment by timing the bubble at known distance (0.8m)

$Re_{solution}$	Re_{air}	Time of bubble travel (sec)/0.8m					Average (sec/0.8 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
2735	3.17	2.06	2.07	2.06	2.06	2.07	2.06 ± 0.01	0.39	0.39	0.39	0.39	0.39	0.39 ± 0.001	0.38
2735	5.64	2.06	2.06	2.07	2.09	2.06	2.07 ± 0.01	0.39	0.39	0.39	0.38	0.39	0.39 ± 0.002	0.38
2735	8.11	2.06	2.03	2.03	2.09	2.07	2.06 ± 0.03	0.39	0.39	0.39	0.38	0.39	0.39 ± 0.005	0.39
2735	10.59	2.09	2.06	2.04	2.07	2.03	2.06 ± 0.02	0.38	0.39	0.39	0.39	0.39	0.39 ± 0.005	0.39
2735	13.06	2.06	2.06	2.03	2.03	2.03	2.04 ± 0.02	0.39	0.39	0.39	0.39	0.39	0.39 ± 0.003	0.39
2735	15.53	2.00	2.06	2.03	2.03	1.97	2.02 ± 0.03	0.40	0.39	0.39	0.39	0.41	0.40 ± 0.007	0.39
2735	18.01	2.00	2.00	1.94	1.97	2.00	1.98 ± 0.03	0.40	0.40	0.41	0.41	0.40	0.40 ± 0.006	0.40
2735	20.48	1.97	1.93	1.97	1.94	2.00	1.96 ± 0.03	0.41	0.41	0.41	0.41	0.40	0.41 ± 0.006	0.40
2735	22.94	1.94	1.97	1.93	1.97	1.97	1.96 ± 0.02	0.41	0.41	0.41	0.41	0.41	0.41 ± 0.004	0.40
2735	28.06	1.94	1.94	1.91	1.91	1.90	1.92 ± 0.02	0.41	0.41	0.42	0.42	0.42	0.42 ± 0.004	0.41
2735	33.19	1.90	1.92	1.91	1.90	1.91	1.91 ± 0.01	0.42	0.42	0.42	0.42	0.42	0.42 ± 0.002	0.41
2735	38.31	1.87	1.91	1.87	1.87	1.87	1.88 ± 0.02	0.43	0.42	0.43	0.43	0.43	0.43 ± 0.004	0.42
2735	43.44	1.84	1.85	1.88	1.84	1.85	1.85 ± 0.02	0.43	0.43	0.43	0.43	0.43	0.43 ± 0.004	0.42
2735	48.57	1.80	1.80	1.78	1.81	1.78	1.79 ± 0.01	0.44	0.44	0.45	0.44	0.45	0.45 ± 0.003	0.43
2735	58.82	1.72	1.75	1.75	1.72	1.72	1.73 ± 0.02	0.47	0.46	0.46	0.47	0.47	0.46 ± 0.004	0.44
2735	69.07	1.69	1.72	1.72	1.69	1.72	1.71 ± 0.02	0.47	0.47	0.47	0.47	0.47	0.47 ± 0.005	0.45
2735	79.32	1.69	1.65	1.66	1.71	1.68	1.68 ± 0.02	0.47	0.48	0.48	0.47	0.48	0.48 ± 0.007	0.46
2735	89.57	1.63	1.64	1.63	1.63	1.65	1.64 ± 0.01	0.49	0.49	0.49	0.49	0.48	0.49 ± 0.003	0.47
2735	99.82	1.59	1.56	1.59	1.57	1.62	1.59 ± 0.02	0.50	0.51	0.50	0.51	0.49	0.50 ± 0.007	0.48
2735	177	1.38	1.44	1.35	1.41	1.41	1.40 ± 0.03	0.58	0.56	0.59	0.57	0.57	0.57 ± 0.014	0.55
2735	296	1.12	1.12	1.09	1.09	1.15	1.11 ± 0.03	0.71	0.71	0.73	0.73	0.70	0.72 ± 0.016	0.67

$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
2735	3.17	0.90	0.90	0.90	0.90	0.90	0.90 ± 0.002	0.89
2735	5.64	0.90	0.90	0.90	0.89	0.90	0.90 ± 0.006	0.89
2735	8.11	0.90	0.91	0.91	0.89	0.90	0.90 ± 0.011	0.90
2735	10.59	0.89	0.90	0.91	0.90	0.91	0.90 ± 0.010	0.90
2735	13.06	0.90	0.90	0.91	0.91	0.91	0.91 ± 0.007	0.91
2735	15.53	0.93	0.90	0.91	0.91	0.94	0.92 ± 0.016	0.91
2735	18.01	0.93	0.93	0.96	0.94	0.93	0.94 ± 0.013	0.92
2735	20.48	0.94	0.96	0.94	0.96	0.93	0.94 ± 0.013	0.92
2735	22.94	0.96	0.94	0.96	0.94	0.94	0.95 ± 0.009	0.93
2735	28.06	0.96	0.96	0.97	0.97	0.98	0.97 ± 0.009	0.94
2735	33.19	0.98	0.97	0.97	0.98	0.97	0.97 ± 0.004	0.95
2735	38.31	0.99	0.97	0.99	0.99	0.99	0.99 ± 0.009	0.97
2735	43.44	1.01	1.00	0.99	1.01	1.00	1.00 ± 0.009	0.98
2735	48.57	1.03	1.03	1.04	1.02	1.04	1.03 ± 0.008	0.99
2735	58.82	1.08	1.06	1.06	1.08	1.08	1.07 ± 0.010	1.01
2735	69.07	1.10	1.08	1.08	1.10	1.08	1.08 ± 0.010	1.04
2735	79.32	1.10	1.12	1.12	1.08	1.10	1.10 ± 0.016	1.06
2735	89.57	1.14	1.13	1.14	1.14	1.12	1.13 ± 0.006	1.08
2735	99.82	1.17	1.19	1.17	1.18	1.14	1.17 ± 0.017	1.11
2735	177	1.34	1.29	1.37	1.31	1.31	1.33 ± 0.033	1.28
2735	296	1.65	1.65	1.70	1.70	1.61	1.66 ± 0.037	1.56



○ Bubble and slug velocity from experiment by using $Re_{solution}$ = 2735

—— Bubble and slug velocity from Nicklin's, Wilkes's and Davidson's theory by using $Re_{solution}$ = 2735

Figure J4 Comparison bubble and slug velocity from experiment vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (3CMC) comparing with Nicklin's theory by using pipe diameter of 19 mm.

Table J4 Determination of the pressure gradient for the bubble flow regime from Nicklin's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.317 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Superficial liquid velocity, $j_{liquid} = \dfrac{Q_{liquid}}{A}$ (J3)

Superficial air velocity, $j_{air} = \dfrac{Q_{air}}{A}$ (J4)

Reynolds number of liquid, $\mathrm{Re}_{liquid} = \dfrac{\rho j_{liquid} D}{\mu_{liquid}}$ (J5)

Reynolds number of air, $\mathrm{Re}_{air} = \dfrac{\rho j_{air} D}{\mu_{air}}$ (J6)

Bubble velocity rising in stagnant liquid, $u_b = 1.00\sqrt{g R_b}$ (J7)

where R_b is equivalent radius of the bubble which defined as the radius of a sphere that has the same volume as the bubble

Void fraction, $\varepsilon = \dfrac{Q_{air}}{Q_{air} + Q_{liquid} + u_b A}$ (J8)

Pressure gradient for bubble flow regime, $\dfrac{dp}{dz} = -\rho_l g(1-\varepsilon)$ (J9)

$Q_{solution}$ (ml/min)	Sup. solution velocity $j_{solution}$ (m/s)	$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Q_{air} (L/min)	Sup. Air velocity j_{air} (m/s)	Q_{air} (m^3/sec)	Re_{air}	Flow regime	U_b (m/s)	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
3229	0.1899	5.38E-05	2735	0.0444	0.0026	7.4E-07	3.17	Bubble	0.2471	0.0059	9.7351
3229	0.1899	5.38E-05	2735	0.0792	0.0047	1.3E-06	5.64	Bubble	0.2479	0.0105	9.6903
3229	0.1899	5.38E-05	2735	0.1139	0.0067	1.9E-06	8.12	Bubble	0.2508	0.0150	9.6467
3229	0.1899	5.38E-05	2735	0.1486	0.0087	2.5E-06	10.59	Bubble	0.2521	0.0194	9.6035
3229	0.1899	5.38E-05	2735	0.1833	0.0108	3.1E-06	13.07	Bubble	0.2598	0.0234	9.5640
3229	0.1899	5.38E-05	2735	0.2180	0.0128	3.6E-06	15.54	Bubble	0.2684	0.0272	9.5268
3229	0.1899	5.38E-05	2735	0.2528	0.0149	4.2E-06	18.02	Bubble	0.2743	0.0310	9.4894
3229	0.1899	5.38E-05	2735	0.2875	0.0169	4.8E-06	20.49	Bubble	0.2850	0.0344	9.4567
3229	0.1899	5.38E-05	2735	0.3220	0.0189	5.4E-06	22.95	Bubble	0.2934	0.0377	9.4241
3229	0.1899	5.38E-05	2735	0.3939	0.0232	6.6E-06	28.08	Bubble	0.3042	0.0448	9.3547
3229	0.1899	5.38E-05	2735	0.4659	0.0274	7.8E-06	33.21	Bubble	0.3173	0.0513	9.2914

Table J5 Determination of the pressure gradient for the slug flow regime from Nicklin's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution} = 1.317 \times 10^{-3}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Mean liquid velocity, $u_l = \dfrac{Q_{air} + Q_{liquid}}{A}$ (J10)

Reynolds number of the liquid slug, $\mathrm{Re}_{slug} = \dfrac{\rho_{liquid} u_l D}{\mu_{liquid}}$ (J11)

Fanning friction factor, $f_F = \dfrac{16}{\mathrm{Re}_{slug}}$ for laminar flow ($\mathrm{Re}_{slug} < 2000$) (J12)

$f_F = 0.079\,\mathrm{Re}_{slug}^{-1/4}$ for turbulent flow ($\mathrm{Re}_{slug} > 4000$) (J13)

Single-phase frictional pressure gradient for liquid only, $\left(\dfrac{dp}{dz}\right)_{sp} = \dfrac{2 f_F \rho_{liquid} u_l}{D}$ (J14)

Void fraction, $\varepsilon = \dfrac{Q_{air}}{1.2\left(Q_{air} + Q_{liquid}\right) + 0.35 A\sqrt{gD}}$ (J15)

Pressure gradient for slug flow regime, $\dfrac{dp}{dz} = (1-\varepsilon)\left[-\rho_{liquid}\, g + \left(\dfrac{dp}{dz}\right)_{sp}\right]$ (J16)

$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Q_{air} (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
5.381E-05	2735	1.016E-05	43.46	Slug	0.2258	3251	0.0105	56.0326	0.0850	9.0123
5.381E-05	2735	1.136E-05	48.59	Slug	0.2300	3312	0.0104	57.8834	0.0939	8.9264
5.381E-05	2735	1.376E-05	58.85	Slug	0.2385	3434	0.0103	61.6621	0.1111	8.7606
5.381E-05	2735	1.616E-05	69.10	Slug	0.2469	3556	0.0102	65.5428	0.1274	8.6024
5.381E-05	2735	1.856E-05	79.36	Slug	0.2554	3678	0.0101	69.5246	0.1431	8.4513
5.381E-05	2735	2.096E-05	89.62	Slug	0.2638	3800	0.0101	73.6065	0.1581	8.3069
5.381E-05	2735	2.335E-05	99.87	Slug	0.2723	3922	0.0100	77.7879	0.1725	8.1688
5.381E-05	2735	4.134E-05	177	Slug	0.3358	4836	0.0095	112.2423	0.2633	7.2973
5.381E-05	2735	6.922E-05	296	Slug	0.4342	6253	0.0089	175.9794	0.3634	6.3460
5.381E-05	2735	8.631E-05	369	Slug-Churn	0.4945	7121	0.0086	220.9547	0.4091	5.9173
5.381E-05	2735	0.0001205	515	Slug-Churn	0.6151	8858	0.0081	323.7263	0.4782	5.2795
5.381E-05	2735	0.0001718	735	Slug-Churn	0.7960	11464	0.0076	508.3126	0.5479	4.6578
5.381E-05	2735	0.0003399	1454	Slug-Churn	1.3894	20010	0.0066	1347.3594	0.6596	3.7917

Table J6 Determination of the pressure gradient for the slug flow regime from Sylvester's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.317 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

$\beta = L_{TB}/L_{SU}$ (J17)

where: L_{TB} is length of the Taylor bubble

L_{SU} is length of the slug unit

Friction factor associated with the Taylor bubble, $f_{TB} = \dfrac{1}{\left[-2.0\log\left\{\dfrac{\left(1-\alpha_{TB}^{1/2}\right)}{7.4}\right\}\right]^2}$ (J18)

Reynolds number of the liquid slug, $\mathrm{Re}_{LS} = \dfrac{\rho_L U_{LLS} D}{\mu_L}$ (J19)

where: velocity of the liquid in the liquid slug, $U_{LLS} = U_{SG} + U_{SL}$ (J20)

Friction factor associated with the liquid slug, $f_{LS} = \dfrac{1}{\left[-2.0\log\left\{\dfrac{\varepsilon/D}{3.7}-\left(\dfrac{5.02}{\mathrm{Re}_{LS}}\right)\log\left(\dfrac{\varepsilon/D}{3.7}+\dfrac{13}{\mathrm{Re}_{LS}}\right)\right\}\right]^2}$ (J21)

where: ε is the pipe roughness

Acceleration pressure drop, $(\Delta P)_A = \rho_L(U_{LTB} + U_{TB})(1-\alpha_{TB})(U_{LTB} + U_{TB} + U_{LLS})$ (J22)

where: velocity of the liquid film around the Taylor bubble, $U_{LTB} = 9.916\left[gD\left(1-\sqrt{\alpha_{TB}}\right)\right]^{1/2}$ (J23) velocity of the Taylor bubble, $U_{TB} = 1.2(U_{SG} + U_{SL}) + 0.35\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}$ (J24)

area average void fraction of the Taylor bubble, $\alpha_{TB} = \frac{\text{Average all area at Taylor bubble region}}{\text{Average area in Taylor bubble}}$ (J25)

Hydrostatic pressure drop, $(\Delta P)_H = \rho_L(1-\alpha_{LS})gL_{LS}$ (J26)

where: void fraction of the liquid slug, $\alpha_{LS} = \frac{U_{SG}}{0.425 + 2.65(U_{SG} + U_{SL})}$ (J27)

length of the liquid slug, L_{LS}

Frictional pressure drop of slug unit, $(\Delta P)_F = \frac{L_{LS}}{2D}\left[\frac{\rho_G \beta f_{TB} U_{TB}^2}{(1-\beta)[1-(1-\alpha_{TB}^{1/2}]} + U_{LLS}^2 \rho_L (1-\alpha_{LS}) f_{LS} (1-\beta)\right]$ (J28)

Total pressure drop in the slug unit, $(\Delta P)_T = (\Delta P)_A + (\Delta P)_H + (\Delta P)_F$ (J29)

$Re_{solution}$	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
2735	43.46	Slug	0.2317	0.0585	3251	0.0423	318	1177	5.2427	1500.7	1.5007	9.2541
2735	48.59	Slug	0.2494	0.0582	3312	0.0421	314	1222	5.4886	1541.3	1.5413	8.9122
2735	58.85	Slug	0.2947	0.0579	3434	0.0416	312	1100	4.9421	1416.7	1.4167	8.4878
2735	69.10	Slug	0.2753	0.0558	3556	0.0412	275	1293	6.3350	1574.6	1.5746	8.1851
2735	79.36	Slug	0.2697	0.0559	3678	0.0408	282	1399	7.3139	1688.6	1.6886	8.1201
2735	89.62	Slug	0.3009	0.0558	3800	0.0404	286	1239	6.5598	1531.4	1.5314	7.9058
2735	99.87	Slug	0.2780	0.0559	3922	0.0401	292	1477	8.5228	1778.0	1.7780	7.8995
2735	177	Slug	0.2880	0.0465	4836	0.0377	162	1930	15.7310	2107.7	2.1077	6.7687
2735	296	Slug	0.3481	0.0380	6253	0.0352	87	2258	26.2429	2371.0	2.3710	5.6653

Table J7 Determination of the pressure gradient for the annular and mist flow regime from Wallis's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.317 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Fanning friction factor, $f_F = \dfrac{16}{\mathrm{Re}}$ for laminar flow (Re < 2000) (J30)

$f_F = 0.079\,\mathrm{Re}^{-1/4}$ for turbulent flow (Re > 4000) (J31)

Pressure gradient for air, $\left(\dfrac{dp}{dz}\right)_{air} = \dfrac{2 f_F \rho_{air} j_{air}}{D}$ (J32)

Pressure gradient for liquid, $\left(\dfrac{dp}{dz}\right)_{liquid} = \dfrac{2 f_F \rho_{liquid} j_{liquid}}{D}$ (J33)

Martinelli parameter, X

from $\left(1+X^{2/3.61}\right)^{3.61}\left(\dfrac{dp}{dz}\right)_{air} - \rho_{air} g = \dfrac{\left(1+X^{2/3.61}\right)^{3.61}}{X^2}\left(\dfrac{dp}{dz}\right)_{liquid} - [\dfrac{1}{(1+0.0904X^{0.548})^{2.82}}\rho_{air} + (1-\dfrac{1}{(1+0.0904X^{0.548})^{2.82}})\rho_{liquid}]g$ (J34)

Void fraction, $\varepsilon = \dfrac{1}{\left(1+0.0904\,X^{0.548}\right)^{2.82}}$ (J35)

Gas two-phase flow multiplier, $\phi_g = \left(1+X^{2/3.61}\right)^{3.61/2}$ (J36)

Pressure gradient for two-phase flow, $\left(\frac{dp}{dz}\right) = \phi_g^2 \left(\frac{dp}{dz}\right)_{air} - \rho_{air} g$ (J37)

$Q_{solution}$ (ml/min)	$Re_{solution}$	Q_{air} (L/min)	Re_{air}	Flow regime	f_F of air	f_F of solution	$(-dp/dz)_{air}$ (Pa/m)	$(-dp/dz)_{solution}$ (Pa/m)	Martinelli parameter *(X)*	Void fraction (ε)	Φ_g^2	Pressue gradient $(-dp/dz)_{tp}$ (kPa/m)
3229	2735	400	28510	Annular	0.0061	0.0059	418	22.1690	0.3679	0.8662	5.1505	2.1641
3229	2735	500	35637	Annular	0.0057	0.0059	618	22.1690	0.2533	0.8890	3.9912	2.4765
3229	2735	600	42765	Annular	0.0055	0.0059	850	22.1690	0.1971	0.9023	3.4271	2.9235
3229	2735	700	49892	Annular	0.0053	0.0059	1113	22.1690	0.1633	0.9113	3.0861	3.4458
3229	2735	800	57020	Mist	0.0051	0.0059	1406	22.1690	0.1404	0.9179	2.8533	4.0226
3229	2735	900	64147	Mist	0.0050	0.0059	1728	22.1690	0.1238	0.9231	2.6819	4.6446
3229	2735	1000	71275	Mist	0.0048	0.0059	2077	22.1690	0.1110	0.9274	2.5491	5.3067

Table J8 Determination of the pressure gradient from experiment for octylbenzyldimethylammonium chloride solution (3CMC)

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.317 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m;

cross-sectional area of pipe, A = 0.00028 m^2; pressure taps difference = 0.4 m

Procedure to determine of pressure gradient from experiment:

1. Read the highest and lowest difference level from manometer.
2. Put the value of difference level in $-\frac{dp}{dz} = \frac{\rho_l g(100 - level_{liquid,L}) - (100 - level_{liquid,R})}{100x0.4x1000}$ (J38)

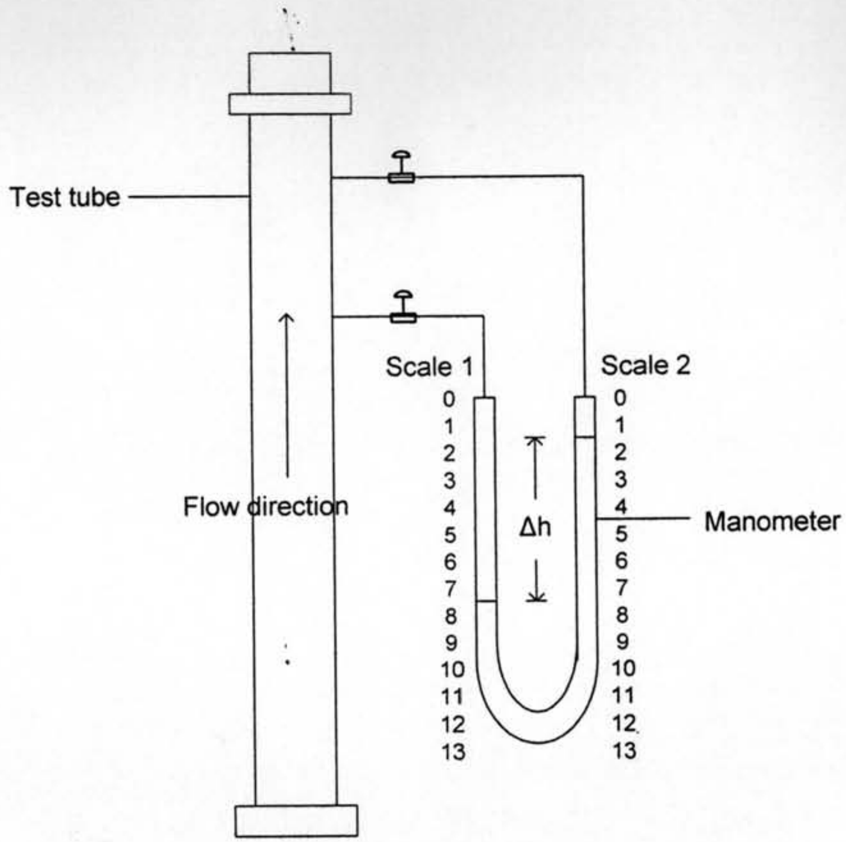


Figure J5 Appearance scale and water level in manometer.

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2735	3.17	Bubble	69.1	69.1	69.1	69.1	69.1	30.4	30.4	30.4	30.4	30.4
2735	5.64	Bubble	69	69	69	69	69	30.4	30.4	30.4	30.4	30.4
2735	8.12	Bubble	68.6	68.6	68.6	68.6	68.6	30.3	30.3	30.3	30.3	30.3
2735	10.59	Bubble	68.2	68.5	68.2	68	68.1	30.1	29.6	29.8	29.6	29.6
2735	13.07	Bubble	67.5	67.5	67.5	67.5	67.4	30.1	30	30	30	29.9
2735	15.54	Bubble	60.8	61.3	61.6	61.6	61.4	23.7	23.9	24.1	23.8	23.7
2735	18.02	Bubble	61	61	60.8	61.1	61	23.3	23.2	23.3	23.2	23
2735	20.49	Bubble	59.3	59.3	58.8	58.6	58.5	21.5	21.5	21.3	21.3	21.2
2735	22.95	Bubble	57.5	57.5	57.5	57.4	57.3	20.5	20.3	20.3	20.4	20.2
2735	28.08	Bubble	56.3	56.3	55.8	55.8	55	20.1	19.6	19.9	19.5	20
2735	33.21	Bubble	53.5	53.3	53.2	53	53	17.5	17.5	17.4	17.5	17.3
2735	38.33	Bubble-Slug	52	52	51.7	51.5	50.2	16.1	15.5	15.3	15.3	15.3
2735	43.46	Slug	73.5	73	72.8	72.5	72.8	37.3	37.3	37.4	37.3	37
2735	48.59	Slug	71.6	71.5	71.5	71.5	71.5	37	36.9	37	37	36.8
2735	58.85	Slug	65.5	66.1	65.9	65	64.3	33.1	32.3	31.3	31	30.3
2735	69.10	Slug	58.8	58.6	58.3	58	57.7	26	25.8	25.8	25.2	24.3
2735	79.36	Slug	53.8	53.3	53.3	52.5	51.8	20.3	20.5	20	20.1	18.8
2735	89.62	Slug	46	45.6	45.3	45.4	45	14.6	14.5	14.3	13.6	13.4
2735	99.87	Slug	40	39.5	39.3	39.5	38.8	10	9.6	9.2	8.3	7.8
2735	177	Slug	31.5	31	31	30	29.8	6.2	6	4.5	4.3	4.1
2735	296	Slug	86	86.2	85.8	85.4	84	67.3	66.9	66.2	65.4	64.3
2735	369	Slug-Churn	68.5	67	65.8	65	64	52.3	49.8	49.2	48.5	47.2
2735	515	Slug-Churn	43	41.2	41	40.5	39.3	28.5	28.2	26	25.6	24.8
2735	735	Slug-Churn	22	22.8	23	23.2	22.5	10.5	9.9	9.8	9.3	9.8
2735	1454	Slug-Churn	70.5	69	69.2	68.5	68	61	60.8	59.3	59.3	59
2735	2474	Churn	67.8	67.5	67.3	67.5	67.6	55.3	55.4	55.3	55	55

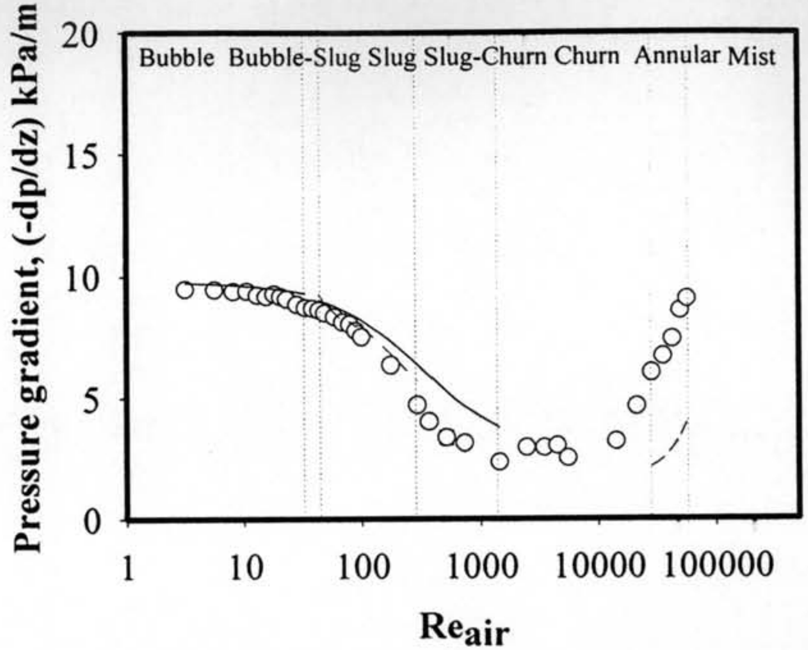
Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2735	3495	Churn	66.5	66.5	66.5	66.5	66.5	54.5	54.5	54.4	54.4	54.5
2735	4516	Churn	66	66	65.9	65.9	65.8	53.5	53.5	53.5	53.5	53.5
2735	5537	Churn	93.8	93.4	93.4	93.5	93.6	83.4	83.1	83.4	83	82.8
2735	14255	Churn	77.3	75.5	74.5	72.5	73.8	63.5	62	61.6	59.5	60
2735	21382	Churn	65	63.5	63.5	63.5	63.5	45.6	44.5	44.5	44.5	44.5
2735	28510	Annular	62.3	62.3	62.3	62.3	62.3	37.7	37.7	37.7	37.7	37.7
2735	35637	Annular	61.1	61.1	61.1	61.1	61.1	33.8	33.8	33.8	33.8	33.8
2735	42765	Annular	61.5	61.5	61.5	61.5	61.5	31.3	31.3	31.3	31.3	31.3
2735	49892	Annular	64.8	64.8	64.8	64.8	64.8	29.8	29.8	29.8	29.8	29.8
2735	57020	Mist	68.7	68.7	68.7	68.7	68.7	31.7	31.7	31.7	31.7	31.7

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2735	3.17	Bubble	69.1	69.1	69.1	69.1	69.1	30.4	30.4	30.4	30.4	30.4
2735	5.64	Bubble	69	69	69	69	69	30.4	30.4	30.4	30.4	30.4
2735	8.12	Bubble	68.6	68.6	68.6	68.6	68.6	30.3	30.3	30.3	30.3	30.3
2735	10.59	Bubble	67.9	68	67.8	67.9	68	29.7	29.6	29.7	29.6	29.8
2735	13.07	Bubble	67.4	67.4	67.3	67.3	67.3	29.8	29.6	29.5	29.3	29.3
2735	15.54	Bubble	61.5	61	61	61	61.1	23.8	23.7	23.8	23.8	23.6
2735	18.02	Bubble	61	61.1	61.2	61.3	61.2	23	23.2	23.3	23.1	23.4
2735	20.49	Bubble	58.5	58.5	58	58.3	58.1	20.8	21	21	21	21.1
2735	22.95	Bubble	57	56.8	57	57	57	20.3	20.3	20	19.9	19.8
2735	28.08	Bubble	55	55.4	55.4	55	55	20	19.1	18.8	18.8	18.4
2735	33.21	Bubble	52.9	53	53	53	53	17.3	17.9	17.8	17.8	17.7
2735	38.33	Bubble-Slug	50	50	49.5	49.5	49	15.3	14.8	14.6	14.8	14.6
2735	43.46	Slug	72.3	72	72	72	71.9	37.6	37.6	37.5	37.4	37.5
2735	48.59	Slug	71.3	71.3	71.3	71.3	70.6	37	36.9	37	36.9	35
2735	58.85	Slug	63.5	63.3	63.2	63.2	63	29.7	29.5	29.2	28.7	28.5
2735	69.10	Slug	57	57	57	56.7	56.5	24.4	24.3	23.6	23	22.9
2735	79.36	Slug	51.8	51	50.5	50.4	50.2	18.9	18.6	18.3	18.3	18.1
2735	89.62	Slug	45	44.8	44.5	43.3	43	13.3	12.8	12.3	11.8	11.5
2735	99.87	Slug	38.3	37.8	37.4	36.9	37.3	7.4	7.2	7.3	6.6	6
2735	177	Slug	29.1	29	28.8	28	27.5	3.5	3	2.6	2.4	0.7
2735	296	Slug	82.7	80.5	79.8	78	76.3	63.3	61	60	60.4	57.5
2735	369	Slug-Churn	63	61.6	55	57.5	55.5	46.2	45.2	37.5	42.8	39.5
2735	515	Slug-Churn	38	37.2	35	30	29.5	24.8	22.2	22.2	18.5	16.3
2735	735	Slug-Churn	22.3	22.5	22.5	22.5	22	9.8	9.4	9.4	9.5	9.5
2735	1454	Slug-Churn	68.5	68.3	68.3	67.8	67.8	58.3	58	58	58.3	58
2735	2474	Churn	67.2	67	66.8	66.8	66.6	55.3	55	55	55	55.1

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2735	3495	Churn	66.3	66.3	66.3	66.2	66.3	54.3	54.4	54.2	54.1	54.1
2735	4516	Churn	65.9	65.7	65.7	65.7	65.6	53.4	53.4	53.4	53.4	53.4
2735	5537	Churn	91	89.8	89.3	89.4	87.8	81.2	80	79.3	79	77.3
2735	14255	Churn	71.6	71.5	71	71.4	71.4	58.8	58.8	58.3	58.2	58.8
2735	21382	Churn	63.5	63.5	63.5	63.5	63.5	44.5	44.5	44.5	44.5	44.5
2735	28510	Annular	62.3	62.3	62.3	62.3	62.3	37.7	37.7	37.7	37.7	37.7
2735	35637	Annular	61.1	61.1	61.1	61.1	61.1	33.8	33.8	33.8	33.8	33.8
2735	42765	Annular	61.5	61.5	61.5	61.5	61.5	31.3	31.3	31.3	31.3	31.3
2735	49892	Annular	64.8	64.8	64.8	64.8	64.8	29.8	29.8	29.8	29.8	29.8
2735	57020	Mist	68.7	68.7	68.7	68.7	68.7	31.7	31.7	31.7	31.7	31.7

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2735	3.17	Bubble	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750	9.4750 ± 0.00
2735	5.64	Bubble	9.4506	9.4506	9.4506	9.4506	9.4506	9.4506	9.4506	9.4506	9.4506	9.4506	9.4506 ± 0.00
2735	8.12	Bubble	9.3771	9.3771	9.3771	9.3771	9.3771	9.3771	9.3771	9.3771	9.3771	9.3771	9.3771 ± 0.00
2735	10.59	Bubble	9.3281	9.5240	9.4016	9.4016	9.4261	9.3526	9.4016	9.3281	9.3771	9.3526	9.3893 ± 0.06
2735	13.07	Bubble	9.1568	9.1812	9.1812	9.1812	9.1812	9.2057	9.2547	9.2547	9.3037	9.3037	9.2204 ± 0.05
2735	15.54	Bubble	9.0833	9.1568	9.1812	9.2547	9.2302	9.2302	9.1323	9.1078	9.1078	9.1812	9.1666 ± 0.06
2735	18.02	Bubble	9.2302	9.2547	9.1812	9.2792	9.3037	9.3037	9.2792	9.2792	9.3526	9.2547	9.2718 ± 0.05
2735	20.49	Bubble	9.2547	9.2547	9.1812	9.1323	9.1323	9.2302	9.1812	9.0588	9.1323	9.0588	9.1617 ± 0.07
2735	22.95	Bubble	9.0588	9.1078	9.1078	9.0588	9.0833	8.9854	8.9364	9.0588	9.0833	9.1078	9.0588 ± 0.06
2735	28.08	Bubble	8.8630	8.9854	8.7895	8.8874	8.5692	8.5692	8.8874	8.9609	8.8630	8.9609	8.8336 ± 0.15
2735	33.21	Bubble	8.8140	8.7650	8.7650	8.6916	8.7405	8.7161	8.5936	8.6181	8.6181	8.6426	8.6965 ± 0.08
2735	38.33	Bubble-Slug	8.7895	8.9364	8.9119	8.8630	8.5447	8.4957	8.6181	8.5447	8.4957	8.4223	8.6622 ± 0.19
2735	43.46	Slug	8.8630	8.7405	8.6671	8.6181	8.7650	8.4957	8.4223	8.4467	8.4712	8.4223	8.5912 ± 0.16
2735	48.59	Slug	8.4712	8.4712	8.4467	8.4467	8.4957	8.3978	8.4223	8.3978	8.4223	8.7161	8.4688 ± 0.09
2735	58.85	Slug	7.9326	8.2754	8.4712	8.3243	8.3243	8.2754	8.2754	8.3243	8.4467	8.4467	8.3096 ± 0.15
2735	69.10	Slug	8.0305	8.0305	7.9571	8.0305	8.1774	7.9816	8.0060	8.1774	8.2509	8.2264	8.0868 ± 0.11
2735	79.36	Slug	8.2019	8.0305	8.1529	7.9326	8.0795	8.0550	7.9326	7.8836	7.8591	7.8591	7.9987 ± 0.12
2735	89.62	Slug	7.6878	7.6143	7.5898	7.7857	7.7367	7.7612	7.8347	7.8836	7.7122	7.7122	7.7318 ± 0.09
2735	99.87	Slug	7.3450	7.3205	7.3695	7.6388	7.5898	7.5653	7.4919	7.3695	7.4184	7.6633	7.4772 ± 0.13
2735	177	Slug	6.1943	6.1208	6.4881	6.2922	6.2922	6.2677	6.3657	6.4146	6.2677	6.5615	6.3265 ± 0.13
2735	296	Slug	4.5784	4.7253	4.7987	4.8967	4.8232	4.7498	4.7742	4.8477	4.3091	4.6029	4.7106 ± 0.17
2735	369	Slug-Churn	3.9663	4.2111	4.0642	4.0397	4.1132	4.1132	4.0153	4.2846	3.5990	3.9173	4.0324 ± 0.19
2735	515	Slug-Churn	3.5501	3.1828	3.6725	3.6480	3.5501	3.2318	3.6725	3.1339	2.8156	3.2318	3.3689 ± 0.29
2735	735	Slug-Churn	2.8156	3.1583	3.2318	3.4032	3.1094	3.0604	3.2073	3.2073	3.1828	3.0604	3.1437 ± 0.15
2735	1454	Slug-Churn	2.3259	2.0076	2.4238	2.2525	2.2035	2.4973	2.5218	2.5218	2.3259	2.3994	2.3479 ± 0.16
2735	2474	Churn	3.0604	2.9625	2.9380	3.0604	3.0849	2.9135	2.9380	2.8890	2.8890	2.8156	2.9551 ± 0.09

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2735	3495	Churn	2.9380	2.9380	2.9625	2.9625	2.9380	2.9380	2.9135	2.9625	2.9625	2.9870	2.9502 ± 0.02
2735	4516	Churn	3.0604	3.0604	3.0359	3.0359	3.0114	3.0604	3.0114	3.0114	3.0114	2.9870	3.0286 ± 0.03
2735	5537	Churn	2.5463	2.5218	2.4483	2.5707	2.6442	2.3994	2.3994	2.4483	2.5463	2.5707	2.5095 ± 0.08
2735	14255	Churn	3.3787	3.3052	3.1583	3.1828	3.3787	3.1339	3.1094	3.1094	3.2318	3.0849	3.2073 ± 0.11
2735	21382	Churn	4.7498	4.6518	4.6518	4.6518	4.6518	4.6518	4.6518	4.6518	4.6518	4.6518	4.6616 ± 0.03
2735	28510	Annular	6.0229	6.0229	6.0229	6.0229	6.0229	6.0229	6.0229	6.0229	6.0229	6.0229	6.0229 ± 0.00
2735	35637	Annular	6.6839	6.6839	6.6839	6.6839	6.6839	6.6839	6.6839	6.6839	6.6839	6.6839	6.6839 ± 0.00
2735	42765	Annular	7.3940	7.3940	7.3940	7.3940	7.3940	7.3940	7.3940	7.3940	7.3940	7.3940	7.3940 ± 0.00
2735	49892	Annular	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692	8.5692 ± 0.00
2735	57020	Mist	9.0588	9.0588	9.0588	9.0588	9.0588	9.0588	9.0588	9.0588	9.0588	9.0588	9.0588 ± 0.00



○ dp/dz for octylbenzyldimethylammonium chloride solution (3CMC) from experiment

——— dp/dz from Nicklin's, Wilkes's and Davidson's theory

— — — dp/dz from Sylvester's theory

- - - - - - dp/dz from Wallis's theory

Figure J6 Comparison between Nicklin's theory, Sylvester's theory and experimental pressure gradient vs. air Reynolds number of octylbenzyldimethylammonium chloride solution (3CMC) at $Re_{solution}$ = 2735 by using pipe diameter 19 mm.

Table J9 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes of octylbenzyldimethylammonium chloride solution (3CMC) by using pipe diameter of 19 mm

Pipe diameter (mm)	$Re_{solution}$	Re_{air}(critical) for each flow regime					
		Bubble-Slug	Slug	Slug-Churn	Churn	Annular	Mist
19	2735	38.33	43.46	369	2474	28510	57020

Appendix K Hexadecylbenzyldimethylammonium Chloride Surfactant (1CMC) – Air Flow for the Pipe Diameter of 19 mm

Table K1 Determination of bubble size from hexadecylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the bubble size:

1. Make a movie of the bubble flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the bubble size by Scion Image software program.

Equivalent diameter (D_e) of the bubble is defined as the diameter of a sphere that has the same volume as the bubble.

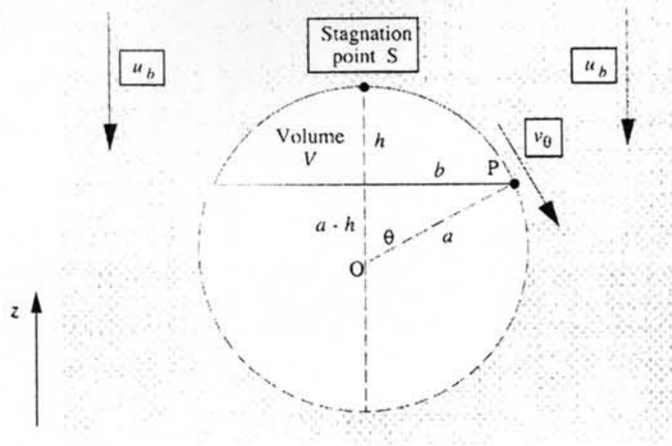


Figure K1 Flow around a spherical cap bubble (Wilkes, 1999).

$$\text{Equivalent diameter } (D_e) \; = \; \sqrt[3]{3.94h\left[\frac{h^2+b^2}{2h}\right]^2 - 1.94b^2\left[\left(\frac{h^2+b^2}{2h}\right) - h\right]} \qquad \text{(K1)}$$

$Re_{solution}$	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble width, W_b (mm)			Average bubble width (mm)	Equivalent diameter, D_e (mm)			Average equivalent diameter, De (mm)
		1	2	3		1	2	3		1	2	3	
2741	3.17	7.2	7.3	7.7	7.4 ± 0.3	11.3	11.5	11.3	11.4 ± 0.1	10.1	10.3	10.5	10.3 ± 0.2
2741	5.64	7.8	8.0	7.4	7.7 ± 0.3	11.5	12.1	11.4	11.6 ± 0.4	10.7	11.0	10.3	10.7 ± 0.4
2741	8.12	8.4	8.7	8.4	8.5 ± 0.2	11.8	11.6	11.9	11.8 ± 0.1	11.3	11.4	11.3	11.4 ± 0.1
2741	10.59	9.8	9.8	10.0	9.8 ± 0.1	12.3	12.0	11.8	12.0 ± 0.3	12.6	12.5	12.6	12.6 ± 0.1
2741	13.07	10.0	10.9	10.6	10.5 ± 0.4	12.9	12.3	12.2	12.4 ± 0.4	13.0	13.5	13.2	13.3 ± 0.2
2741	15.54	11.8	11.2	11.5	11.5 ± 0.3	12.5	12.8	13.1	12.8 ± 0.3	14.4	13.9	14.3	14.2 ± 0.2
2741	18.02	11.8	12.7	11.8	12.1 ± 0.5	13.2	13.2	12.7	13.0 ± 0.3	14.6	15.4	14.4	14.8 ± 0.5
2741	20.49	13.5	13.1	13.1	13.3 ± 0.2	12.3	13.3	13.6	13.1 ± 0.7	15.8	15.8	15.9	15.8 ± 0.1
2741	22.95	15.0	14.9	14.9	14.9 ± 0.1	12.8	13.2	13.9	13.3 ± 0.5	17.3	17.3	17.5	17.3 ± 0.1
2741	28.08	17.0	17.6	17.9	17.5 ± 0.5	13.4	13.1	13.4	13.3 ± 0.2	19.2	19.7	20.0	19.6 ± 0.4
2741	33.21	20.0	19.2	19.2	19.5 ± 0.5	13.2	14.1	13.2	13.5 ± 0.5	21.9	21.4	21.1	21.5 ± 0.4

$Re_{solution}$	Re_{air}	Bubble height / Pipe diameter			Average, R_h/D	Bubble width / Pipe diameter			Average, W_b/D	Equivalent diameter / Pipe diameter			Average equivalent diameter, De/D
		1	2	3		1	2	3		1	2	3	
2741	3.17	0.38	0.38	0.41	0.39 ± 0.02	0.60	0.61	0.59	0.60 ± 0.01	0.53	0.54	0.55	0.54 ± 0.01
2741	5.64	0.41	0.42	0.39	0.41 ± 0.01	0.60	0.64	0.60	0.61 ± 0.02	0.56	0.58	0.54	0.56 ± 0.02
2741	8.12	0.44	0.46	0.44	0.45 ± 0.01	0.62	0.61	0.63	0.62 ± 0.01	0.59	0.60	0.60	0.60 ± 0.00
2741	10.59	0.51	0.51	0.53	0.52 ± 0.01	0.65	0.63	0.62	0.63 ± 0.01	0.66	0.66	0.66	0.66 ± 0.00
2741	13.07	0.53	0.57	0.56	0.55 ± 0.02	0.68	0.65	0.64	0.66 ± 0.02	0.69	0.71	0.70	0.70 ± 0.01
2741	15.54	0.62	0.59	0.60	0.60 ± 0.02	0.66	0.67	0.69	0.67 ± 0.01	0.76	0.73	0.75	0.75 ± 0.01
2741	18.02	0.62	0.67	0.62	0.64 ± 0.03	0.70	0.69	0.67	0.69 ± 0.02	0.77	0.81	0.76	0.78 ± 0.03
2741	20.49	0.71	0.69	0.69	0.70 ± 0.01	0.65	0.70	0.72	0.69 ± 0.04	0.83	0.83	0.84	0.83 ± 0.00
2741	22.95	0.79	0.78	0.78	0.78 ± 0.00	0.68	0.70	0.73	0.70 ± 0.03	0.91	0.91	0.92	0.91 ± 0.01
2741	28.08	0.89	0.93	0.94	0.92 ± 0.02	0.71	0.69	0.71	0.70 ± 0.01	1.01	1.04	1.05	1.03 ± 0.02
2741	33.21	1.05	1.01	1.01	1.02 ± 0.02	0.69	0.74	0.70	0.71 ± 0.03	1.15	1.12	1.11	1.13 ± 0.02

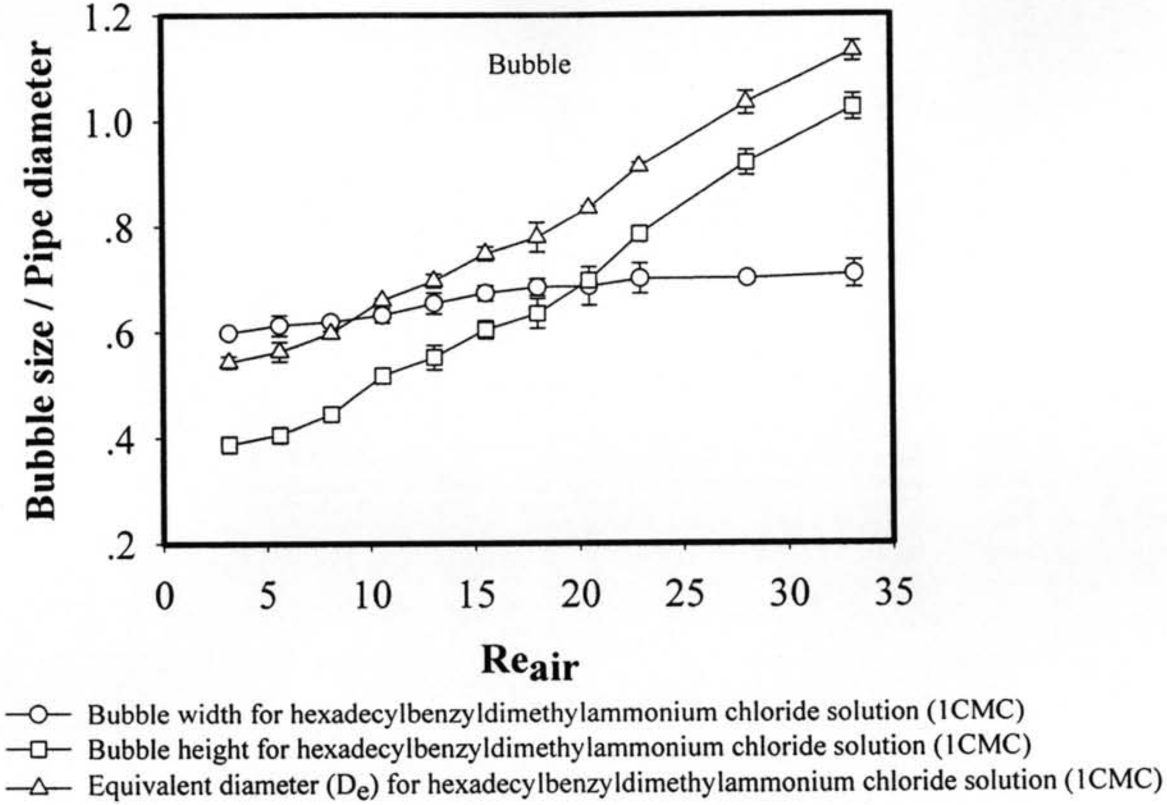


Figure K2 Bubble width, bubble height and equivalent diameter vs. air Reynolds number of hexadecylbenzyldimethylammonium chloride solution (1CMC) at $Re_{solution} = 2741$ by using pipe diameter of 19 mm.

Table K2 Determination of slug height from hexadecylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Procedure to determine the slug height:

1. Make a movie of the slug flow regime by video camera.
2. Capture the picture from movie by Snagit 8.0 software program.
3. Measure the slug height by Scion Image software program.

$Re_{solution}$	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
		1	2	3		1	2	3	
2741	48.59	34.9	36.6	34.9	35.4 ± 1.0	1.8	1.9	1.8	1.9 ± 0.05
2741	58.85	44.4	44.6	43.6	44.2 ± 0.5	2.3	2.3	2.3	2.3 ± 0.03
2741	69.10	49.3	50.2	51.6	50.3 ± 1.1	2.6	2.6	2.7	2.6 ± 0.06
2741	79.36	57.7	57.7	56.9	57.5 ± 0.5	3.0	3.0	3.0	3.0 ± 0.02
2741	89.62	63.7	64.8	64.4	64.3 ± 0.6	3.4	3.4	3.4	3.4 ± 0.03
2741	99.87	69.0	70.0	69.9	69.6 ± 0.5	3.6	3.7	3.7	3.7 ± 0.03
2741	177	101.0	99.0	102.0	100.7 ± 1.5	5.3	5.2	5.4	5.3 ± 0.08
2741	296	180	177	183	180.0 ± 3.0	9.5	9.3	9.6	9.5 ± 0.16

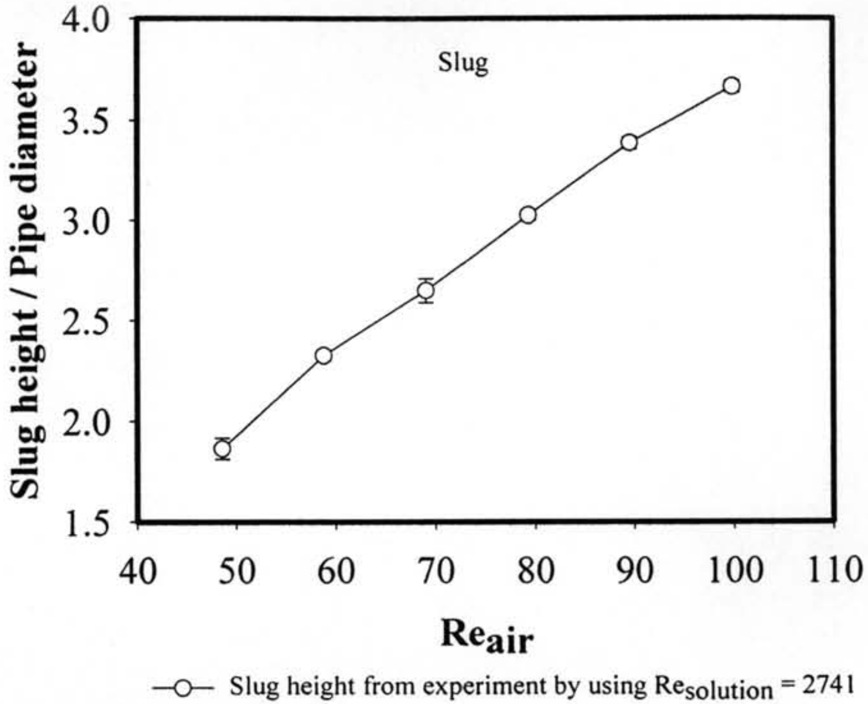


Figure K3 Slug height from experiment vs. air Reynolds number of hexadecylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table K3 Determination of bubble and slug velocity for hexadecylbenzyldimethylammonium chloride solution (1CMC) from Nicklin's theory and experiment

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Bubble velocity from theory, $u_s = 1.2(\frac{Q_{qir} + Q_{liquid}}{A}) + 0.35\sqrt{gD}$ (K2)

Determination of bubble velocity from experiment by timing the bubble at known distance (0.8m)

$Re_{solution}$	Re_{air}	Time of bubble travel (sec)/0.8m					Average (sec/0.8 m)	Bubble and slug velocity (m/s)					Average bubble and slug velocity from experiment (m/s)	Bubble and slug velocity from Nicklin's theory (m/s)
		1	2	3	4	5		1	2	3	4	5		
2741	3.17	2.22	2.22	2.19	2.18	2.19	2.20 ± 0.02	0.36	0.36	0.37	0.37	0.37	0.36 ± 0.003	0.35
2741	5.64	2.19	2.22	2.19	2.22	2.18	2.20 ± 0.02	0.37	0.36	0.37	0.36	0.37	0.36 ± 0.003	0.35
2741	8.11	2.19	2.16	2.21	2.20	2.21	2.19 ± 0.02	0.37	0.37	0.36	0.36	0.36	0.36 ± 0.003	0.35
2741	10.59	2.19	2.15	2.19	2.19	2.19	2.18 ± 0.02	0.37	0.37	0.37	0.37	0.37	0.37 ± 0.003	0.35
2741	13.06	2.18	2.15	2.18	2.22	2.16	2.18 ± 0.03	0.37	0.37	0.37	0.36	0.37	0.37 ± 0.004	0.36
2741	15.53	2.15	2.16	2.19	2.18	2.16	2.17 ± 0.02	0.37	0.37	0.37	0.37	0.37	0.37 ± 0.003	0.36
2741	18.01	2.16	2.16	2.19	2.16	2.16	2.17 ± 0.01	0.37	0.37	0.37	0.37	0.37	0.37 ± 0.002	0.36
2741	20.48	2.15	2.16	2.13	2.16	2.15	2.15 ± 0.01	0.37	0.37	0.38	0.37	0.37	0.37 ± 0.002	0.36
2741	22.94	2.13	2.16	2.15	2.15	2.13	2.14 ± 0.01	0.38	0.37	0.37	0.37	0.38	0.37 ± 0.002	0.37
2741	28.06	2.13	2.16	2.12	2.13	2.15	2.14 ± 0.02	0.38	0.37	0.38	0.38	0.37	0.37 ± 0.003	0.37
2741	33.19	2.06	2.06	2.13	2.09	2.06	2.08 ± 0.03	0.39	0.39	0.38	0.38	0.39	0.38 ± 0.006	0.38
2741	38.31	2.07	2.06	2.04	2.03	2.03	2.05 ± 0.02	0.39	0.39	0.39	0.39	0.39	0.39 ± 0.003	0.38
2741	43.44	2.03	2.03	2.00	2.00	2.07	2.03 ± 0.03	0.39	0.39	0.40	0.40	0.39	0.39 ± 0.006	0.39
2741	48.57	2.06	2.03	2.00	2.00	2.04	2.03 ± 0.03	0.39	0.39	0.40	0.40	0.39	0.39 ± 0.005	0.39
2741	58.82	1.96	2.00	1.93	1.94	1.94	1.95 ± 0.03	0.41	0.40	0.41	0.41	0.41	0.41 ± 0.006	0.40
2741	69.07	1.91	1.88	1.94	1.97	1.88	1.92 ± 0.04	0.42	0.43	0.41	0.41	0.43	0.42 ± 0.008	0.41
2741	79.32	1.81	1.91	1.87	1.87	1.85	1.86 ± 0.04	0.44	0.42	0.43	0.43	0.43	0.43 ± 0.008	0.42
2741	89.57	1.78	1.75	1.78	1.84	1.78	1.79 ± 0.03	0.45	0.46	0.45	0.43	0.45	0.45 ± 0.008	0.43
2741	99.82	1.78	1.78	1.75	1.72	1.75	1.76 ± 0.03	0.45	0.45	0.46	0.47	0.46	0.46 ± 0.007	0.44
2741	177	1.50	1.50	1.47	1.54	1.50	1.50 ± 0.02	0.53	0.53	0.54	0.52	0.53	0.53 ± 0.009	0.52
2741	296	1.22	1.18	1.22	1.25	1.22	1.22 ± 0.02	0.66	0.68	0.66	0.64	0.66	0.66 ± 0.014	0.64

$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$	Bubble and slug velocity from Nicklin's theory, $\frac{u}{(gD)^{0.5}}$
		1	2	3	4	5		
2741	3.17	0.83	0.83	0.85	0.85	0.85	0.84 ± 0.007	0.80
2741	5.64	0.85	0.83	0.85	0.83	0.85	0.84 ± 0.007	0.81
2741	8.11	0.85	0.86	0.84	0.84	0.84	0.84 ± 0.008	0.81
2741	10.59	0.85	0.86	0.85	0.85	0.85	0.85 ± 0.007	0.82
2741	13.06	0.85	0.86	0.85	0.83	0.86	0.85 ± 0.010	0.82
2741	15.53	0.86	0.86	0.85	0.85	0.86	0.85 ± 0.006	0.83
2741	18.01	0.86	0.86	0.85	0.86	0.86	0.86 ± 0.005	0.83
2741	20.48	0.86	0.86	0.87	0.86	0.86	0.86 ± 0.005	0.84
2741	22.94	0.87	0.86	0.86	0.86	0.87	0.86 ± 0.005	0.85
2741	28.06	0.87	0.86	0.87	0.87	0.86	0.87 ± 0.007	0.86
2741	33.19	0.90	0.90	0.87	0.89	0.90	0.89 ± 0.013	0.87
2741	38.31	0.90	0.90	0.91	0.91	0.91	0.91 ± 0.008	0.88
2741	43.44	0.91	0.91	0.93	0.93	0.90	0.91 ± 0.013	0.89
2741	48.57	0.90	0.91	0.93	0.93	0.91	0.91 ± 0.012	0.90
2741	58.82	0.95	0.93	0.96	0.96	0.96	0.95 ± 0.013	0.93
2741	69.07	0.97	0.99	0.96	0.94	0.99	0.97 ± 0.020	0.95
2741	79.32	1.02	0.97	0.99	0.99	1.00	1.00 ± 0.019	0.98
2741	89.57	1.04	1.06	1.04	1.01	1.04	1.04 ± 0.019	1.00
2741	99.82	1.04	1.04	1.06	1.08	1.06	1.06 ± 0.015	1.02
2741	177	1.24	1.24	1.26	1.20	1.24	1.23 ± 0.020	1.20
2741	296	1.52	1.57	1.52	1.48	1.52	1.52 ± 0.031	1.47

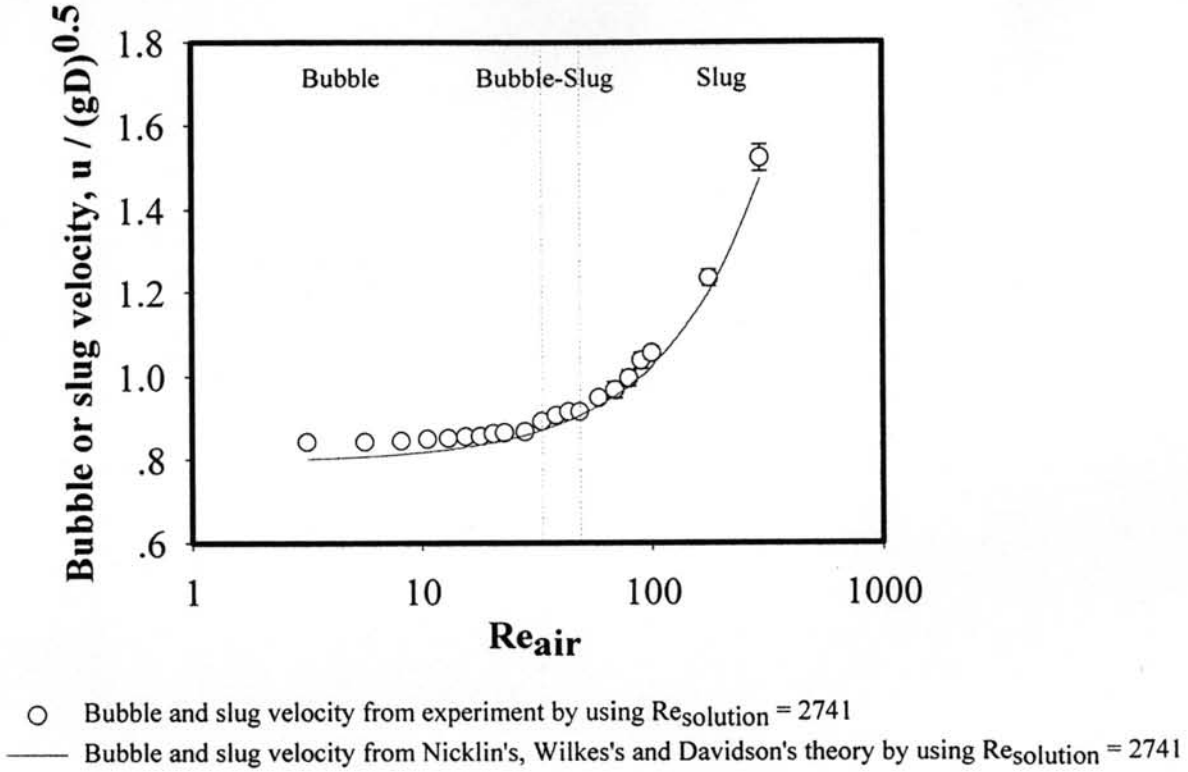


Figure K4 Comparison bubble and slug velocity from experiment vs. air Reynolds number of hexadecylbenzyldimethylammonium chloride solution (1CMC) comparing with Nicklin's theory by using pipe diameter of 19 mm.

Table K4 Determination of the pressure gradient for the bubble flow regime from Nicklin's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Superficial liquid velocity, $j_{liquid} = \frac{Q_{liquid}}{A}$ (K3)

Superficial air velocity, $j_{air} = \frac{Q_{air}}{A}$ (K4)

Reynolds number of liquid, $\mathrm{Re}_{liquid} = \frac{\rho j_{liquid} D}{\mu_{liquid}}$ (K5)

Reynolds number of air, $\mathrm{Re}_{air} = \frac{\rho j_{air} D}{\mu_{air}}$ (K6)

Bubble velocity rising in stagnant liquid, $u_b = 1.00\sqrt{g R_b}$ (K7)

where R_b is equivalent radius of the bubble which defined as the radius of a sphere that has the same volume as the bubble

Void fraction, $\varepsilon = \frac{Q_{air}}{Q_{air} + Q_{liquid} + u_b A}$ (K8)

Pressure gradient for bubble flow regime, $\frac{dp}{dz} = -\rho_l g(1-\varepsilon)$ (K9)

$Q_{solution}$ (ml/min)	Sup. solution velocity $j_{solution}$ (m/s)	$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Q_{air} (L/min)	Sup. Air velocity j_{air} (m/s)	Q_{air} (m^3/sec)	Re_{air}	Flow regime	U_b (m/s)	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
2713	0.1596	4.52E-05	2741	0.0444	0.0026	7.4E-07	3.17	Bubble	0.2249	0.0068	9.7175
2713	0.1596	4.52E-05	2741	0.0792	0.0047	1.3E-06	5.64	Bubble	0.2290	0.0118	9.6677
2713	0.1596	4.52E-05	2741	0.1139	0.0067	1.9E-06	8.12	Bubble	0.2360	0.0166	9.6206
2713	0.1596	4.52E-05	2741	0.1486	0.0087	2.5E-06	10.59	Bubble	0.2482	0.0210	9.5782
2713	0.1596	4.52E-05	2741	0.1833	0.0108	3.1E-06	13.07	Bubble	0.2550	0.0253	9.5355
2713	0.1596	4.52E-05	2741	0.2180	0.0128	3.6E-06	15.54	Bubble	0.2641	0.0294	9.4961
2713	0.1596	4.52E-05	2741	0.2528	0.0149	4.2E-06	18.02	Bubble	0.2694	0.0335	9.4558
2713	0.1596	4.52E-05	2741	0.2875	0.0169	4.8E-06	20.49	Bubble	0.2786	0.0372	9.4200
2713	0.1596	4.52E-05	2741	0.3220	0.0189	5.4E-06	22.95	Bubble	0.2917	0.0403	9.3895
2713	0.1596	4.52E-05	2741	0.3939	0.0232	6.6E-06	28.08	Bubble	0.3102	0.0470	9.3237
2713	0.1596	4.52E-05	2741	0.4659	0.0274	7.8E-06	33.21	Bubble	0.3244	0.0536	9.2593

Table K5 Determination of the pressure gradient for the slug flow regime from Nicklin's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Mean liquid velocity, $u_l = \dfrac{Q_{air} + Q_{liquid}}{A}$ (K10)

Reynolds number of the liquid slug, $\mathrm{Re}_{slug} = \dfrac{\rho_{liquid} u_l D}{\mu_{liquid}}$ (K11)

Fanning friction factor, $f_F = \dfrac{16}{\mathrm{Re}_{slug}}$ for laminar flow ($\mathrm{Re}_{slug} < 2000$) (K12)

$f_F = 0.079\,\mathrm{Re}_{slug}^{-1/4}$ for turbulent flow ($\mathrm{Re}_{slug} > 4000$) (K13)

Single-phase frictional pressure gradient for liquid only, $\left(\dfrac{dp}{dz}\right)_{sp} = \dfrac{2 f_F \rho_{liquid} u_l}{D}$ (K14)

Void fraction, $\varepsilon = \dfrac{Q_{air}}{1.2\left(Q_{air} + Q_{liquid}\right) + 0.35A\sqrt{gD}}$ (K15)

Pressure gradient for slug flow regime, $\dfrac{dp}{dz} = (1-\varepsilon)\left[-\rho_{liquid}\, g + \left(\dfrac{dp}{dz}\right)_{sp}\right]$ (K16)

$Q_{solution}$ (m^3/sec)	$Re_{solution}$	Q_{air} (m^3/sec)	Re_{air}	Flow regime	Mean liquid velocity U_l(m/s)	Re_{slug}	f_F	$(-dp/dz)_{sp}$	Void fraction	$(-dp/dz)_{tp}$ from theory (kPa/m)
4.522E-05	2741	1.136E-05	48.59	Slug	0.1997	3430	0.0103	43.2011	0.1026	8.8183
4.522E-05	2741	1.376E-05	58.85	Slug	0.2081	3575	0.0102	46.4564	0.1211	8.6392
4.522E-05	2741	1.616E-05	69.10	Slug	0.2166	3721	0.0101	49.8126	0.1387	8.4691
4.522E-05	2741	1.856E-05	79.36	Slug	0.2251	3866	0.0100	53.2686	0.1555	8.3073
4.522E-05	2741	2.096E-05	89.62	Slug	0.2335	4012	0.0099	56.8234	0.1714	8.1533
4.522E-05	2741	2.335E-05	99.87	Slug	0.2420	4157	0.0098	60.4763	0.1867	8.0064
4.522E-05	2741	4.134E-05	177	Slug	0.3055	5247	0.0093	90.9132	0.2818	7.0916
4.522E-05	2741	6.922E-05	296	Slug	0.4038	6938	0.0087	148.1987	0.3843	6.1154
4.522E-05	2741	8.631E-05	369	Slug-Churn	0.4641	7974	0.0084	189.0667	0.4301	5.6829
4.522E-05	2741	0.0001205	515	Slug-Churn	0.5847	10045	0.0079	283.2475	0.4986	5.0478
4.522E-05	2741	0.0001718	735	Slug-Churn	0.7656	13153	0.0074	453.9687	0.5665	4.4380
4.522E-05	2741	0.0003399	1454	Slug-Churn	1.3590	23347	0.0064	1239.1657	0.6731	3.6031

Table K6 Determination of the pressure gradient for the slug flow regime from Sylvester's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$ = 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

$$\beta = L_{TB}/L_{SU} \quad \text{(K17)}$$

where: L_{TB} is length of the Taylor bubble

L_{SU} is length of the slug unit

Friction factor associated with the Taylor bubble, $$f_{TB} = \frac{1}{\left[-2.0\log\left\{\frac{\left(1-\alpha_{TB}^{1/2}\right)}{7.4}\right\}\right]^2} \quad \text{(K18)}$$

Reynolds number of the liquid slug, $$\mathrm{Re}_{LS} = \frac{\rho_L U_{LLS} D}{\mu_L} \quad \text{(K19)}$$

where: velocity of the liquid in the liquid slug, $$U_{LLS} = U_{SG} + U_{SL} \quad \text{(K20)}$$

Friction factor associated with the liquid slug, $$f_{LS} = \frac{1}{\left[-2.0\log\left\{\frac{\varepsilon/D}{3.7} - \left(\frac{5.02}{\mathrm{Re}_{LS}}\right)\log\left(\frac{\varepsilon/D}{3.7} + \frac{13}{\mathrm{Re}_{LS}}\right)\right\}\right]^2} \quad \text{(K21)}$$

where: ε is the pipe roughness

Acceleration pressure drop, $$(\Delta P)_A = \rho_L(U_{LTB} + U_{TB})(1-\alpha_{TB})(U_{LTB} + U_{TB} + U_{LLS}) \quad \text{(K22)}$$

where: velocity of the liquid film around the Taylor bubble, $$U_{LTB} = 9.916\left[gD\left(1-\sqrt{\alpha_{TB}}\right)\right]^{1/2} \quad \text{(K23)}$$

velocity of the Taylor bubble, $U_{TB} = 1.2(U_{SG} + U_{SL}) + 0.35\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}$ (K24)

area average void fraction of the Taylor bubble, $\alpha_{TB} = \frac{\text{Average all area at Taylor bubble region}}{\text{Average area in Taylor bubble}}$ (K25)

Hydrostatic pressure drop, $(\Delta P)_H = \rho_L(1-\alpha_{LS})gL_{LS}$ (K26)

where: void fraction of the liquid slug, $\alpha_{LS} = \frac{U_{SG}}{0.425 + 2.65(U_{SG} + U_{SL})}$ (K27)

length of the liquid slug, L_{LS}

Frictional pressure drop of slug unit, $(\Delta P)_F = \frac{L_{LS}}{2D}\left[\frac{\rho_G \beta f_{TB} U_{TB}^2}{(1-\beta)[1-(1-\alpha_{TB}^{1/2}]} + U_{LLS}^2 \rho_L (1-\alpha_{LS}) f_{LS} (1-\beta)\right]$ (K28)

Total pressure drop in the slug unit, $(\Delta P)_T = (\Delta P)_A + (\Delta P)_H + (\Delta P)_F$ (K29)

$Re_{solution}$	Re_{air}	Flow regime	β	f_{TB}	Re_{LS}	f_{LS}	Acceleration pressure drop (ΔP), Pa	Hydrostatic pressure drop (ΔP), Pa	Frictional pressure drop (ΔP), Pa	Total pressure drop in slug unit (ΔP), Pa	Total pressure drop in slug unit (ΔP), kPa	Pressure gradient (dp/dz), kPa/m
2741	48.59	Slug	0.3419	0.0541	3430	0.0416	219	639	1.8820	859.8	0.8598	8.2977
2741	58.85	Slug	0.2746	0.0536	3575	0.0411	216	1085	3.7750	1304.8	1.3048	8.1090
2741	69.10	Slug	0.2830	0.0537	3721	0.0407	221	1177	4.3318	1402.3	1.4023	7.8833
2741	79.36	Slug	0.2922	0.0536	3866	0.0402	223	1275	4.9475	1502.7	1.5027	7.6408
2741	89.62	Slug	0.3039	0.0534	4012	0.0398	225	1339	5.4452	1568.8	1.5688	7.4146
2741	99.87	Slug	0.2994	0.0535	4157	0.0394	231	1471	6.3981	1707.6	1.7076	7.3434
2741	177	Slug	0.2868	0.0345	5247	0.0369	42	2160	14.2506	2215.8	2.2158	6.3127
2741	296	Slug	0.4932	0.0558	6938	0.0342	372	1514	11.6076	1898.1	1.8981	5.2002

Table K7 Determination of the pressure gradient for the annular and mist flow regime from Wallis's theory

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution} = 997.3$ kg/m^3; viscosity of solution, $\mu_{solution} = 1.103 \times 10^{-3}$ Pa.s

density of air, $\rho_{air} = 1.18$ kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

Fanning friction factor, $f_F = \dfrac{16}{\text{Re}}$ for laminar flow (Re < 2000) (K30)

$f_F = 0.079\,\text{Re}^{-1/4}$ for turbulent flow (Re > 4000) (K31)

Pressure gradient for air, $\left(\dfrac{dp}{dz}\right)_{air} = \dfrac{2 f_F \rho_{air} j_{air}}{D}$ (K32)

Pressure gradient for liquid, $\left(\dfrac{dp}{dz}\right)_{liquid} = \dfrac{2 f_F \rho_{liquid} j_{liquid}}{D}$ (K33)

Martinelli parameter, X

from $\left(1+X^{2/3.61}\right)^{3.61}\left(\dfrac{dp}{dz}\right)_{air} - \rho_{air} g = \dfrac{\left(1+X^{2/3.61}\right)^{3.61}}{X^2}\left(\dfrac{dp}{dz}\right)_{liquid} - [\dfrac{1}{(1+0.0904X^{0.548})^{2.82}}\rho_{air} + (1-\dfrac{1}{(1+0.0904X^{0.548})^{2.82}})\rho_{liquid}]g$ (K34)

Void fraction, $\varepsilon = \dfrac{1}{\left(1+0.0904\,X^{0.548}\right)^{2.82}}$ (K35)

Gas two-phase flow multiplier, $\phi_g = \left(1+X^{2/3.61}\right)^{3.61/2}$ (K36)

Pressure gradient for two-phase flow, $\left(\frac{dp}{dz}\right) = \phi_g^2 \left(\frac{dp}{dz}\right)_{air} - \rho_{air} g$ (K37)

$\dot{Q}_{solution}$ (ml/min)	$Re_{solution}$	Q_{air} (L/min)	Re_{air}	Flow regime	f_F of air	f_F of solution	$(-dp/dz)_{air}$ (Pa/m)	$(-dp/dz)_{solution}$ (Pa/m)	Martinelli parameter (X)	Void fraction (ε)	Φ_g^2	Pressue gradient $(-dp/dz)_{tp}$ (kPa/m)
2713	2741	400	28510	Annular	0.0061	0.0058	418	15.6013	0.3164	0.8759	4.6274	1.9455
2713	2741	500	35637	Annular	0.0057	0.0058	618	15.6013	0.2139	0.8981	3.5967	2.2328
2713	2741	600	42765	Annular	0.0055	0.0058	850	15.6013	0.1656	0.9107	3.1097	2.6539
2713	2741	700	49892	Annular	0.0053	0.0058	1113	15.6013	0.1369	0.9190	2.8178	3.1472
2713	2741	800	57020	Mist	0.0051	0.0058	1406	15.6013	0.1177	0.9251	2.6188	3.6929
2713	2741	900	64147	Mist	0.0050	0.0058	1728	15.6013	0.1037	0.9299	2.4721	4.2822
2713	2741	1000	71275	Mist	0.0048	0.0058	2077	15.6013	0.0930	0.9338	2.3583	4.9105

Table K8 Determination of the pressure gradient from experiment for hexadecylbenzyldimethylammonium chloride solution (1CMC)

Physical properties of air and solution used in experiment:

density of solution, $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution} = 1.103 \times 10^{-3}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

temperature, T = 31 °C (± 1 °C); inner pipe diameter, D = 0.019 m;

cross-sectional area of pipe, A = 0.00028 m^2; pressure taps difference = 0.4 m

Procedure to determine of pressure gradient from experiment:

1. Read the highest and lowest difference level from manometer.
2. Put the value of difference level in $-\frac{dp}{dz} = \frac{\rho_l g(100 - level_{liquid,L}) - (100 - level_{liquid,R})}{100x0.4x1000}$ (K38)

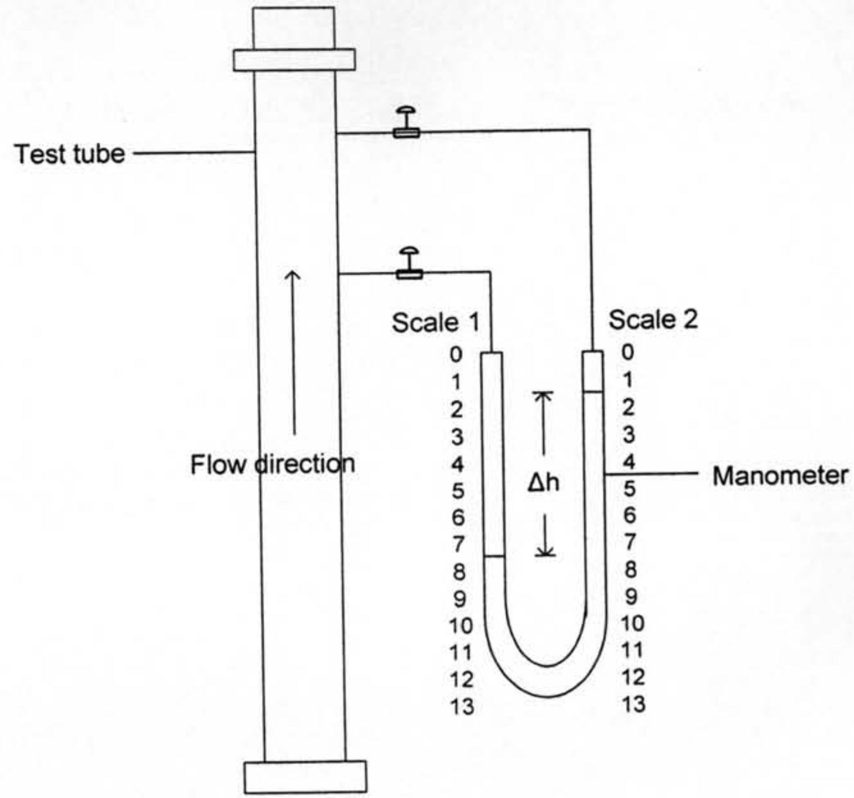


Figure K5 Appearance scale and water level in manometer.

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2741	3.17	Bubble	79.3	79.3	79.3	79.3	79.3	42.7	42.7	42.7	42.7	42.7
2741	5.64	Bubble	79	79	79	79	79	42.7	42.7	42.7	42.7	42.7
2741	8.12	Bubble	79	79	79	79	79	42.9	42.9	42.9	42.9	42.9
2741	10.59	Bubble	78.9	78.9	78.9	78.9	78.9	42.9	42.9	42.9	42.9	42.9
2741	13.07	Bubble	78.7	78.7	78.7	78.7	78.7	43	43	43	43	43
2741	15.54	Bubble	78.6	78.6	78.6	78.6	78.6	43	43	43	43	43
2741	18.02	Bubble	78.5	78.5	78.5	78.5	78.5	43	43	43	43	43
2741	20.49	Bubble	78.5	78.5	78.5	78.5	78.5	43.2	43.2	43.2	43.2	43.2
2741	22.95	Bubble	78.3	78.3	78.3	78.3	78.3	43.2	43.2	43.2	43.2	43.2
2741	28.08	Bubble	78.2	78.2	78.2	78.2	78.2	43.3	43.3	43.3	43.3	43.3
2741	33.21	Bubble	77.8	77.8	77.8	77.8	77.8	43.5	43.5	43.5	43.5	43.5
2741	38.33	Bubble-Slug	76.7	76.7	76.7	76.7	76.7	42.7	42.7	42.7	42.7	42.7
2741	43.46	Bubble-Slug	76.3	76.3	76.5	76.3	76.3	42.5	42.4	42.3	42.6	42.5
2741	48.59	Slug	74.7	74.9	75	74.9	74.9	42.4	42.3	42.2	41.9	41.8
2741	58.85	Slug	74	74	74	74	74	42.1	42.2	42.2	42.2	42.2
2741	69.10	Slug	73.7	73.7	73.7	73.7	73.7	42.3	42.2	42.3	42.2	42.2
2741	79.36	Slug	73.3	73.3	73.3	73.1	73.1	42.7	42.6	42.6	42.6	42.5
2741	89.62	Slug	72	72	72	71.9	71.8	42.3	42.2	42.3	42.3	42.4
2741	99.87	Slug	71.4	71.3	71.3	71.4	71.4	42.6	42.7	42.5	42.5	42.5
2741	177	Slug	67.3	67.4	67.4	67.3	67.2	42.3	42.2	42.2	42.1	42.1
2741	296	Slug	74.5	74.8	74.8	74.6	74.8	54	53.3	53.5	53.5	53.4
2741	369	Slug-Churn	69.7	69.7	69.7	69.3	69	50.1	50	49.8	50.5	50.2
2741	515	Slug-Churn	62.8	61.3	61.4	58.6	56	49	48.2	47	44.8	42
2741	735	Slug-Churn	45.3	45.3	45.5	45.5	45.3	33.8	33.8	33	33.4	33.5
2741	1454	Slug-Churn	79.3	78.2	78.8	79.2	79.2	70	71.3	70.8	70.2	70
2741	2474	Churn	78.5	78	78.5	78.5	78	68.3	68.5	68.3	67.8	68.1

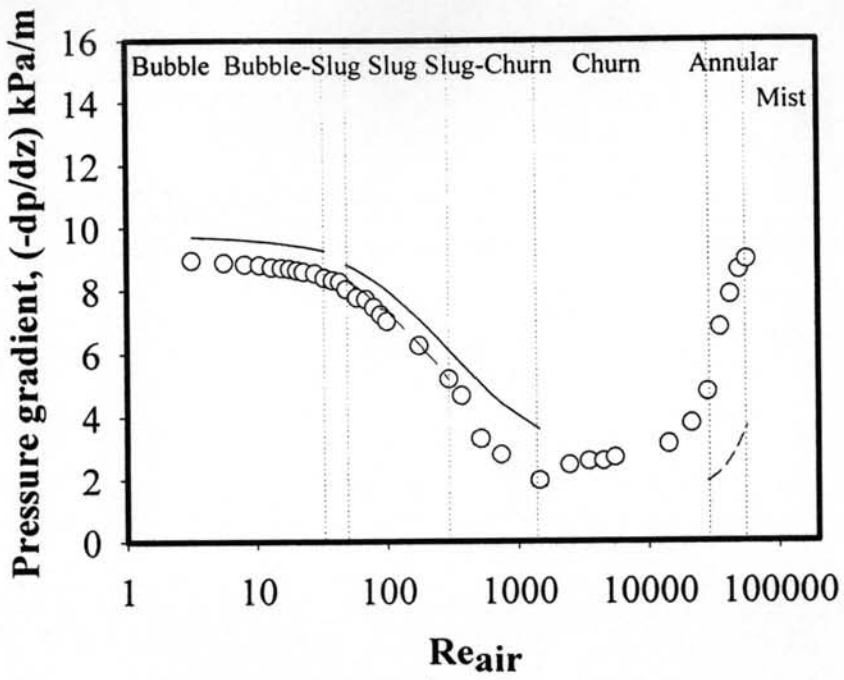
Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (lowest)					Right hand side (highest)				
			1	2	3	4	5	1	2	3	4	5
2741	3495	Churn	78.2	78	77.9	77.9	78	67.2	67.2	67.3	67.3	67.4
2741	4516	Churn	77.6	77.6	77.6	77.6	77.6	67	67	67	67	67
2741	5537	Churn	87.5	87	86.5	86.5	86.5	77	76.5	76.3	75.5	75
2741	14255	Churn	82.2	82	82.3	82	81.8	69.3	69.3	69	69	69
2741	21382	Churn	82.8	82.5	81.3	81.3	80.6	66.4	66	65.5	65.5	65.5
2741	28510	Annular	80.8	80.7	80.3	80	80	60.9	60.5	60.8	60.8	60.8
2741	35637	Annular	85.1	85.1	85.1	85.1	85.1	57.4	57.4	57.4	57.4	57.4
2741	42765	Annular	85.6	85.6	85.6	85.6	85.6	53.5	53.5	53.5	53.5	53.5
2741	49892	Annular	85.7	85.7	85.7	85.7	85.7	50.5	50.5	50.5	50.5	50.5
2741	57020	Mist	85.4	85.4	85.4	85.4	85.4	48.8	48.8	48.8	48.8	48.8

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2741	3.17	Bubble	79.3	79.3	79.3	79.3	79.3	42.7	42.7	42.7	42.7	42.7
2741	5.64	Bubble	79	79	79	79	79	42.7	42.7	42.7	42.7	42.7
2741	8.12	Bubble	79	79	79	79	79	42.9	42.9	42.9	42.9	42.9
2741	10.59	Bubble	78.9	78.9	78.9	78.9	78.9	42.9	42.9	42.9	42.9	42.9
2741	13.07	Bubble	78.7	78.7	78.7	78.7	78.7	43	43	43	43	43
2741	15.54	Bubble	78.6	78.6	78.6	78.6	78.6	43	43	43	43	43
2741	18.02	Bubble	78.5	78.5	78.5	78.5	78.5	43	43	43	43	43
2741	20.49	Bubble	78.5	78.5	78.5	78.5	78.5	43.2	43.2	43.2	43.2	43.2
2741	22.95	Bubble	78.3	78.3	78.3	78.3	78.3	43.2	43.2	43.2	43.2	43.2
2741	28.08	Bubble	78.2	78.2	78.2	78.2	78.2	43.3	43.3	43.3	43.3	43.3
2741	33.21	Bubble	77.8	77.8	77.8	77.8	77.8	43.5	43.5	43.5	43.5	43.5
2741	38.33	Bubble-Slug	76.7	76.7	76.7	76.7	76.7	42.7	42.7	42.7	42.7	42.7
2741	43.46	Bubble-Slug	76	76	76	75.8	77	42.6	42.6	42.7	42.6	41.5
2741	48.59	Slug	74.9	74.9	74.8	74.7	74.8	41.8	42	41.9	41.8	41.8
2741	58.85	Slug	74	74	74	74	74	42.3	42.3	42.3	42.2	42.2
2741	69.10	Slug	73.6	73.7	74	73.8	73.5	42.2	42.1	41.6	42.2	42.4
2741	79.36	Slug	73.3	73.3	72.9	72.7	72.5	42	42.5	42.9	42.7	42.6
2741	89.62	Slug	71.8	71.8	71.9	71.9	71.8	42.3	42.3	42.4	42.3	42.3
2741	99.87	Slug	71.3	71.3	71	71.2	71.3	42.6	42.2	42.7	42.6	42.6
2741	177	Slug	67.1	67.5	67.6	67.6	65.5	42	41.5	41.3	41.3	39.1
2741	296	Slug	74.6	74.8	74.6	74.6	74.7	53.4	53.3	53.3	53.4	53.5
2741	369	Slug-Churn	69.3	69	68.9	69.2	69	50.2	50.5	50.4	50.1	50.1
2741	515	Slug-Churn	53	53.3	51	51	51.5	40.6	39.3	38.8	38	37
2741	735	Slug-Churn	44.6	45	45	45	44.6	34	33.5	33.8	33.7	34
2741	1454	Slug-Churn	78	78	77.8	77.9	77.9	70.4	70.3	70	70.5	70.4
2741	2474	Churn	77.8	78.2	77.9	78	78	68	67.9	68	67.8	67.8

Re_{liquid}	Re_{air}	Flow regime	Appearance liquid levels difference in manometer, (cm)									
			Left hand side (highest)					Right hand side (lowest)				
			6	7	8	9	10	6	7	8	9	10
2741	3495	Churn	77.7	77.6	77.6	77.6	77.6	67.3	67.2	67.2	67.1	67.1
2741	4516	Churn	77.6	77.6	77.6	77.6	77.6	67	67	67	67	67
2741	5537	Churn	86	85.5	84.8	84.8	84.8	73.5	74	74.2	73.8	73.5
2741	14255	Churn	81.5	81.4	81.5	81.5	81.5	68.9	68.9	68.8	68.8	68.5
2741	21382	Churn	80.7	80.5	80.5	80.4	80.5	65.5	65.5	65.5	65.4	65.4
2741	28510	Annular	80	80	80	80	80	60.5	60.5	60.5	60.5	60.5
2741	35637	Annular	85.1	85.1	85.1	85.1	85.1	57	57	57	57	57
2741	42765	Annular	85.6	85.6	85.6	85.6	85.6	53.5	53.5	53.5	53.5	53.5
2741	49892	Annular	85.7	85.7	85.7	85.7	85.7	50.3	50.3	50.3	50.3	50.3
2741	57020	Mist	85.4	85.4	85.4	85.4	85.4	48.8	48.8	48.8	48.8	48.8

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2741	3.17	Bubble	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519 ± 0.00
2741	5.64	Bubble	8.8785	8.8785	8.8785	8.8785	8.8785	8.8785	8.8785	8.8785	8.8785	8.8785	8.8785 ± 0.00
2741	8.12	Bubble	8.8296	8.8296	8.8296	8.8296	8.8296	8.8296	8.8296	8.8296	8.8296	8.8296	8.8296 ± 0.00
2741	10.59	Bubble	8.8052	8.8052	8.8052	8.8052	8.8052	8.8052	8.8052	8.8052	8.8052	8.8052	8.8052 ± 0.00
2741	13.07	Bubble	8.7318	8.7318	8.7318	8.7318	8.7318	8.7318	8.7318	8.7318	8.7318	8.7318	8.7318 ± 0.00
2741	15.54	Bubble	8.7073	8.7073	8.7073	8.7073	8.7073	8.7073	8.7073	8.7073	8.7073	8.7073	8.7073 ± 0.00
2741	18.02	Bubble	8.6829	8.6829	8.6829	8.6829	8.6829	8.6829	8.6829	8.6829	8.6829	8.6829	8.6829 ± 0.00
2741	20.49	Bubble	8.6340	8.6340	8.6340	8.6340	8.6340	8.6340	8.6340	8.6340	8.6340	8.6340	8.6340 ± 0.00
2741	22.95	Bubble	8.5850	8.5850	8.5850	8.5850	8.5850	8.5850	8.5850	8.5850	8.5850	8.5850	8.5850 ± 0.00
2741	28.08	Bubble	8.5361	8.5361	8.5361	8.5361	8.5361	8.5361	8.5361	8.5361	8.5361	8.5361	8.5361 ± 0.00
2741	33.21	Bubble	8.3894	8.3894	8.3894	8.3894	8.3894	8.3894	8.3894	8.3894	8.3894	8.3894	8.3894 ± 0.00
2741	38.33	Bubble-Slug	8.3160	8.3160	8.3160	8.3160	8.3160	8.3160	8.3160	8.3160	8.3160	8.3160	8.3160 ± 0.00
2741	43.46	Bubble-Slug	8.2671	8.2915	8.3649	8.2426	8.2671	8.1692	8.1692	8.1448	8.1203	8.6829	8.2720 ± 0.16
2741	48.59	Slug	7.9002	7.9736	8.0225	8.0714	8.0959	8.0959	8.0469	8.0469	8.0469	8.0714	8.0372 ± 0.06
2741	58.85	Slug	7.8024	7.7779	7.7779	7.7779	7.7779	7.7534	7.7534	7.7534	7.7779	7.7779	7.7730 ± 0.02
2741	69.10	Slug	7.6801	7.7045	7.6801	7.7045	7.7045	7.6801	7.7290	7.9246	7.7290	7.6067	7.7143 ± 0.08
2741	79.36	Slug	7.4844	7.5088	7.5088	7.4599	7.4844	7.6556	7.5333	7.3376	7.3376	7.3132	7.4624 ± 0.11
2741	89.62	Slug	7.2643	7.2887	7.2643	7.2398	7.1909	7.2153	7.2153	7.2153	7.2398	7.2153	7.2349 ± 0.03
2741	99.87	Slug	7.0441	6.9952	7.0441	7.0686	7.0686	7.0197	7.1175	6.9218	6.9952	7.0197	7.0295 ± 0.05
2741	177	Slug	6.1147	6.1636	6.1636	6.1636	6.1392	6.1392	6.3593	6.4327	6.4327	6.4571	6.2566 ± 0.14
2741	296	Slug	5.0141	5.2586	5.2097	5.1608	5.2342	5.1853	5.2586	5.2097	5.1853	5.1853	5.1902 ± 0.07
2741	369	Slug-Churn	4.7939	4.8184	4.8673	4.5983	4.5983	4.6716	4.5249	4.5249	4.6716	4.6227	4.6692 ± 0.12
2741	515	Slug-Churn	3.3753	3.2041	3.5221	3.3753	3.4242	3.0329	3.4242	2.9840	3.1796	3.5465	3.3068 ± 0.20
2741	735	Slug-Churn	2.8128	2.8128	3.0573	2.9595	2.8861	2.5926	2.8128	2.7394	2.7638	2.5926	2.8030 ± 0.15
2741	1454	Slug-Churn	2.2747	1.6877	1.9567	2.2013	2.2502	1.8589	1.8833	1.9078	1.8099	1.8344	1.9665 ± 0.20
2741	2474	Churn	2.4948	2.3236	2.4948	2.6171	2.4214	2.3970	2.5193	2.4214	2.4948	2.4948	2.4679 ± 0.08

Re_{liquid}	Re_{air}	Flow regime	Measured pressure gradient (-dp/dz), kPa/m										Average pressure gradient, (kPa/m)
			1	2	3	4	5	6	7	8	9	10	
2741	3495	Churn	2.6905	2.6415	2.5926	2.5926	2.5926	2.5437	2.5437	2.5437	2.5682	2.5682	2.5877 ± 0.05
2741	4516	Churn	2.5926	2.5926	2.5926	2.5926	2.5926	2.5926	2.5926	2.5926	2.5926	2.5926	2.5926 ± 0.00
2741	5537	Churn	2.5682	2.5682	2.4948	2.6905	2.8128	3.0573	2.8128	2.5926	2.6905	2.7638	2.7051 ± 0.17
2741	14255	Churn	3.1552	3.1063	3.2530	3.1796	3.1307	3.0818	3.0573	3.1063	3.1063	3.1796	3.1356 ± 0.06
2741	21382	Churn	4.0112	4.0357	3.8645	3.8645	3.6933	3.7177	3.6688	3.6688	3.6688	3.6933	3.7887 ± 0.14
2741	28510	Annular	4.8673	4.9407	4.7695	4.6961	4.6961	4.7695	4.7695	4.7695	4.7695	4.7695	4.7817 ± 0.07
2741	35637	Annular	6.7751	6.7751	6.7751	6.7751	6.7751	6.8729	6.8729	6.8729	6.8729	6.8729	6.8240 ± 0.05
2741	42765	Annular	7.8513	7.8513	7.8513	7.8513	7.8513	7.8513	7.8513	7.8513	7.8513	7.8513	7.8513 ± 0.00
2741	49892	Annular	8.6095	8.6095	8.6095	8.6095	8.6095	8.6584	8.6584	8.6584	8.6584	8.6584	8.6340 ± 0.03
2741	57020	Mist	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519	8.9519 ± 0.00



○ dp/dz for hexadecylbenzyldimethylammonium chloride solution (1CMC) from experiment
——— dp/dz from Nicklin's, Wilkes's and Davidson's theory
— — — dp/dz from Sylvester's theory
- - - - - - dp/dz from Wallis's theory

Figure K6 Comparison between Nicklin's theory, Sylvester's theory and experimental pressure gradient vs. air Reynolds number of hexadecylbenzyldimethylammonium chloride solution (1CMC) at $Re_{solution}$ = 2741 by using pipe diameter 19 mm.

Table K9 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes of hexadecylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm

Pipe diameter (mm)	$Re_{solution}$	Re_{air}(critical) for each flow regime					
		Bubble-Slug	Slug	Slug-Churn	Churn	Annular	Mist
19	2741	38.33	48.59	369	2474	28510	57020

Appendix L Comparison the Experimental Data of Octylbenzyldimethylammonium Chloride Solution (1, 2 and 3 CMC) by Using the Pipe Diameter of 19 mm

Table L1 Comparison of bubble width for octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution (1CMC), $\mu_{solution} = 9.73 \times 10^{-4}$ Pa.s

density of solution (2CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (2CMC), $\mu_{solution} = 1.189 \times 10^{-3}$ Pa.s

density of solution (3CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (3CMC), $\mu_{solution} = 1.317 \times 10^{-3}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

Surfactant concentration	$Re_{solution}$	Re_{air}	Bubble width, W_b (mm)			Average bubble width, (mm)	Bubble width / Pipe diameter			Average bubble width / Pipe diameter
			1	2	3		1	2	3	
1 CMC	2749	3.2	10.3	11.1	8.9	10.1 ± 1.1	0.54	0.59	0.47	0.53 ± 0.06
1 CMC	2749	5.6	10.2	11.4	10.4	10.7 ± 0.6	0.54	0.60	0.55	0.56 ± 0.03
1 CMC	2749	8.12	11.3	11.8	11.3	11.5 ± 0.3	0.59	0.62	0.60	0.60 ± 0.02
1 CMC	2749	10.59	11.6	11.9	11.3	11.6 ± 0.3	0.61	0.62	0.60	0.61 ± 0.01
1 CMC	2749	13.07	12.6	11.5	12.1	12.1 ± 0.6	0.66	0.60	0.64	0.63 ± 0.03
1 CMC	2749	15.54	12.4	11.6	12.0	12.0 ± 0.4	0.65	0.61	0.63	0.63 ± 0.02
1 CMC	2749	18.02	12.1	12.7	11.9	12.2 ± 0.4	0.64	0.67	0.63	0.64 ± 0.02
1 CMC	2749	20.49	12.9	12.2	13.3	12.8 ± 0.6	0.68	0.64	0.70	0.67 ± 0.03
1 CMC	2749	22.95	13.0	12.9	13.4	13.1 ± 0.2	0.68	0.68	0.70	0.69 ± 0.01
1 CMC	2749	28.1	13.2	12.9	13.1	13.1 ± 0.1	0.69	0.68	0.69	0.69 ± 0.01
2 CMC	2731	3.17	10.6	9.7	10.5	10.3 ± 0.5	0.56	0.51	0.55	0.54 ± 0.03
2 CMC	2731	5.64	10.5	10.9	10.6	10.7 ± 0.2	0.55	0.57	0.56	0.56 ± 0.01
2 CMC	2731	8.12	10.8	10.4	11.5	10.9 ± 0.6	0.57	0.55	0.61	0.57 ± 0.03
2 CMC	2731	10.59	10.4	11.5	10.9	10.9 ± 0.6	0.55	0.60	0.58	0.58 ± 0.03
2 CMC	2731	13.07	11.5	10.4	11.2	11.0 ± 0.6	0.61	0.55	0.59	0.58 ± 0.03
2 CMC	2731	15.54	11.3	11.2	11.7	11.4 ± 0.3	0.60	0.59	0.62	0.60 ± 0.01
2 CMC	2731	18.02	11.4	11.6	12.6	11.8 ± 0.6	0.60	0.61	0.66	0.62 ± 0.03
2 CMC	2731	20.49	12.1	12.3	12.4	12.2 ± 0.2	0.64	0.65	0.65	0.64 ± 0.01
2 CMC	2731	22.95	12.1	12.7	12.4	12.4 ± 0.3	0.64	0.67	0.65	0.65 ± 0.02
2 CMC	2731	28.08	13.0	13.5	12.5	13.0 ± 0.5	0.68	0.71	0.66	0.68 ± 0.03
2 CMC	2731	33.21	13.8	13.6	12.9	13.5 ± 0.5	0.73	0.72	0.68	0.71 ± 0.02
3 CMC	2735	3.17	11.8	10.9	10.9	11.2 ± 0.5	0.62	0.57	0.57	0.59 ± 0.03
3 CMC	2735	5.64	11.2	11.5	11.1	11.3 ± 0.2	0.59	0.61	0.58	0.59 ± 0.01
3 CMC	2735	8.12	11.3	11.5	11.6	11.5 ± 0.1	0.60	0.61	0.61	0.60 ± 0.01
3 CMC	2735	10.59	11.2	11.9	11.7	11.6 ± 0.3	0.59	0.63	0.62	0.61 ± 0.02
3 CMC	2735	13.07	11.6	11.3	12.1	11.7 ± 0.4	0.61	0.60	0.64	0.62 ± 0.02
3 CMC	2735	15.54	12.2	11.6	11.6	11.8 ± 0.4	0.64	0.61	0.61	0.62 ± 0.02
3 CMC	2735	18.02	12.1	11.6	11.9	11.9 ± 0.3	0.64	0.61	0.63	0.63 ± 0.01

Surfactant concentration	$Re_{solution}$	Re_{air}	Bubble width, W_b (mm)			Average bubble width, (mm)	Bubble width / Pipe diameter			Average bubble width / Pipe diameter
			1	2	3		1	2	3	
3 CMC	2735	20.49	12.6	11.8	12.8	12.4 ± 0.5	0.66	0.62	0.68	0.65 ± 0.03
3 CMC	2735	22.95	12.7	12.3	12.7	12.6 ± 0.2	0.67	0.65	0.67	0.66 ± 0.01
3 CMC	2735	28.08	13.1	12.4	12.4	12.6 ± 0.4	0.69	0.65	0.65	0.66 ± 0.02
3 CMC	2735	33.21	12.5	12.4	12.8	12.6 ± 0.2	0.66	0.65	0.68	0.66 ± 0.01

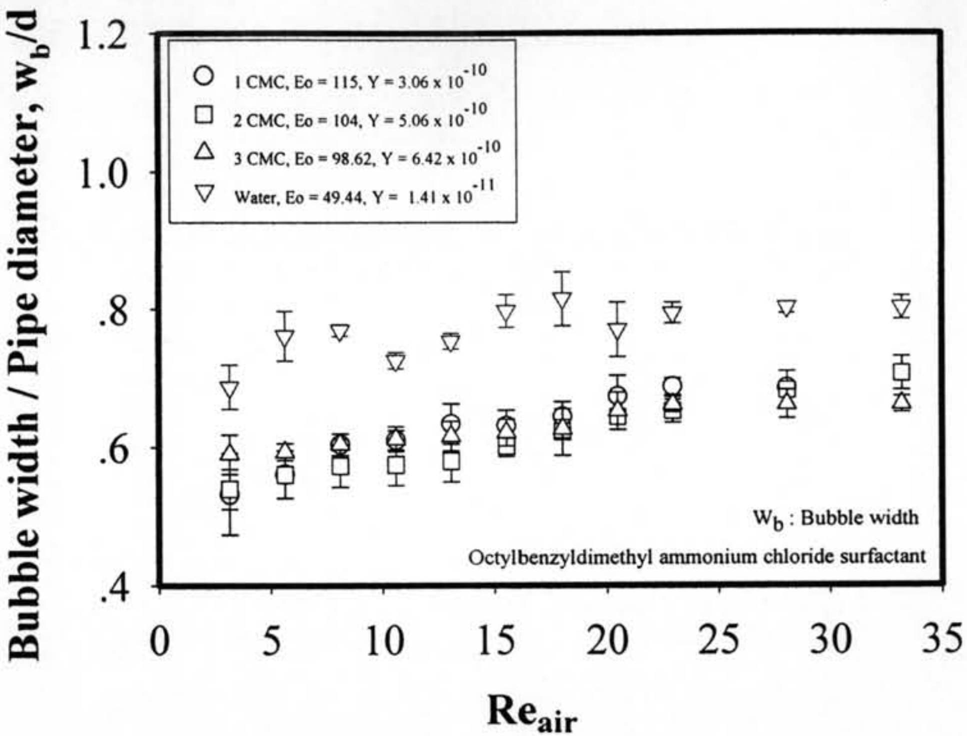


Figure L1 Comparison the bubble width from experiment between octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) by using pipe diameter of 19 mm.

Table L2 Comparison of bubble height for octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution (1CMC), $\mu_{solution}$ = 9.73 × 10^{-4} Pa.s

density of solution (2CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (2CMC), $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of solution (3CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (3CMC), $\mu_{solution}$ = 1.317 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

Surfactant concentration	$Re_{solution}$	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble height / Pipe diameter			Average, R_h/D
			1	2	3		1	2	3	
1 CMC	2749	3.2	7.9	7.6	7.1	7.5 ± 0.4	0.42	0.40	0.37	0.40 ± 0.02
1 CMC	2749	5.6	8.3	8.5	8.8	8.5 ± 0.3	0.43	0.45	0.46	0.45 ± 0.01
1 CMC	2749	8.12	8.8	8.3	8.8	8.7 ± 0.3	0.46	0.44	0.46	0.46 ± 0.01
1 CMC	2749	10.59	9.3	9.2	9.0	9.2 ± 0.2	0.49	0.48	0.47	0.48 ± 0.01
1 CMC	2749	13.07	10.1	9.4	10.1	9.9 ± 0.4	0.53	0.50	0.53	0.52 ± 0.02
1 CMC	2749	15.54	10.9	11.3	10.8	11.0 ± 0.3	0.57	0.60	0.57	0.58 ± 0.01
1 CMC	2749	18.02	12.6	11.4	12.5	12.2 ± 0.6	0.66	0.60	0.66	0.64 ± 0.03
1 CMC	2749	20.49	13.6	14.3	15.3	14.4 ± 0.8	0.71	0.75	0.80	0.76 ± 0.04
1 CMC	2749	22.95	16.3	16.8	15.4	16.2 ± 0.7	0.86	0.88	0.81	0.85 ± 0.04
1 CMC	2749	28.1	20.8	19.8	19.6	20.0 ± 0.6	1.09	1.04	1.03	1.05 ± 0.03
2 CMC	2731	3.17	8.6	8.8	8.0	8.5 ± 0.4	0.45	0.46	0.42	0.45 ± 0.02
2 CMC	2731	5.64	8.7	9.7	9.2	9.2 ± 0.5	0.46	0.51	0.48	0.48 ± 0.03
2 CMC	2731	8.12	9.3	9.5	9.8	9.6 ± 0.3	0.49	0.50	0.52	0.50 ± 0.01
2 CMC	2731	10.59	10.2	9.7	9.7	9.9 ± 0.3	0.54	0.51	0.51	0.52 ± 0.02
2 CMC	2731	13.07	10.4	10.3	10.5	10.4 ± 0.1	0.55	0.54	0.55	0.55 ± 0.01
2 CMC	2731	15.54	11.1	11.7	11.6	11.5 ± 0.3	0.59	0.61	0.61	0.60 ± 0.02
2 CMC	2731	18.02	12.4	12.5	12.7	12.5 ± 0.2	0.65	0.66	0.67	0.66 ± 0.01
2 CMC	2731	20.49	13.2	13.1	13.4	13.2 ± 0.2	0.69	0.69	0.71	0.70 ± 0.01
2 CMC	2731	22.95	14.7	15.2	15.6	15.2 ± 0.4	0.77	0.80	0.82	0.80 ± 0.02
2 CMC	2731	28.08	17.8	17.4	17.4	17.5 ± 0.3	0.94	0.91	0.92	0.92 ± 0.01
2 CMC	2731	33.21	19.4	19.7	19.3	19.5 ± 0.2	1.02	1.03	1.02	1.02 ± 0.01
3 CMC	2735	3.17	10.0	9.9	10.3	10.0 ± 0.2	0.53	0.52	0.54	0.53 ± 0.01
3 CMC	2735	5.64	9.7	10.7	10.0	10.1 ± 0.5	0.51	0.56	0.53	0.53 ± 0.03
3 CMC	2735	8.12	10.3	10.6	10.3	10.4 ± 0.2	0.54	0.56	0.54	0.55 ± 0.01
3 CMC	2735	10.59	10.4	10.3	10.7	10.5 ± 0.2	0.55	0.54	0.56	0.55 ± 0.01
3 CMC	2735	13.07	11.4	11.4	11.4	11.4 ± 0.0	0.60	0.60	0.60	0.60 ± 0.00
3 CMC	2735	15.54	12.1	12.4	12.7	12.4 ± 0.3	0.64	0.65	0.67	0.65 ± 0.02
3 CMC	2735	18.02	13.2	12.7	13.5	13.1 ± 0.4	0.70	0.67	0.71	0.69 ± 0.02

Surfactant concentration	$Re_{solution}$	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble height / Pipe diameter			Average, R_h/D
			1	2	3		1	2	3	
3 CMC	2735	20.49	14.7	14.1	14.3	14.4 ± 0.3	0.77	0.74	0.75	0.76 ± 0.02
3 CMC	2735	22.95	15.4	15.3	15.6	15.4 ± 0.1	0.81	0.81	0.82	0.81 ± 0.01
3 CMC	2735	28.08	17.2	16.9	16.6	16.9 ± 0.3	0.90	0.89	0.87	0.89 ± 0.01
3 CMC	2735	33.21	18.5	18.8	18.8	18.7 ± 0.2	0.98	0.99	0.99	0.99 ± 0.01

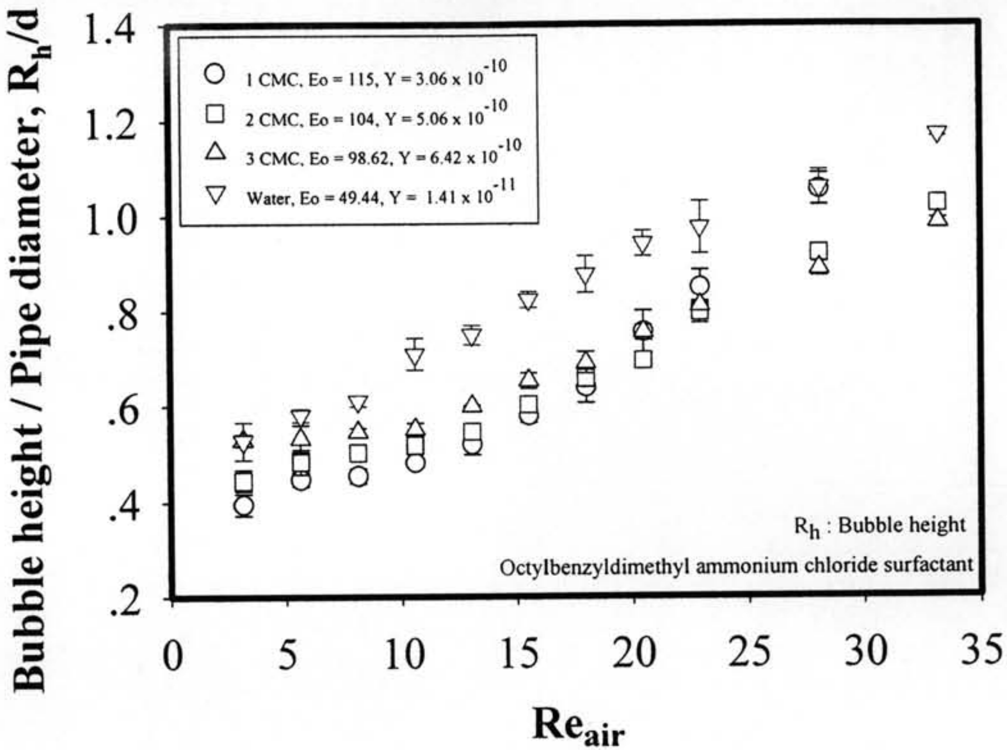


Figure L2 Comparison the bubble height from experiment between octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) by using pipe diameter of 19 mm.

Table L3 Comparison of slug height for octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution (1CMC), $\mu_{solution} = 9.73 \times 10^{-4}$ Pa.s

density of solution (2CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (2CMC), $\mu_{solution} = 1.189 \times 10^{-3}$ Pa.s

density of solution (3CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (3CMC), $\mu_{solution} = 1.317 \times 10^{-3}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

Surfactant concentration	$Re_{solution}$	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
			1	2	3		1	2	3	
1 CMC	2749	43.46	34.9	36.4	34.1	35.1 ± 1.2	1.8	1.9	1.8	1.8 ± 0.06
1 CMC	2749	48.59	37.0	38.0	36.1	37.0 ± 0.9	1.9	2.0	1.9	1.9 ± 0.05
1 CMC	2749	58.85	41.0	43.0	41.0	41.7 ± 1.2	2.2	2.3	2.2	2.2 ± 0.06
1 CMC	2749	69.10	44.0	45.0	43.0	44.0 ± 1.0	2.3	2.4	2.3	2.3 ± 0.05
1 CMC	2749	79.36	48.0	49.0	48.0	48.3 ± 0.6	2.5	2.6	2.5	2.5 ± 0.03
1 CMC	2749	89.62	54.6	52.1	51.1	52.6 ± 1.8	2.9	2.7	2.7	2.8 ± 0.09
1 CMC	2749	99.87	54.2	56.3	55.2	55.2 ± 1.0	2.9	3.0	2.9	2.9 ± 0.05
1 CMC	2749	177	80.8	80.8	80.9	80.8 ± 2.1	4.3	4.3	4.3	4.3 ± 0.11
1 CMC	2749	296	137	140	139	138 ± 1.6	7.2	7.4	7.3	7.3 ± 0.08
2 CMC	2731	43.46	37.3	37.2	37.8	37.5 ± 0.3	2.0	2.0	2.0	2.0 ± 0.02
2 CMC	2731	48.59	40.7	40.6	41.5	40.9 ± 0.5	2.1	2.1	2.2	2.2 ± 0.03
2 CMC	2731	58.85	43.5	43.0	44.1	43.5 ± 0.6	2.3	2.3	2.3	2.3 ± 0.03
2 CMC	2731	69.10	48.3	49.7	48.0	48.6 ± 0.9	2.5	2.6	2.5	2.6 ± 0.05
2 CMC	2731	79.36	51.1	52.0	52.0	51.7 ± 0.5	2.7	2.7	2.7	2.7 ± 0.03
2 CMC	2731	89.62	55.5	55.0	56.0	55.5 ± 0.5	2.9	2.9	2.9	2.9 ± 0.03
2 CMC	2731	99.87	60.5	59.4	59.3	59.7 ± 0.7	3.2	3.1	3.1	3.1 ± 0.04
2 CMC	2731	177	84.7	85.0	84.8	84.8 ± 0.2	4.5	4.5	4.5	4.5 ± 0.01
2 CMC	2731	296	143	144	141	142.6 ± 1.2	7.5	7.6	7.4	7.5 ± 0.06
3 CMC	2735	43.46	38.0	37.6	37.1	37.6 ± 0.5	2.0	2.0	2.0	2.0 ± 0.02
3 CMC	2735	48.59	43.0	43.5	42.9	43.1 ± 0.3	2.3	2.3	2.3	2.3 ± 0.02
3 CMC	2735	58.85	49.4	49.0	49.1	49.2 ± 0.2	2.6	2.6	2.6	2.6 ± 0.01
3 CMC	2735	69.10	52.3	53.6	53.0	53.0 ± 0.6	2.8	2.8	2.8	2.8 ± 0.03
3 CMC	2735	79.36	56.2	56.1	55.9	56.1 ± 0.2	3.0	3.0	2.9	3.0 ± 0.01
3 CMC	2735	89.62	58.3	58.3	58.2	58.3 ± 0.1	3.1	3.1	3.1	3.1 ± 0.00
3 CMC	2735	99.87	63.0	61.9	62.9	62.6 ± 0.6	3.3	3.3	3.3	3.3 ± 0.03
3 CMC	2735	177	90.5	89.2	89.2	89.7 ± 0.7	4.8	4.7	4.7	4.7 ± 0.04
3 CMC	2735	296	145	146	146	145.7 ± 0.7	7.6	7.7	7.7	7.7 ± 0.04

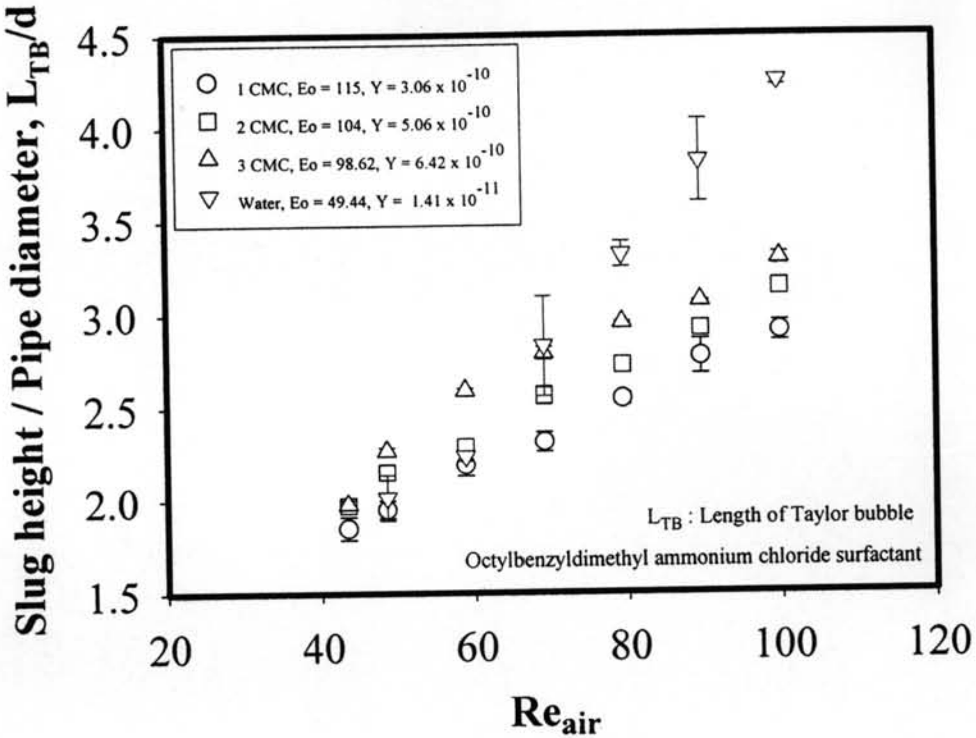


Figure L3 Comparison the slug height from experiment between octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) by using pipe diameter of 19 mm.

Table L4 Comparison of bubble and slug velocity for octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution (1CMC), $\mu_{solution}$ = 9.73 × 10^{-4} Pa.s

density of solution (2CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (2CMC), $\mu_{solution}$ = 1.189 × 10^{-3} Pa.s

density of solution (3CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (3CMC), $\mu_{solution}$ = 1.317 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

Surfactant concentration	$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
1 CMC	2749	3.17	0.77	0.77	0.77	0.77	0.77	0.77 ± 0.002
1 CMC	2749	5.64	0.79	0.78	0.78	0.78	0.79	0.78 ± 0.006
1 CMC	2749	8.11	0.80	0.81	0.81	0.81	0.80	0.81 ± 0.006
1 CMC	2749	10.59	0.81	0.81	0.80	0.81	0.82	0.81 ± 0.008
1 CMC	2749	13.06	0.81	0.82	0.81	0.81	0.81	0.81 ± 0.005
1 CMC	2749	15.53	0.81	0.83	0.83	0.80	0.81	0.82 ± 0.015
1 CMC	2749	18.01	0.82	0.85	0.85	0.85	0.85	0.84 ± 0.011
1 CMC	2749	20.48	0.83	0.85	0.85	0.85	0.85	0.85 ± 0.006
1 CMC	2749	22.94	0.85	0.83	0.86	0.85	0.85	0.85 ± 0.008
1 CMC	2749	28.06	0.86	0.87	0.85	0.86	0.85	0.86 ± 0.010
1 CMC	2749	33.19	0.86	0.87	0.87	0.87	0.86	0.87 ± 0.008
1 CMC	2749	38.31	0.87	0.87	0.88	0.86	0.87	0.87 ± 0.007
1 CMC	2749	43.44	0.88	0.89	0.86	0.87	0.87	0.88 ± 0.009
1 CMC	2749	48.57	0.89	0.88	0.89	0.89	0.88	0.88 ± 0.002
1 CMC	2749	58.82	0.91	0.93	0.93	0.93	0.93	0.92 ± 0.006
1 CMC	2749	69.07	0.96	0.96	0.96	0.95	0.96	0.95 ± 0.005
1 CMC	2749	79.32	0.96	0.99	0.96	0.99	0.98	0.97 ± 0.016
1 CMC	2749	89.57	1.02	1.04	1.04	1.02	1.02	1.03 ± 0.006
1 CMC	2749	99.82	1.04	1.04	1.04	1.02	1.04	1.04 ± 0.008
1 CMC	2749	177	1.17	1.17	1.21	1.19	1.17	1.18 ± 0.020
1 CMC	2749	296	1.41	1.43	1.40	1.41	1.43	1.42 ± 0.009
2 CMC	2731	3.17	0.85	0.83	0.86	0.83	0.87	0.85 ± 0.017
2 CMC	2731	5.64	0.87	0.89	0.90	0.87	0.86	0.88 ± 0.016
2 CMC	2731	8.11	0.89	0.90	0.88	0.90	0.87	0.89 ± 0.012
2 CMC	2731	10.59	0.90	0.90	0.88	0.87	0.88	0.89 ± 0.013
2 CMC	2731	13.06	0.89	0.88	0.90	0.88	0.90	0.89 ± 0.009

Surfactant concentration	$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
2 CMC	2731	15.53	0.90	0.89	0.90	0.89	0.89	0.89 ± 0.007
2 CMC	2731	18.01	0.90	0.88	0.90	0.90	0.90	0.89 ± 0.007
2 CMC	2731	20.48	0.93	0.93	0.89	0.88	0.90	0.90 ± 0.021
2 CMC	2731	22.94	0.93	0.91	0.91	0.93	0.93	0.92 ± 0.009
2 CMC	2731	28.06	0.95	0.94	0.96	0.91	0.91	0.93 ± 0.019
2 CMC	2731	33.19	0.96	0.91	0.96	0.93	0.94	0.94 ± 0.018
2 CMC	2731	38.31	0.93	0.93	0.96	0.94	0.96	0.94 ± 0.016
2 CMC	2731	43.44	0.96	0.96	0.97	0.93	0.94	0.95 ± 0.017
2 CMC	2731	48.57	0.94	0.97	0.94	0.97	0.99	0.96 ± 0.020
2 CMC	2731	58.82	1.04	1.04	1.00	0.99	1.00	1.01 ± 0.024
2 CMC	2731	69.07	1.04	1.04	1.02	1.04	1.04	1.04 ± 0.007
2 CMC	2731	79.32	1.06	1.04	1.06	1.06	1.04	1.05 ± 0.010
2 CMC	2731	89.57	1.10	1.12	1.10	1.10	1.06	1.10 ± 0.022
2 CMC	2731	99.82	1.12	1.10	1.12	1.08	1.12	1.10 ± 0.017
2 CMC	2731	177	1.24	1.26	1.21	1.26	1.18	1.23 ± 0.034
2 CMC	2731	296	1.56	1.56	1.64	1.64	1.65	1.61 ± 0.048
3 CMC	2735	3.17	0.90	0.90	0.90	0.90	0.90	0.90 ± 0.002
3 CMC	2735	5.64	0.90	0.90	0.90	0.89	0.90	0.90 ± 0.006
3 CMC	2735	8.11	0.90	0.91	0.91	0.89	0.90	0.90 ± 0.011
3 CMC	2735	10.59	0.89	0.90	0.91	0.90	0.91	0.90 ± 0.010
3 CMC	2735	13.06	0.90	0.90	0.91	0.91	0.91	0.91 ± 0.007
3 CMC	2735	15.53	0.93	0.90	0.91	0.91	0.94	0.92 ± 0.016
3 CMC	2735	18.01	0.93	0.93	0.96	0.94	0.93	0.94 ± 0.013
3 CMC	2735	20.48	0.94	0.96	0.94	0.96	0.93	0.94 ± 0.013
3 CMC	2735	22.94	0.96	0.94	0.96	0.94	0.94	0.95 ± 0.009
3 CMC	2735	28.06	0.96	0.96	0.97	0.97	0.98	0.97 ± 0.009

Surfactant concentration	$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
3 CMC	2735	33.19	0.98	0.97	0.97	0.98	0.97	0.97 ± 0.004
3 CMC	2735	38.31	0.99	0.97	0.99	0.99	0.99	0.99 ± 0.009
3 CMC	2735	43.44	1.01	1.00	0.99	1.01	1.00	1.00 ± 0.009
3 CMC	2735	48.57	1.03	1.03	1.04	1.02	1.04	1.03 ± 0.008
3 CMC	2735	58.82	1.08	1.06	1.06	1.08	1.08	1.07 ± 0.010
3 CMC	2735	69.07	1.10	1.08	1.08	1.10	1.08	1.08 ± 0.010
3 CMC	2735	79.32	1.10	1.12	1.12	1.08	1.10	1.10 ± 0.016
3 CMC	2735	89.57	1.14	1.13	1.14	1.14	1.12	1.13 ± 0.006
3 CMC	2735	99.82	1.17	1.19	1.17	1.18	1.14	1.17 ± 0.017
3 CMC	2735	177	1.34	1.29	1.37	1.31	1.31	1.33 ± 0.033
3 CMC	2735	296	1.65	1.65	1.70	1.70	1.61	1.66 ± 0.037

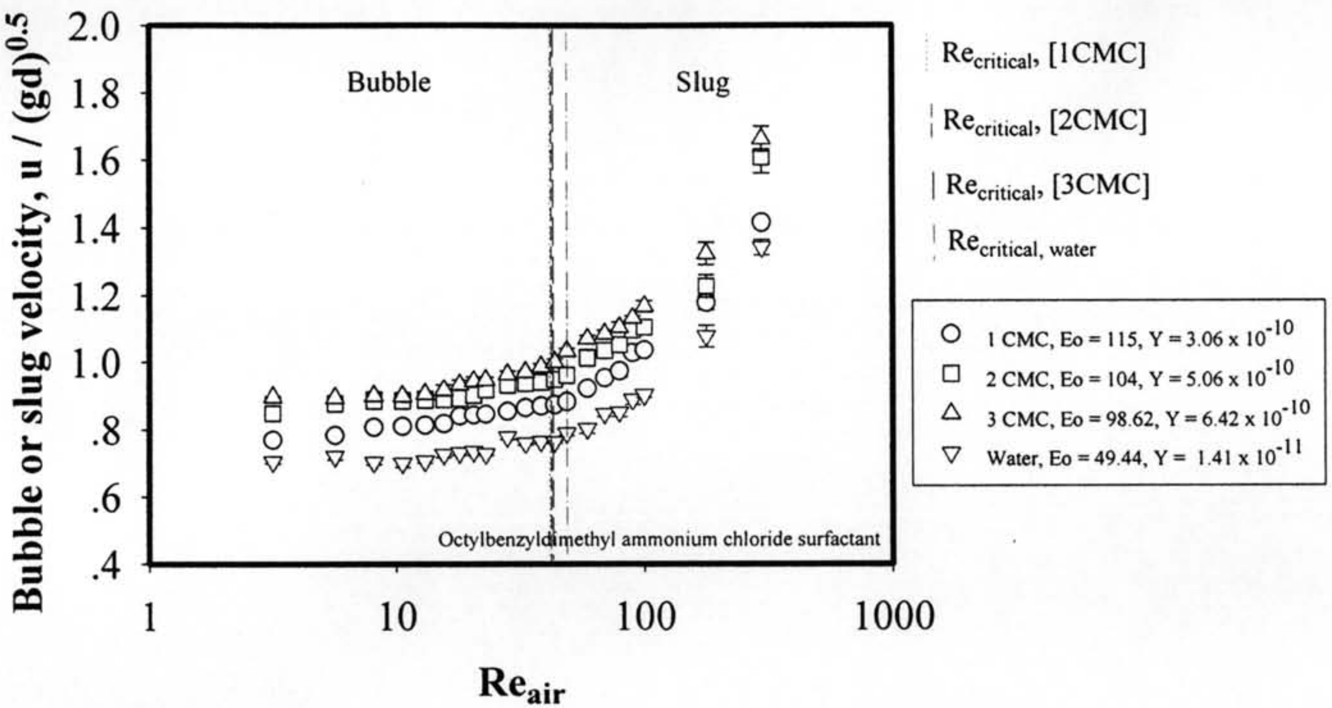


Figure L4 Comparison bubble or slug velocity from experiment between octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) by using pipe diameter of 19 mm.

Table L5 Comparison of the pressure gradient for octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) from experiment

Physical properties of air and solution used in experiment:

density of solution (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution (1CMC), $\mu_{solution} = 9.73 \times 10^{-4}$ Pa.s

density of solution (2CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (2CMC), $\mu_{solution} = 1.189 \times 10^{-3}$ Pa.s

density of solution (3CMC), $\rho_{solution}$ = 998.3 kg/m^3; viscosity of solution (3CMC), $\mu_{solution} = 1.317 \times 10^{-3}$ Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

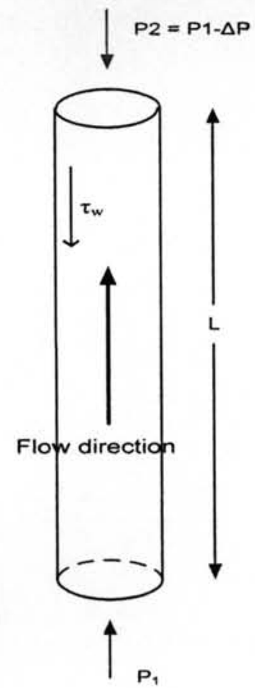


Figure L5 Pressure drop in a vertical pipe.

Upward flow in a vertical pipe is depicted in Fig. D13. A steady-state momentum balance in the direction of flow on the fluid in the pipe gives:

$$(P_1 - P_2)\frac{\pi D^2}{4} - \tau_w \pi D L - \frac{\pi D^2}{4}\rho L g = 0 \qquad \text{(L1)}$$

$$(P_1 - P_2)\frac{D}{4} - \tau_w L - \frac{D}{4}\rho L g = 0 \qquad \text{(L2)}$$

$$(P_1 - P_2)\frac{D}{4} - \rho L g\frac{D}{4} = \tau_w L \qquad \text{(L3)}$$

$$\left(\frac{P_1 - P_2}{L}\right)\frac{D}{4} - \rho g\frac{D}{4} = \tau_w \qquad \text{(L4)}$$

We define the pressure drop: $\Delta P = P_1 - P_2$. Equation (L4) can be written as:

$$\frac{D}{4}\left[\left(\frac{\Delta P}{L}\right)_d - \rho g\right] = \tau_w \qquad \text{(L5)}$$

Elimination of the gravity term from Equation (L5) gives:

$$\frac{D}{4}\left(\frac{\Delta P}{L}\right)_d = \tau_{w,d} \qquad \text{(L6)}$$

From the definition of friction factor (f_F):

$$f_F = \frac{8\tau_{w,d}}{\rho_w \bar{u}_{liq}^{2}} \tag{L7}$$

Rearrangement of Equation (L7) gives:

$$f_F = \frac{8\frac{D}{4}(\frac{\Delta P}{L})_d}{\rho_w \bar{u}_{liq}^{2}} \tag{L8}$$

or

$$f_F = \frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}} \tag{L9}$$

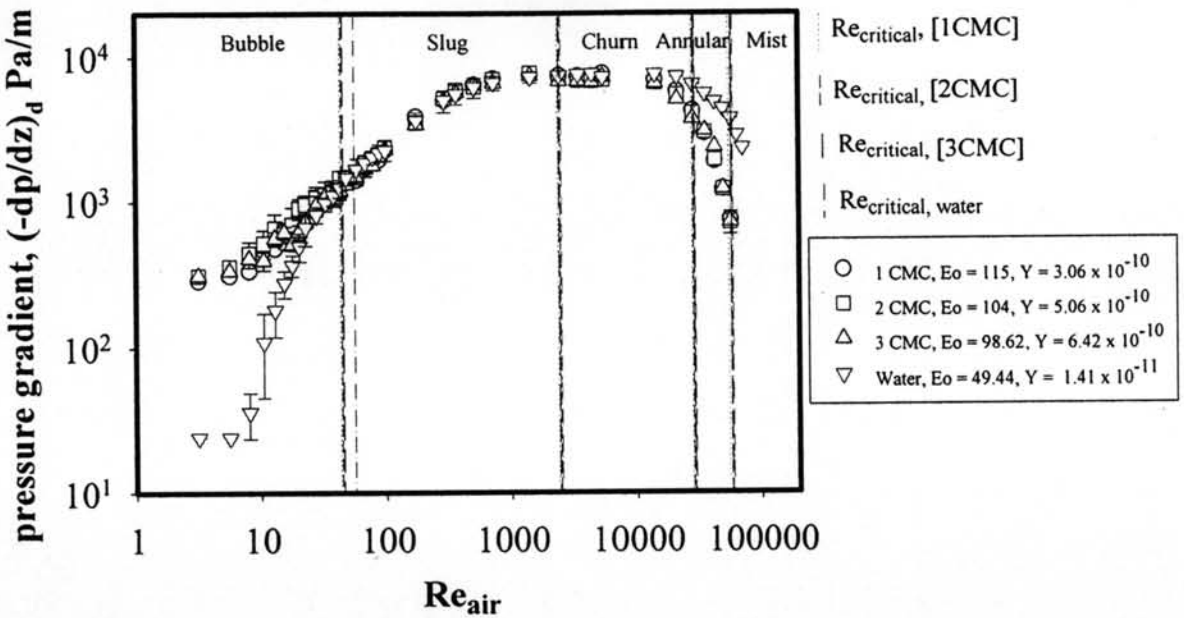
Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
			1	2	3	4	5	6	7	8	9	10	
2749	3.17	Bubble	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562 ± 1.2E-16
2749	5.64	Bubble	0.6088	0.6088	0.6088	0.6088	0.6088	0.6088	0.6088	0.6088	0.6088	0.6088	0.6088 ± 0
2749	8.12	Bubble	0.6556	0.6556	0.6556	0.6556	0.6556	0.6556	0.6556	0.6556	0.6556	0.6556	0.6556 ± 1.2E-16
2749	10.59	Bubble	0.8898	0.8898	0.8898	0.8898	0.8898	0.9366	0.9366	0.9366	0.9366	0.9366	0.9132 ± 0.02468
2749	13.07	Bubble	0.9366	0.9366	0.9366	0.9366	0.9366	0.9366	0.9366	0.9366	0.9366	0.9366	0.9366 ± 0
2749	15.54	Bubble	1.0303	1.0303	1.0303	1.0303	1.0303	1.0303	1.0303	1.0303	1.0303	1.0303	1.0303 ± 2.3E-16
2749	18.02	Bubble	1.0771	1.0771	1.0771	1.0771	1.0771	1.0771	1.0771	1.0771	1.0771	1.0771	1.0771 ± 0
2749	20.49	Bubble	1.1708	1.0771	1.1708	1.2176	1.0771	1.2644	1.2644	1.3112	1.2176	1.2176	1.1989 ± 0.07711
2749	22.95	Bubble	1.3581	1.3112	1.2644	1.3112	1.3112	2.1542	2.0605	2.1074	2.0605	2.1074	1.7046 ± 0.41606
2749	28.08	Bubble	1.6391	1.6859	1.5922	1.6859	1.6391	2.2947	2.482	2.482	2.1074	2.0605	1.9669 ± 0.36207
2749	33.21	Bubble-Slug	1.4049	1.6391	1.9669	1.9669	2.1074	2.3415	2.2947	2.3415	2.3415	2.2947	2.0699 ± 0.32878
2749	38.33	Bubble-Slug	2.9035	2.6693	2.2478	2.2947	2.0137	2.3415	2.7161	2.0137	1.4986	2.2478	2.2947 ± 0.40646
2749	43.46	Slug	2.1542	2.201	2.1542	2.1542	2.1074	2.8566	2.763	2.6225	3.044	2.4352	2.4492 ± 0.34769
2749	48.59	Slug	2.3883	2.5288	2.3415	2.482	2.4352	2.9035	2.8566	2.8566	2.8098	2.8098	2.6412 ± 0.22426
2749	58.85	Slug	2.5288	2.482	2.3415	2.7161	2.9035	2.9035	2.9035	2.8098	2.5757	2.9971	2.7161 ± 0.22186
2749	69.10	Slug	2.9503	3.044	2.6693	3.9806	2.9503	3.2781	3.3249	3.4186	3.7932	3.6528	3.3062 ± 0.41547
2749	79.36	Slug	3.8869	3.7932	3.6528	3.6528	3.6996	4.1211	4.1679	4.1211	3.6059	3.7464	3.8448 ± 0.21681
2749	89.62	Slug	3.6528	3.6528	3.5591	3.7932	3.5123	3.8401	4.1211	4.0274	3.9337	3.6528	3.7745 ± 0.20377
2749	99.87	Slug	4.5425	4.5894	4.5894	3.9806	4.1679	4.3552	4.3084	4.5425	4.5425	4.3084	4.3927 ± 0.20567
2749	177	Slug	6.9309	7.3523	7.3992	7.7738	7.7738	7.4928	7.5865	7.5865	7.5865	7.5865	7.5069 ± 0.24389
2749	296	Slug	10.209	10.068	9.9748	9.9748	9.8343	9.647	9.5534	9.5065	9.3192	9.5065	9.7594 ± 0.29304
2749	369	Slug-Churn	11.146	10.865	10.818	10.818	10.818	10.958	11.005	10.865	10.818	10.818	10.893 ± 0.11082
2749	515	Slug-Churn	12.597	12.597	12.55	12.55	12.129	12.269	12.316	12.176	12.223	12.316	12.373 ± 0.18311
2749	735	Slug-Churn	13.487	13.768	13.628	13.581	13.534	13.44	13.487	13.534	13.909	13.815	13.618 ± 0.15889
2749	1454	Slug-Churn	14.705	14.705	14.705	14.705	14.705	14.377	14.33	14.424	14.377	14.424	14.545 ± 0.16986
2749	2474	Churn	14.19	14.19	14.19	14.19	14.19	14.236	14.236	14.236	14.236	14.236	14.213 ± 0.02468

Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
			1	2	3	4	5	6	7	8	9	10	
2749	3495	Churn	14.096	14.096	14.096	14.096	14.096	14.096	14.096	14.096	14.096	14.096	14.096 ± 0
2749	4516	Churn	14.002	14.002	14.002	14.002	14.002	14.002	14.002	14.002	14.002	14.002	14.002 ± 3.7E-15
2749	5537	Churn	14.517	14.517	14.517	14.517	14.517	14.845	14.845	14.845	14.845	14.845	14.681 ± 0.17277
2749	14255	Churn	13.3	13.3	13.3	13.3	13.3	13.534	13.534	13.534	13.534	13.534	13.417 ± 0.12341
2749	21382	Churn	11.099	11.099	11.099	11.099	11.099	11.146	11.146	11.146	11.146	11.146	11.122 ± 0.02468
2749	28510	Annular	8.1953	8.1953	8.1953	8.1953	8.1953	8.1953	8.1953	8.1953	8.1953	8.1953	8.1953 ± 1.9E-15
2749	35637	Annular	5.7133	5.7133	5.7133	5.7133	5.7133	5.7133	5.7133	5.7133	5.7133	5.7133	5.7133 ± 9.4E-16
2749	42765	Annular	3.6528	3.6528	3.6528	3.6528	3.6528	3.6528	3.6528	3.6528	3.6528	3.6528	3.6528 ± 4.7E-16
2749	49892	Annular	2.3415	2.3415	2.3415	2.3415	2.3415	2.3415	2.3415	2.3415	2.3415	2.3415	2.3415 ± 4.7E-16
2749	57020	Mist	1.4517	1.4517	1.4517	1.4517	1.4517	1.4517	1.4517	1.4517	1.4517	1.4517	1.4517 ± 2.3E-16
2731	3.17	Bubble	0.4134	0.4134	0.4134	0.4134	0.4134	0.4134	0.4134	0.4134	0.4134	0.4134	0.4134 ± 0
2731	5.64	Bubble	0.4771	0.4771	0.4771	0.4771	0.4771	0.4771	0.4771	0.4771	0.4771	0.4771	0.4771 ± 0
2731	8.12	Bubble	0.4771	0.4771	0.4771	0.4771	0.4771	0.6997	0.6997	0.6997	0.6997	0.6997	0.5884 ± 0.11733
2731	10.59	Bubble	1.0177	0.7951	0.5725	0.5089	0.5725	0.7951	0.6679	0.6679	0.6679	0.6361	0.6901 ± 0.14693
2731	13.07	Bubble	0.6679	0.9859	0.9541	1.2085	1.0495	0.9859	0.8905	0.6361	0.8269	0.5089	0.8714 ± 0.21319
2731	15.54	Bubble	0.9859	0.8905	0.7315	0.7633	0.7951	0.6679	0.6679	0.9541	0.9859	0.8587	0.8301 ± 0.12313
2731	18.02	Bubble	0.6679	0.6679	0.6043	1.1131	1.2403	0.6997	1.0495	1.3994	0.9541	0.8269	0.9223 ± 0.27317
2731	20.49	Bubble	1.1449	1.2721	1.3994	1.1131	1.0177	0.7951	1.2403	1.1449	1.4312	1.2721	1.1831 ± 0.18653
2731	22.95	Bubble	1.0177	1.2721	1.0813	0.9541	1.2721	1.463	1.2721	1.5266	1.4312	1.2721	1.2562 ± 0.19038
2731	28.08	Bubble	0.9859	1.1131	1.304	1.2085	1.3676	1.5902	1.5266	1.6538	1.8128	1.463	1.4025 ± 0.25639
2731	33.21	Bubble	1.8128	1.7174	1.7492	1.1767	1.1449	1.2085	0.9859	1.2721	1.8446	1.781	1.4693 ± 0.33785
2731	38.33	Bubble-Slug	1.3358	1.5266	1.6856	1.5584	1.8764	1.5584	1.463	1.7174	1.3358	1.2403	1.5298 ± 0.19574
2731	43.46	Slug	1.7492	2.0354	2.2263	2.1308	1.8446	1.7492	1.9718	2.0036	1.8446	1.7174	1.9273 ± 0.17368
2731	48.59	Slug	2.0036	1.9082	2.0672	2.1945	2.1627	1.8764	1.9718	1.5584	1.8764	1.9082	1.9527 ± 0.17941
2731	58.85	Slug	2.0036	2.3217	2.0036	2.0354	2.099	1.9082	1.9718	2.2899	2.2581	1.94	2.0831 ± 0.15234
2731	69.10	Slug	2.5125	2.7033	2.6079	2.7351	2.5443	2.2581	2.4171	2.2263	2.2899	2.1308	2.4425 ± 0.21032

Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
			1	2	3	4	5	6	7	8	9	10	
2731	79.36	Slug	2.8623	2.4807	2.5443	2.5125	2.6397	2.7987	2.6397	2.7351	2.6715	2.7033	2.6588 ± 0.1229
2731	89.62	Slug	2.8623	2.7033	2.5443	2.8623	2.9259	2.8623	2.7669	2.8623	2.8941	2.8623	2.8146 ± 0.11442
2731	99.87	Slug	3.403	3.2122	3.2758	3.3076	3.1804	2.9577	3.1804	2.9259	3.0532	2.9577	3.1454 ± 0.16454
2731	177	Slug	4.8024	4.7706	5.0886	4.5161	4.6115	4.866	4.4525	4.6433	4.5161	4.4525	4.672 ± 0.20744
2731	296	Slug	6.7424	6.8378	7.1558	6.7742	6.3925	6.4243	6.9014	6.8378	6.806	6.8378	6.771 ± 0.2221
2731	369	Slug-Churn	7.6647	7.7283	7.5375	7.7283	7.8237	8.0463	7.5693	7.5375	7.8237	7.9509	7.741 ± 0.17303
2731	515	Slug-Churn	8.2054	8.3644	8.3326	8.269	8.2372	7.7601	8.1099	8.1099	8.0781	8.1735	8.164 ± 0.17097
2731	735	Slug-Churn	9.2549	9.2231	9.1913	9.1595	9.2231	9.0641	9.1913	9.1595	9.2231	9.2549	9.1944 ± 0.05699
2731	1454	Slug-Churn	9.8591	9.9228	10.114	10.082	10.05	9.8591	9.8273	9.9864	10.813	10.018	10.053 ± 0.28503
2731	2474	Churn	9.3185	9.1277	9.1595	9.3503	9.2231	9.3185	9.3821	9.2867	9.3503	9.3503	9.2867 ± 0.08742
2731	3495	Churn	8.9686	8.9686	8.9686	8.9686	8.9686	9.0004	9.0004	9.0004	9.0004	9.0004	8.9845 ± 0.01676
2731	4516	Churn	8.8096	9.1595	9.0641	9.0641	9.0004	8.7778	8.7778	8.7778	8.7778	8.7778	8.8987 ± 0.15421
2731	5537	Churn	9.1277	9.3821	9.3821	9.4775	9.8591	8.4916	8.905	8.6824	8.746	8.8414	9.0895 ± 0.42848
2731	14255	Churn	8.587	8.6824	8.6824	8.7778	9.0004	8.9368	8.4916	8.587	8.5552	8.5552	8.6856 ± 0.17058
2731	21382	Churn	7.3148	7.124	7.124	7.124	7.124	7.0922	7.0922	7.1558	7.1558	7.1558	7.1463 ± 0.0637
2731	28510	Annular	5.343	5.343	5.343	5.343	5.343	5.343	5.343	5.343	5.343	5.343	5.343 ± 9.4E-16
2731	35637	Annular	3.721	3.9755	3.9755	3.9755	3.9755	3.9755	3.9755	3.9755	3.9755	3.9755	3.95 ± 0.08046
2731	42765	Annular	2.5443	2.5443	2.5443	2.5443	2.5443	2.5443	2.5443	2.5443	2.5443	2.5443	2.5443 ± 4.7E-16
2731	49892	Annular	1.5902	1.5584	1.5902	1.5902	1.5902	1.5902	1.5902	1.5902	1.5902	1.5902	1.587 ± 0.01006
2731	57020	Mist	0.5089	0.9859	1.1449	0.9859	0.9859	0.9859	0.9859	0.8905	0.9859	0.9859	0.9446 ± 0.16495
2735	3.17	Bubble	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336 ± 0
2735	5.64	Bubble	0.3618	0.3618	0.3618	0.3618	0.3618	0.3618	0.3618	0.3618	0.3618	0.3618	0.3618 ± 0
2735	8.12	Bubble	0.4393	0.4393	0.4393	0.4393	0.4393	0.4393	0.4393	0.4393	0.4393	0.4393	0.4393 ± 5.9E-17
2735	10.59	Bubble	0.491	0.2843	0.4135	0.4135	0.3877	0.4652	0.4135	0.491	0.4393	0.4652	0.4264 ± 0.06122
2735	13.07	Bubble	0.6719	0.6461	0.6461	0.6461	0.6461	0.6203	0.5686	0.5686	0.5169	0.5169	0.6047 ± 0.0574
2735	15.54	Bubble	0.7495	0.6719	0.6461	0.5686	0.5944	0.5944	0.6978	0.7236	0.7236	0.6461	0.6616 ± 0.06236

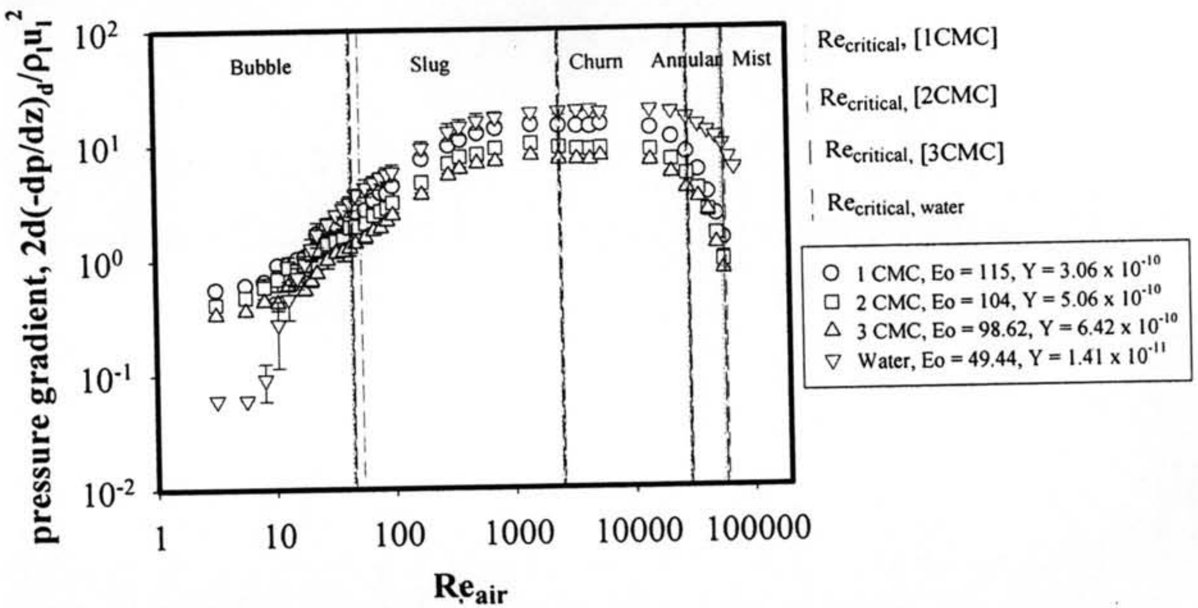
Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \overline{u}_{liq}^{2}}$										Average dimensionless pressure gradient
			1	2	3	4	5	6	7	8	9	10	
2735	18.02	Bubble	0.5944	0.5686	0.6461	0.5427	0.5169	0.5169	0.5427	0.5427	0.4652	0.5686	0.5505 ± 0.04881
2735	20.49	Bubble	0.5686	0.5686	0.6461	0.6978	0.6978	0.5944	0.6461	0.7753	0.6978	0.7753	0.6668 ± 0.07589
2735	22.95	Bubble	0.7753	0.7236	0.7236	0.7753	0.7495	0.8528	0.9045	0.7753	0.7495	0.7236	0.7753 ± 0.05968
2735	28.08	Bubble	0.9821	0.8528	1.0596	0.9562	1.2922	1.2922	0.9562	0.8787	0.9821	0.8787	1.0131 ± 0.15922
2735	33.21	Bubble	1.0338	1.0854	1.0854	1.163	1.1113	1.1371	1.2663	1.2405	1.2405	1.2147	1.1578 ± 0.0797
2735	38.33	Bubble-Slug	1.0596	0.9045	0.9304	0.9821	1.318	1.3697	1.2405	1.318	1.3697	1.4473	1.194 ± 0.20415
2735	43.46	Slug	0.9821	1.1113	1.1888	1.2405	1.0854	1.3697	1.4473	1.4214	1.3956	1.4473	1.2689 ± 0.17032
2735	48.59	Slug	1.3956	1.3956	1.4214	1.4214	1.3697	1.4731	1.4473	1.4731	1.4473	1.1371	1.3982 ± 0.09781
2735	58.85	Slug	1.9641	1.6023	1.3956	1.5506	1.5506	1.6023	1.6023	1.5506	1.4214	1.4214	1.5661 ± 0.16126
2735	69.10	Slug	1.8608	1.8608	1.9383	1.8608	1.7057	1.9124	1.8866	1.7057	1.6282	1.654	1.8013 ± 0.11497
2735	79.36	Slug	1.6799	1.8608	1.7315	1.9641	1.8091	1.8349	1.9641	2.0158	2.0417	2.0417	1.8944 ± 0.13011
2735	89.62	Slug	2.2226	2.3001	2.3259	2.1192	2.1709	2.145	2.0675	2.0158	2.1967	2.1967	2.1761 ± 0.09577
2735	99.87	Slug	2.5844	2.6102	2.5585	2.2743	2.3259	2.3518	2.4293	2.5585	2.5069	2.2484	2.4448 ± 0.13632
2735	177	Slug	3.799	3.8766	3.4889	3.6957	3.6957	3.7215	3.6181	3.5665	3.7215	3.4114	3.6595 ± 0.14061
2735	296	Slug	5.5047	5.3497	5.2721	5.1688	5.2463	5.3238	5.298	5.2205	5.789	5.4789	5.3652 ± 0.18282
2735	369	Slug-Churn	6.1508	5.8924	6.0475	6.0733	5.9958	5.9958	6.0992	5.8149	6.5385	6.2025	6.0811 ± 0.19759
2735	515	Slug-Churn	6.5902	6.9778	6.461	6.4868	6.5902	6.9262	6.461	7.0295	7.3655	6.9262	6.7814 ± 0.30705
2735	735	Slug-Churn	7.3655	7.0037	6.9262	6.7452	7.0554	7.1071	6.952	6.952	6.9778	7.1071	7.0192 ± 0.16033
2735	1454	Slug-Churn	7.8824	8.2183	7.779	7.9599	8.0116	7.7015	7.6756	7.6756	7.8824	7.8048	7.8591 ± 0.17162
2735	2474	Churn	7.1071	7.2104	7.2363	7.1071	7.0812	7.2621	7.2363	7.288	7.288	7.3655	7.2182 ± 0.09282
2735	3495	Churn	7.2363	7.2363	7.2104	7.2104	7.2363	7.2363	7.2621	7.2104	7.2104	7.1846	7.2234 ± 0.02196
2735	4516	Churn	7.1071	7.1071	7.1329	7.1329	7.1587	7.1071	7.1587	7.1587	7.1587	7.1846	7.1407 ± 0.02738
2735	5537	Churn	7.6498	7.6756	7.7532	7.6239	7.5464	7.8048	7.8048	7.7532	7.6498	7.6239	7.6885 ± 0.08636
2735	14255	Churn	6.7711	6.8486	7.0037	6.9778	6.7711	7.0295	7.0554	7.0554	6.9262	7.0812	6.952 ± 0.11749
2735	21382	Churn	5.3238	5.4272	5.4272	5.4272	5.4272	5.4272	5.4272	5.4272	5.4272	5.4272	5.4169 ± 0.03269
2735	28510	Annular	3.98	3.98	3.98	3.98	3.98	3.98	3.98	3.98	3.98	3.98	3.98 ± 9.4E-16

Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^2}$										Average dimensionless pressure gradient
			1	2	3	4	5	6	7	8	9	10	
2735	35637	Annular	3.2822	3.2822	3.2822	3.2822	3.2822	3.2822	3.2822	3.2822	3.2822	3.2822	3.2822 ± 0
2735	42765	Annular	2.5327	2.5327	2.5327	2.5327	2.5327	2.5327	2.5327	2.5327	2.5327	2.5327	2.5327 ± 0
2735	49892	Annular	1.2922	1.2922	1.2922	1.2922	1.2922	1.2922	1.2922	1.2922	1.2922	1.2922	1.2922 ± 0
2735	57020	Mist	0.7753	0.7753	0.7753	0.7753	0.7753	0.7753	0.7753	0.7753	0.7753	0.7753	0.7753 ± 1.2E-16



$(-dp/dz)_d$: Dynamic pressure gradient for octylbenzyldimethyl ammonium chloride surfactant and water

Figure L6 Comparison the dynamic pressure gradient from experiment between octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) by using pipe diameter of 19 mm.



$(-dp/dz)_d$: Dynamic pressure gradient for octylbenzyldimethyl ammonium chloride surfactant and water

ρ_l : Liquid density

u_l : Mean liquid velocity, (Liquid flow rate / Cross section area)

d : Pipe diameter

Figure L7 Comparison the dimensionless pressure gradient from experiment between octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC) by using pipe diameter of 19 mm.

Table L6 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes by using octylbenzyldimethylammonium chloride solution (1, 2 and 3 CMC)

Surfactant concentration	$Re_{solution}$	Re_{air}(critical) for each flow regime					
		Bubble-Slug	Slug	Slug-Churn	Churn	Annular	Mist
1 CMC	2749	33.21	43.46	369	2474	28510	57020
2 CMC	2731	38.33	43.46	369	2474	28510	57020
3 CMC	2735	38.33	43.46	369	2474	28510	57020

Appendix M Comparison the Experimental Data of Octylbenzyldimethylammonium Chloride Solution (1CMC) and Hexadecylbenzyldimethylammonium Chloride Solution (1CMC) by Using the Pipe Diameter of 19 mm

Table M1 Comparison of bubble width for octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of octylbenzyldimethylammonium chloride (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$= 9.73 × 10^{-4} Pa.s

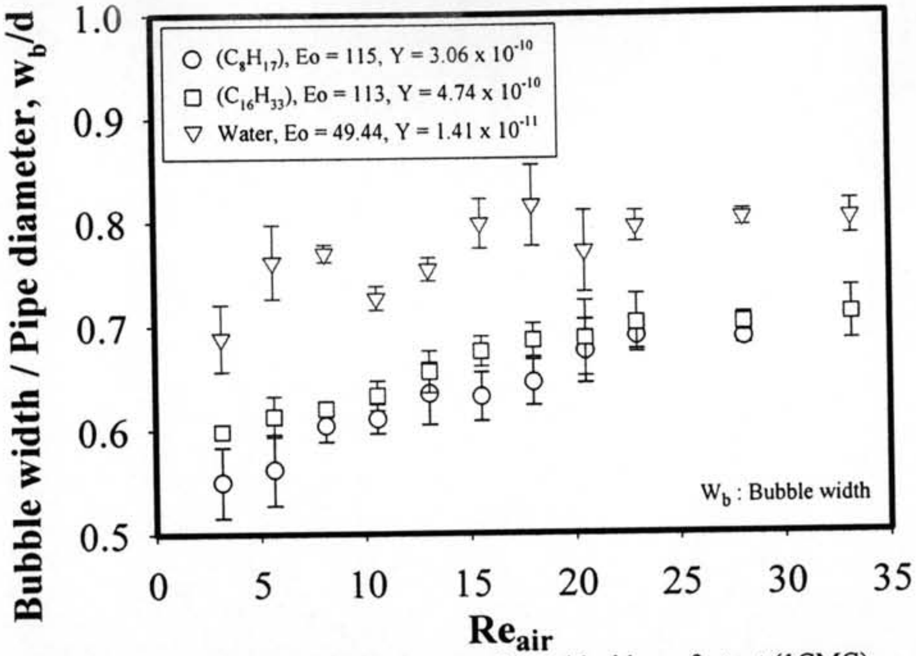
density of hexadecylbenzyldimethylammonium chloride (1CMC), $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$= 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

Liquid	$Re_{solution}$	Re_{air}	Bubble width, W_b (mm)			Average bubble width, (mm)	Bubble width / Pipe diameter			Average bubble width / Pipe diameter
			1	2	3		1	2	3	
Octylbenzyldimethylammonium chloride solution (1 CMC)	2749	3.17	10.3	11.1	8.9	10.1 ± 1.1	0.54	0.59	0.47	0.53 ± 0.06
	2749	5.64	10.2	11.4	10.4	10.7 ± 0.6	0.54	0.60	0.55	0.56 ± 0.03
	2749	8.12	11.3	11.8	11.3	11.5 ± 0.3	0.59	0.62	0.60	0.60 ± 0.02
	2749	10.59	11.6	11.9	11.3	11.6 ± 0.3	0.61	0.62	0.60	0.61 ± 0.01
	2749	13.07	12.6	11.5	12.1	12.1 ± 0.6	0.66	0.60	0.64	0.63 ± 0.03
	2749	15.54	12.4	11.6	12.0	12.0 ± 0.4	0.65	0.61	0.63	0.63 ± 0.02
	2749	18.02	12.1	12.7	11.9	12.2 ± 0.4	0.64	0.67	0.63	0.64 ± 0.02
	2749	20.49	12.9	12.2	13.3	12.8 ± 0.6	0.68	0.64	0.70	0.67 ± 0.03
	2749	22.95	13.0	12.9	13.4	13.1 ± 0.2	0.68	0.68	0.70	0.69 ± 0.01
	2749	28.08	13.2	12.9	13.1	13.1 ± 0.1	0.69	0.68	0.69	0.69 ± 0.01
Hexadecylbenzyldimethylammonium chloride solution (1 CMC)	2741	3.17	11.3	11.5	11.3	11.4 ± 0.1	0.60	0.61	0.59	0.60 ± 0.01
	2741	5.64	11.5	12.1	11.4	11.6 ± 0.4	0.60	0.64	0.60	0.61 ± 0.02
	2741	8.12	11.8	11.6	11.9	11.8 ± 0.1	0.62	0.61	0.63	0.62 ± 0.01
	2741	10.59	12.3	12.0	11.8	12.0 ± 0.3	0.65	0.63	0.62	0.63 ± 0.01
	2741	13.07	12.9	12.3	12.2	12.4 ± 0.4	0.68	0.65	0.64	0.66 ± 0.02
	2741	15.54	12.5	12.8	13.1	12.8 ± 0.3	0.66	0.67	0.69	0.67 ± 0.01
	2741	18.02	13.2	13.2	12.7	13.0 ± 0.3	0.70	0.69	0.67	0.69 ± 0.02
	2741	20.49	12.3	13.3	13.6	13.1 ± 0.7	0.65	0.70	0.72	0.69 ± 0.04
	2741	22.95	12.8	13.2	13.9	13.3 ± 0.5	0.68	0.70	0.73	0.70 ± 0.03
	2741	28.08	13.4	13.1	13.4	13.3 ± 0.2	0.71	0.69	0.71	0.70 ± 0.01
	2741	33.21	13.2	14.1	13.2	13.5 ± 0.5	0.69	0.74	0.70	0.71 ± 0.03



(C_8H_{17}) : Octylbenzyldimethyl ammonium chloride surfactant (1CMC)

($C_{16}H_{33}$) : Hexadecylbenzyldimethyl ammonium chloride surfactant (1CMC)

Figure M1 Comparison the bubble width from experiment between octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table M2 Comparison of bubble height for octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of octylbenzyldimethylammonium chloride (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$= 9.73 × 10^{-4} Pa.s

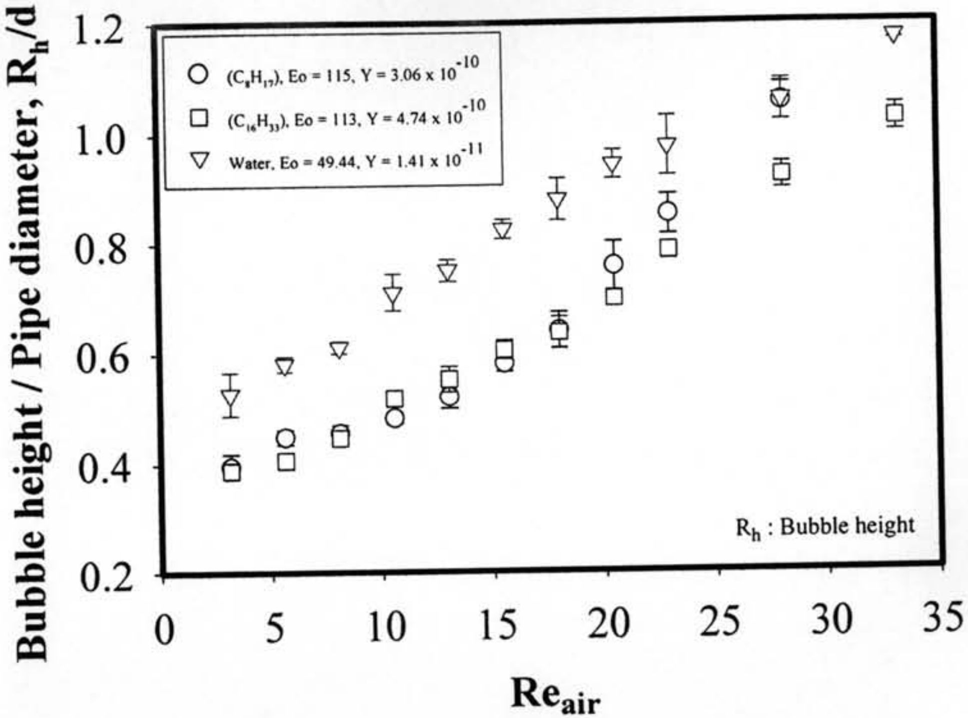
density of hexadecylbenzyldimethylammonium chloride (1CMC), $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$= 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

Liquid	$Re_{solution}$	Re_{air}	Bubble height, R_h (mm)			Average, R_h (mm)	Bubble height / Pipe diameter			Average, R_h/D
			1	2	3		1	2	3	
Octylbenzyldimethylammonium chloride solution (1 CMC)	2749	3.17	7.9	7.6	7.1	7.5 ± 0.4	0.42	0.40	0.37	0.40 ± 0.02
	2749	5.64	8.3	8.5	8.8	8.5 ± 0.3	0.43	0.45	0.46	0.45 ± 0.01
	2749	8.12	8.8	8.3	8.8	8.7 ± 0.3	0.46	0.44	0.46	0.46 ± 0.01
	2749	10.59	9.3	9.2	9.0	9.2 ± 0.2	0.49	0.48	0.47	0.48 ± 0.01
	2749	13.07	10.1	9.4	10.1	9.9 ± 0.4	0.53	0.50	0.53	0.52 ± 0.02
	2749	15.54	10.9	11.3	10.8	11.0 ± 0.3	0.57	0.60	0.57	0.58 ± 0.01
	2749	18.02	12.6	11.4	12.5	12.2 ± 0.6	0.66	0.60	0.66	0.64 ± 0.03
	2749	20.49	13.6	14.3	15.3	14.4 ± 0.8	0.71	0.75	0.80	0.76 ± 0.04
	2749	22.95	16.3	16.8	15.4	16.2 ± 0.7	0.86	0.88	0.81	0.85 ± 0.04
	2749	28.08	20.8	19.8	19.6	20.0 ± 0.6	1.09	1.04	1.03	1.05 ± 0.03
Hexadecylbenzyldimethylammonium chloride solution (1 CMC)	2741	3.17	7.2	7.3	7.7	7.4 ± 0.3	0.38	0.38	0.41	0.39 ± 0.02
	2741	5.64	7.8	8.0	7.4	7.7 ± 0.3	0.41	0.42	0.39	0.41 ± 0.01
	2741	8.12	8.4	8.7	8.4	8.5 ± 0.2	0.44	0.46	0.44	0.45 ± 0.01
	2741	10.59	9.8	9.8	10.0	9.8 ± 0.1	0.51	0.51	0.53	0.52 ± 0.01
	2741	13.07	10.0	10.9	10.6	10.5 ± 0.4	0.53	0.57	0.56	0.55 ± 0.02
	2741	15.54	11.8	11.2	11.5	11.5 ± 0.3	0.62	0.59	0.60	0.60 ± 0.02
	2741	18.02	11.8	12.7	11.8	12.1 ± 0.5	0.62	0.67	0.62	0.64 ± 0.03
	2741	20.49	13.5	13.1	13.1	13.3 ± 0.2	0.71	0.69	0.69	0.70 ± 0.01
	2741	22.95	15.0	14.9	14.9	14.9 ± 0.1	0.79	0.78	0.78	0.78 ± 0.00
	2741	28.08	17.0	17.6	17.9	17.5 ± 0.5	0.89	0.93	0.94	0.92 ± 0.02
	2741	33.21	20.0	19.2	19.2	19.5 ± 0.5	1.05	1.01	1.01	1.02 ± 0.02



(C_8H_{17}) : Octylbenzyldimethyl ammonium chloride surfactant (1CMC)

($C_{16}H_{33}$) : Hexadecylbenzyldimethyl ammonium chloride surfactant (1CMC)

Figure M2 Comparison the bubble height from experiment between octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table M3 Comparison of slug height for octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of octylbenzyldimethylammonium chloride (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$= 9.73 × 10^{-4} Pa.s

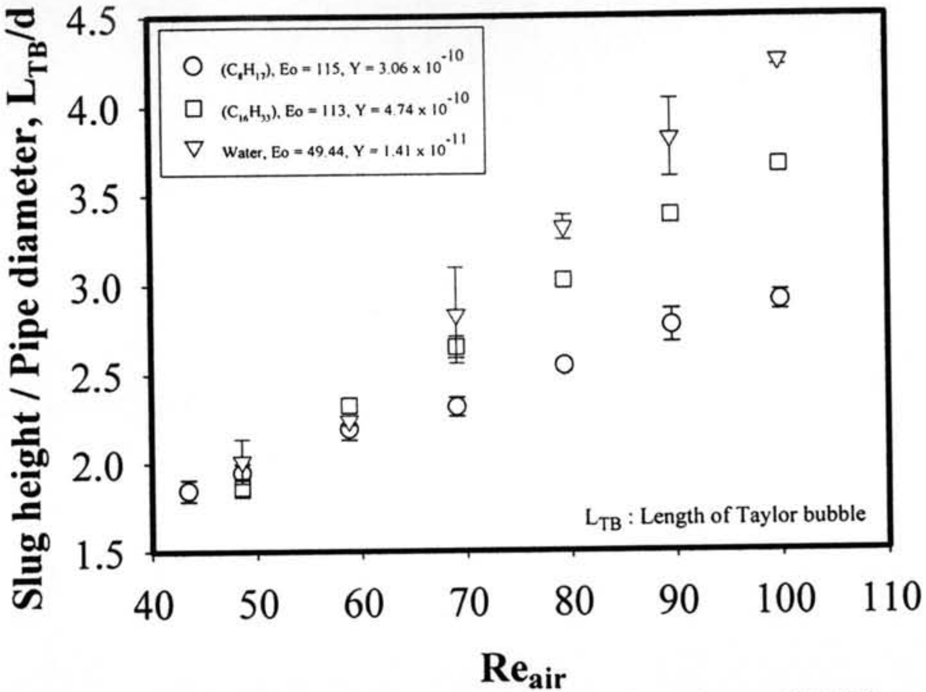
density of hexadecylbenzyldimethylammonium chloride (1CMC), $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$= 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

Liquid	$Re_{solution}$	Re_{air}	Length of Taylor bubble (L_{TB}) ,mm			Average length of Taylor bubble (L_{TB}) ,mm	Length of Taylor bubble / Pipe diameter			Average Length of Taylor bubble / Pipe diameter
			1	2	3		1	2	3	
Octylbenzyldimethylammonium chloride solution (1 CMC)	2749	43.46	34.9	36.4	34.1	35.1 ± 1.2	1.8	1.9	1.8	1.8 ± 0.06
	2749	48.59	37.0	38.0	36.1	37.0 ± 0.9	1.9	2.0	1.9	1.9 ± 0.05
	2749	58.85	41.0	43.0	41.0	41.7 ± 1.2	2.2	2.3	2.2	2.2 ± 0.06
	2749	69.10	44.0	45.0	43.0	44.0 ± 1.0	2.3	2.4	2.3	2.3 ± 0.05
	2749	79.36	48.0	49.0	48.0	48.3 ± 0.6	2.5	2.6	2.5	2.5 ± 0.03
	2749	89.62	54.6	52.1	51.1	52.6 ± 1.8	2.9	2.7	2.7	2.8 ± 0.09
	2749	99.87	54.2	56.3	55.2	55.2 ± 1.0	2.9	3.0	2.9	2.9 ± 0.05
	2749	177	80.8	80.8	80.9	80.8 ± 2.1	4.3	4.3	4.3	4.3 ± 0.11
	2749	296	137	140	139	138 ± 1.6	7.2	7.4	7.3	7.3 ± 0.08
Hexadecylbenzyldimethylammonium chloride solution (1 CMC)	2741	48.59	34.9	36.6	34.9	35.4 ± 1.0	1.8	1.9	1.8	1.9 ± 0.05
	2741	58.85	44.4	44.6	43.6	44.2 ± 0.5	2.3	2.3	2.3	2.3 ± 0.03
	2741	69.10	49.3	50.2	51.6	50.3 ± 1.1	2.6	2.6	2.7	2.6 ± 0.06
	2741	79.36	57.7	57.7	56.9	57.5 ± 0.5	3.0	3.0	3.0	3.0 ± 0.02
	2741	89.62	63.7	64.8	64.4	64.3 ± 0.6	3.4	3.4	3.4	3.4 ± 0.03
	2741	99.87	69.0	70.0	69.9	69.6 ± 0.5	3.6	3.7	3.7	3.7 ± 0.03
	2741	177	101	99	102	101 ± 1.5	5.3	5.2	5.4	5.3 ± 0.08
	2741	296	180	177	183	180 ± 3.0	9.5	9.3	9.6	9.5 ± 0.16



(C_8H_{17}) : Octylbenzyldimethyl ammonium chloride surfactant (1CMC)

($C_{16}H_{33}$) : Hexadecylbenzyldimethyl ammonium chloride surfactant (1CMC)

Figure M3 Comparison the slug height from experiment between octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table M4 Comparison of bubble and slug velocity for octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of octylbenzyldimethylammonium chloride (1CMC), $\rho_{solution} = 998$ kg/m^3; viscosity of solution, $\mu_{solution} = 9.73 \times 10^{-4}$ Pa.s

density of hexadecylbenzyldimethylammonium chloride (1CMC), $\rho_{solution} = 997.3$ kg/m^3; viscosity of solution, $\mu_{solution} = 1.103 \times 10^{-3}$ Pa.s

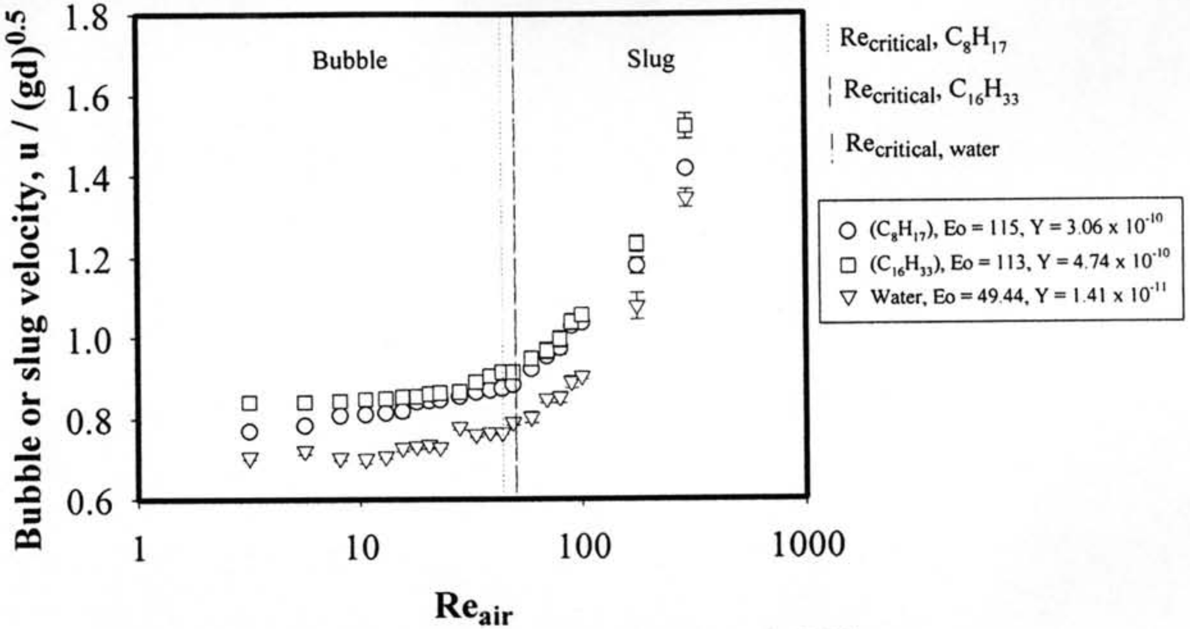
density of air, $\rho_{air} = 1.18$ kg/m^3; viscosity of air, $\mu_{air} = 1.85 \times 10^{-5}$ Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

Liquid	$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
Octylbenzyldimethylammonium chloride solution (1 CMC)	2749	3.17	0.77	0.77	0.77	0.77	0.77	0.77 ± 0.002
	2749	5.64	0.79	0.78	0.78	0.78	0.79	0.78 ± 0.006
	2749	8.11	0.80	0.81	0.81	0.81	0.80	0.81 ± 0.006
	2749	10.59	0.81	0.81	0.80	0.81	0.82	0.81 ± 0.008
	2749	13.06	0.81	0.82	0.81	0.81	0.81	0.81 ± 0.005
	2749	15.53	0.81	0.83	0.83	0.80	0.81	0.82 ± 0.015
	2749	18.01	0.82	0.85	0.85	0.85	0.85	0.84 ± 0.011
	2749	20.48	0.83	0.85	0.85	0.85	0.85	0.85 ± 0.006
	2749	22.94	0.85	0.83	0.86	0.85	0.85	0.85 ± 0.008
	2749	28.06	0.86	0.87	0.85	0.86	0.85	0.86 ± 0.010
	2749	33.19	0.86	0.87	0.87	0.87	0.86	0.87 ± 0.008
	2749	38.31	0.87	0.87	0.88	0.86	0.87	0.87 ± 0.007
	2749	43.44	0.88	0.89	0.86	0.87	0.87	0.88 ± 0.009
	2749	48.57	0.89	0.88	0.89	0.89	0.88	0.88 ± 0.002
	2749	58.82	0.91	0.93	0.93	0.93	0.93	0.92 ± 0.006
	2749	69.07	0.96	0.96	0.96	0.95	0.96	0.95 ± 0.005
	2749	79.32	0.96	0.99	0.96	0.99	0.98	0.97 ± 0.016
	2749	89.57	1.02	1.04	1.04	1.02	1.02	1.03 ± 0.006
	2749	99.82	1.04	1.04	1.04	1.02	1.04	1.04 ± 0.008
	2749	177	1.17	1.17	1.21	1.19	1.17	1.18 ± 0.020
	2749	296	1.41	1.43	1.40	1.41	1.43	1.42 ± 0.009

Liquid	$Re_{solution}$	Re_{air}	Bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$					Average bubble and slug velocity, $\frac{u}{(gD)^{0.5}}$
			1	2	3	4	5	
Hexadecylbenzyldimethylammonium chloride solution (1 CMC)	2741	3.17	0.83	0.83	0.85	0.85	0.85	0.84 ± 0.007
	2741	5.64	0.85	0.83	0.85	0.83	0.85	0.84 ± 0.007
	2741	8.11	0.85	0.86	0.84	0.84	0.84	0.84 ± 0.008
	2741	10.59	0.85	0.86	0.85	0.85	0.85	0.85 ± 0.007
	2741	13.06	0.85	0.86	0.85	0.83	0.86	0.85 ± 0.010
	2741	15.53	0.86	0.86	0.85	0.85	0.86	0.85 ± 0.006
	2741	18.01	0.86	0.86	0.85	0.86	0.86	0.86 ± 0.005
	2741	20.48	0.86	0.86	0.87	0.86	0.86	0.86 ± 0.005
	2741	22.94	0.87	0.86	0.86	0.86	0.87	0.86 ± 0.005
	2741	28.06	0.87	0.86	0.87	0.87	0.86	0.87 ± 0.007
	2741	33.19	0.90	0.90	0.87	0.89	0.90	0.89 ± 0.013
	2741	38.31	0.90	0.90	0.91	0.91	0.91	0.91 ± 0.008
	2741	43.44	0.91	0.91	0.93	0.93	0.90	0.91 ± 0.013
	2741	48.57	0.90	0.91	0.93	0.93	0.91	0.91 ± 0.012
	2741	58.82	0.95	0.93	0.96	0.96	0.96	0.95 ± 0.013
	2741	69.07	0.97	0.99	0.96	0.94	0.99	0.97 ± 0.020
	2741	79.32	1.02	0.97	0.99	0.99	1.00	1.00 ± 0.019
	2741	89.57	1.04	1.06	1.04	1.01	1.04	1.04 ± 0.019
	2741	99.82	1.04	1.04	1.06	1.08	1.06	1.06 ± 0.015
	2741	177	1.24	1.24	1.26	1.20	1.24	1.23 ± 0.020
	2741	296	1.52	1.57	1.52	1.48	1.52	1.52 ± 0.031



(C_8H_{17}) : Octylbenzyldimethyl ammonium chloride surfactant (1CMC)

($C_{16}H_{33}$) : Hexadecylbenzyldimethyl ammonium chloride surfactant (1CMC)

Figure M4 Comparison bubble or slug velocity from experiment between octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table M5 Comparison of the pressure gradient for octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) from experiment

Physical properties of air and solution used in experiment:

density of octylbenzyldimethylammonium chloride (1CMC), $\rho_{solution}$ = 998 kg/m^3; viscosity of solution, $\mu_{solution}$= 9.73 × 10^{-4} Pa.s

density of hexadecylbenzyldimethylammonium chloride (1CMC), $\rho_{solution}$ = 997.3 kg/m^3; viscosity of solution, $\mu_{solution}$= 1.103 × 10^{-3} Pa.s

density of air, ρ_{air} = 1.18 kg/m^3; viscosity of air, μ_{air} = 1.85 × 10^{-5} Pa.s

inner pipe diameter = 0.019 m; cross-sectional area of pipe, A = 0.00028 m^2

temperature, T = 31 °C (± 1 °C)

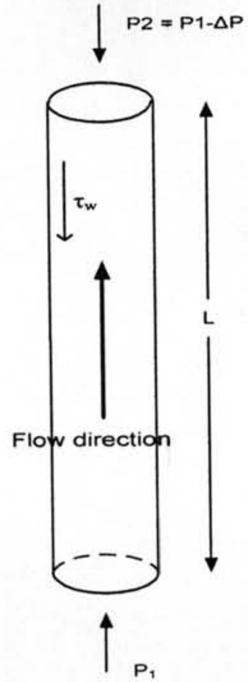


Figure M5 Pressure drop in a vertical pipe.

Upward flow in a vertical pipe is depicted in Fig. D13. A steady-state momentum balance in the direction of flow on the fluid in the pipe gives:

$$(P_1 - P_2)\frac{\pi D^2}{4} - \tau_w \pi D L - \frac{\pi D^2}{4}\rho L g = 0 \tag{M1}$$

$$(P_1 - P_2)\frac{D}{4} - \tau_w L - \frac{D}{4}\rho L g = 0 \tag{M2}$$

$$(P_1 - P_2)\frac{D}{4} - \rho L g\frac{D}{4} = \tau_w L \tag{M3}$$

$$(\frac{P_1 - P_2}{L})\frac{D}{4} - \rho g\frac{D}{4} = \tau_w \tag{M4}$$

We define the pressure drop: $\Delta P = P_1 - P_2$. Equation (M4) can be written as:

$$\frac{D}{4}[(\frac{\Delta P}{L})_d - \rho g] = \tau_w \tag{M5}$$

Elimination of the gravity term from Equation (M5) gives:

$$\frac{D}{4}(\frac{\Delta P}{L})_d = \tau_{w,d} \tag{M6}$$

From the definition of friction factor (f_F):

$$f_F = \frac{8\tau_{w,d}}{\rho_w \bar{u}_{liq}^{2}} \qquad \text{(M7)}$$

Rearrangement of Equation (M7) gives:

$$f_F = \frac{8\frac{D}{4}(\frac{\Delta P}{L})_d}{\rho_w \bar{u}_{liq}^{2}} \qquad \text{(M8)}$$

or

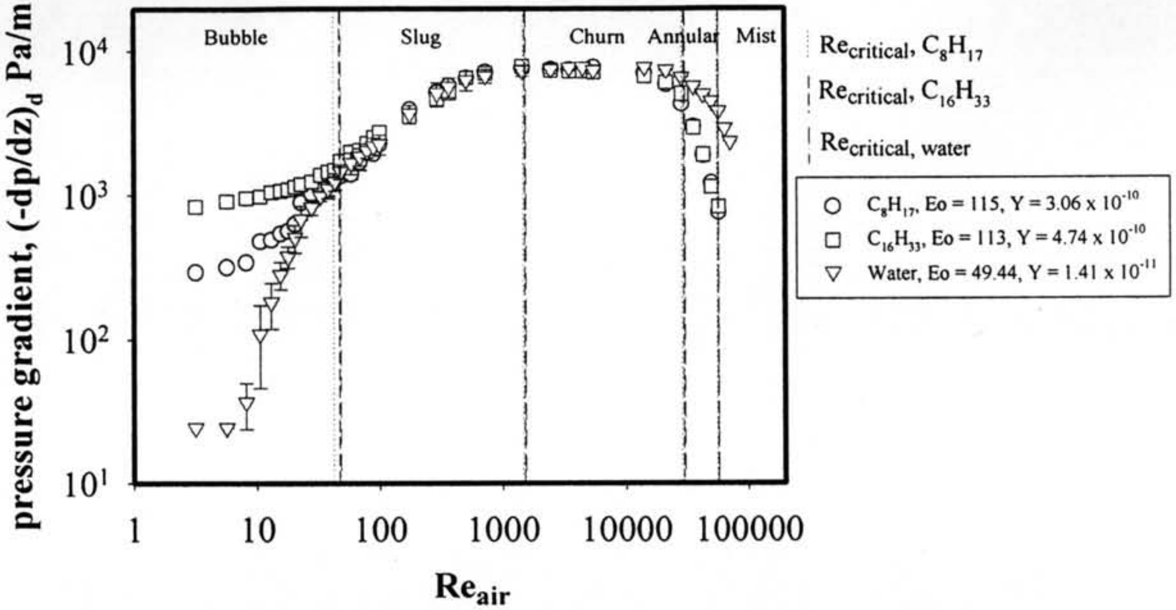
$$f_F = \frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}} \qquad \text{(M9)}$$

Liquid	Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
				1	2	3	4	5	6	7	8	9	10	
Octylbenzyldimethylammonium chloride solution (1 CMC)	2749	3.17	Bubble	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562	0.562 ± 0
	2749	5.64	Bubble	0.609	0.609	0.609	0.609	0.609	0.609	0.609	0.609	0.609	0.609	0.609 ± 0
	2749	8.12	Bubble	0.656	0.656	0.656	0.656	0.656	0.656	0.656	0.656	0.656	0.656	0.656 ± 0
	2749	10.59	Bubble	0.89	0.89	0.89	0.89	0.89	0.937	0.937	0.937	0.937	0.937	0.913 ± 0.02
	2749	13.07	Bubble	0.937	0.937	0.937	0.937	0.937	0.937	0.937	0.937	0.937	0.937	0.937 ± 0
	2749	15.54	Bubble	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03 ± 0
	2749	18.02	Bubble	1.077	1.077	1.077	1.077	1.077	1.077	1.077	1.077	1.077	1.077	1.077 ± 0
	2749	20.49	Bubble	1.171	1.077	1.171	1.218	1.077	1.264	1.264	1.311	1.218	1.218	1.199 ± 0.08
	2749	22.95	Bubble	1.358	1.311	1.264	1.311	1.311	2.154	2.061	2.107	2.061	2.107	1.705 ± 0.42
	2749	28.08	Bubble	1.639	1.686	1.592	1.686	1.639	2.295	2.482	2.482	2.107	2.061	1.967 ± 0.36
	2749	33.21	Bubble-Slug	1.405	1.639	1.967	1.967	2.107	2.342	2.295	2.342	2.342	2.295	2.07 ± 0.33
	2749	38.33	Bubble-Slug	2.903	2.669	2.248	2.295	2.014	2.342	2.716	2.014	1.499	2.248	2.295 ± 0.41
	2749	43.46	Slug	2.154	2.201	2.154	2.154	2.107	2.857	2.763	2.622	3.044	2.435	2.449 ± 0.35
	2749	48.59	Slug	2.388	2.529	2.342	2.482	2.435	2.903	2.857	2.857	2.81	2.81	2.641 ± 0.22
	2749	58.85	Slug	2.529	2.482	2.342	2.716	2.903	2.903	2.903	2.81	2.576	2.997	2.716 ± 0.22
	2749	69.10	Slug	2.95	3.044	2.669	3.981	2.95	3.278	3.325	3.419	3.793	3.653	3.306 ± 0.42
	2749	79.36	Slug	3.887	3.793	3.653	3.653	3.7	4.121	4.168	4.121	3.606	3.746	3.845 ± 0.22
	2749	89.62	Slug	3.653	3.653	3.559	3.793	3.512	3.84	4.121	4.027	3.934	3.653	3.775 ± 0.2
	2749	99.87	Slug	4.543	4.589	4.589	3.981	4.168	4.355	4.308	4.543	4.543	4.308	4.393 ± 0.21
	2749	177	Slug	6.931	7.352	7.399	7.774	7.774	7.493	7.586	7.586	7.586	7.586	7.507 ± 0.24
	2749	296	Slug	10.21	10.07	9.975	9.975	9.834	9.647	9.553	9.507	9.319	9.507	9.759 ± 0.29
	2749	369	Slug-Churn	11.15	10.86	10.82	10.82	10.82	10.96	11.01	10.86	10.82	10.82	10.89 ± 0.11
	2749	515	Slug-Churn	12.6	12.6	12.55	12.55	12.13	12.27	12.32	12.18	12.22	12.32	12.37 ± 0.18
	2749	735	Slug-Churn	13.49	13.77	13.63	13.58	13.53	13.44	13.49	13.53	13.91	13.81	13.62 ± 0.16

Liquid	Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient		
				1	2	3	4	5	6	7	8	9	10			
Octylbenzyldimethylammonium chloride solution (1 CMC)	2749	1454	Slug-Churn	14.705	14.705	14.705	14.705	14.705	14.377	14.33	14.42	14.377	14.42	14.55	±	0.17
	2749	2474	Churn	14.19	14.19	14.19	14.19	14.19	14.236	14.236	14.24	14.236	14.24	14.21	±	0.025
	2749	3495	Churn	14.096	14.096	14.096	14.096	14.096	14.096	14.096	14.1	14.096	14.1	14.1	±	0
	2749	4516	Churn	14.002	14.002	14.002	14.002	14.002	14.002	14.002	14	14.002	14	14	±	4E-15
	2749	5537	Churn	14.517	14.517	14.517	14.517	14.517	14.845	14.845	14.85	14.845	14.85	14.68	±	0.173
	2749	14255	Churn	13.3	13.3	13.3	13.3	13.3	13.534	13.534	13.53	13.534	13.53	13.42	±	0.123
	2749	21382	Churn	11.099	11.099	11.099	11.099	11.099	11.146	11.146	11.15	11.146	11.15	11.12	±	0.025
	2749	28510	Annular	8.1953	8.1953	8.1953	8.1953	8.1953	8.1953	8.1953	8.195	8.1953	8.195	8.195	±	2E-15
	2749	35637	Annular	5.7133	5.7133	5.7133	5.7133	5.7133	5.7133	5.7133	5.713	5.7133	5.713	5.713	±	9E-16
	2749	42765	Annular	3.6528	3.6528	3.6528	3.6528	3.6528	3.6528	3.6528	3.653	3.6528	3.653	3.653	±	5E-16
	2749	49892	Annular	2.3415	2.3415	2.3415	2.3415	2.3415	2.3415	2.3415	2.342	2.3415	2.342	2.342	±	5E-16
	2749	57020	Mist	1.4517	1.4517	1.4517	1.4517	1.4517	1.4517	1.4517	1.452	1.4517	1.452	1.452	±	2E-16

Liquid	Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
				1	2	3	4	5	6	7	8	9	10	
Hexadecylbenzyldimethylammonium chloride solution (1 CMC)	2741	3.17	Bubble	1.2445	1.2445	1.2445	1.2445	1.2445	1.2445	1.2445	1.2445	1.2445	1.2445	1.244 ± 2E-16
	2741	5.64	Bubble	1.3543	1.3543	1.3543	1.3543	1.3543	1.3543	1.3543	1.3543	1.3543	1.3543	1.354 ± 2E-16
	2741	8.12	Bubble	1.4275	1.4275	1.4275	1.4275	1.4275	1.4275	1.4275	1.4275	1.4275	1.4275	1.427 ± 2E-16
	2741	10.59	Bubble	1.4641	1.4641	1.4641	1.4641	1.4641	1.4641	1.4641	1.4641	1.4641	1.4641	1.464 ± 0
	2741	13.07	Bubble	1.5739	1.5739	1.5739	1.5739	1.5739	1.5739	1.5739	1.5739	1.5739	1.5739	1.574 ± 2E-16
	2741	15.54	Bubble	1.6105	1.6105	1.6105	1.6105	1.6105	1.6105	1.6105	1.6105	1.6105	1.6105	1.61 ± 2E-16
	2741	18.02	Bubble	1.6471	1.6471	1.6471	1.6471	1.6471	1.6471	1.6471	1.6471	1.6471	1.6471	1.647 ± 2E-16
	2741	20.49	Bubble	1.7203	1.7203	1.7203	1.7203	1.7203	1.7203	1.7203	1.7203	1.7203	1.7203	1.72 ± 0
	2741	22.95	Bubble	1.7935	1.7935	1.7935	1.7935	1.7935	1.7935	1.7935	1.7935	1.7935	1.7935	1.794 ± 5E-16
	2741	28.08	Bubble	1.8667	1.8667	1.8667	1.8667	1.8667	1.8667	1.8667	1.8667	1.8667	1.8667	1.867 ± 0
	2741	33.21	Bubble	2.0863	2.0863	2.0863	2.0863	2.0863	2.0863	2.0863	2.0863	2.0863	2.0863	2.086 ± 0
	2741	38.33	Bubble-Slug	2.1961	2.1961	2.1961	2.1961	2.1961	2.1961	2.1961	2.1961	2.1961	2.1961	2.196 ± 5E-16
	2741	43.46	Bubble-Slug	2.2693	2.2327	2.1229	2.3059	2.2693	2.4157	2.4157	2.4523	2.489	1.6471	2.262 ± 0.244
	2741	48.59	Slug	2.8184	2.7086	2.6354	2.5622	2.5256	2.5256	2.5988	2.5988	2.5988	2.5622	2.613 ± 0.09
	2741	58.85	Slug	2.9648	3.0014	3.0014	3.0014	3.0014	3.038	3.038	3.038	3.0014	3.0014	3.009 ± 0.023
	2741	69.10	Slug	3.1478	3.1112	3.1478	3.1112	3.1112	3.1478	3.0746	2.7818	3.0746	3.2576	3.097 ± 0.122
	2741	79.36	Slug	3.4406	3.404	3.404	3.4772	3.4406	3.1844	3.3674	3.6602	3.6602	3.6968	3.474 ± 0.159
	2741	89.62	Slug	3.77	3.7334	3.77	3.8066	3.8798	3.8432	3.8432	3.8432	3.8066	3.8432	3.814 ± 0.045
	2741	99.87	Slug	4.0995	4.1727	4.0995	4.0628	4.0628	4.1361	3.9896	4.2825	4.1727	4.1361	4.121 ± 0.079
	2741	177	Slug	5.4903	5.4171	5.4171	5.4171	5.4537	5.4537	5.1243	5.0145	5.0145	4.9779	5.278 ± 0.215
	2741	296	Slug	7.1374	6.7714	6.8446	6.9178	6.808	6.8812	6.7714	6.8446	6.8812	6.8812	6.874 ± 0.105
	2741	369	Slug-Churn	7.4669	7.4303	7.357	7.7597	7.7597	7.6499	7.8695	7.8695	7.6499	7.7231	7.654 ± 0.181
	2741	515	Slug-Churn	9.5898	9.846	9.3702	9.5898	9.5166	10.102	9.5166	10.175	9.8826	9.3336	9.692 ± 0.294
	2741	735	Slug-Churn	10.432	10.432	10.066	10.212	10.322	10.761	10.432	10.541	10.505	10.761	10.45 ± 0.218

Liquid	Re_{liquid}	Re_{air}	Flow regime	Dimensionless pressure gradient, $\frac{2D(-\frac{dp}{dz})_d}{\rho_w \bar{u}_{liq}^{2}}$										Average dimensionless pressure gradient
				1	2	3	4	5	6	7	8	9	10	
Hexadecylbenzyldimethylammonium chloride solution (1 CMC)	2741	1454	Slug-Churn	11.2369	12.115	11.7127	11.3467	11.273	11.8591	11.8225	11.7859	11.9323	11.8957	11.7 ± 0
	2741	2474	Churn	10.9075	11.164	10.9075	10.7245	11.017	11.0539	10.8709	11.0173	10.9075	10.9075	10.95 ± 0
	2741	3495	Churn	10.6146	10.688	10.7611	10.7611	10.761	10.8343	10.8343	10.8343	10.7977	10.7977	10.77 ± 0
	2741	4516	Churn	10.7611	10.761	10.7611	10.7611	10.761	10.7611	10.7611	10.7611	10.7611	10.7611	10.76 ± 0
	2741	5537	Churn	10.7977	10.798	10.9075	10.6146	10.432	10.0656	10.4316	10.7611	10.6146	10.5048	10.59 ± 0
	2741	14255	Churn	9.91921	9.9924	9.7728	9.8826	9.9558	10.029	10.0656	9.99241	9.99241	9.8826	9.948 ± 0
	2741	21382	Churn	8.63813	8.6015	8.85774	8.85774	9.114	9.07735	9.15056	9.15056	9.15056	9.11396	8.971 ± 0
	2741	28510	Annular	7.35705	7.2472	7.50346	7.61327	7.6133	7.50346	7.50346	7.50346	7.50346	7.50346	7.485 ± 0
	2741	35637	Annular	4.50208	4.5021	4.50208	4.50208	4.5021	4.35567	4.35567	4.35567	4.35567	4.35567	4.429 ± 0
	2741	42765	Annular	2.89158	2.8916	2.89158	2.89158	2.8916	2.89158	2.89158	2.89158	2.89158	2.89158	2.892 ± 0
	2741	49892	Annular	1.75691	1.7569	1.75691	1.75691	1.7569	1.6837	1.6837	1.6837	1.6837	1.6837	1.72 ± 0
	2741	57020	Mist	1.24448	1.2445	1.24448	1.24448	1.2445	1.24448	1.24448	1.24448	1.24448	1.24448	1.244 ± 0

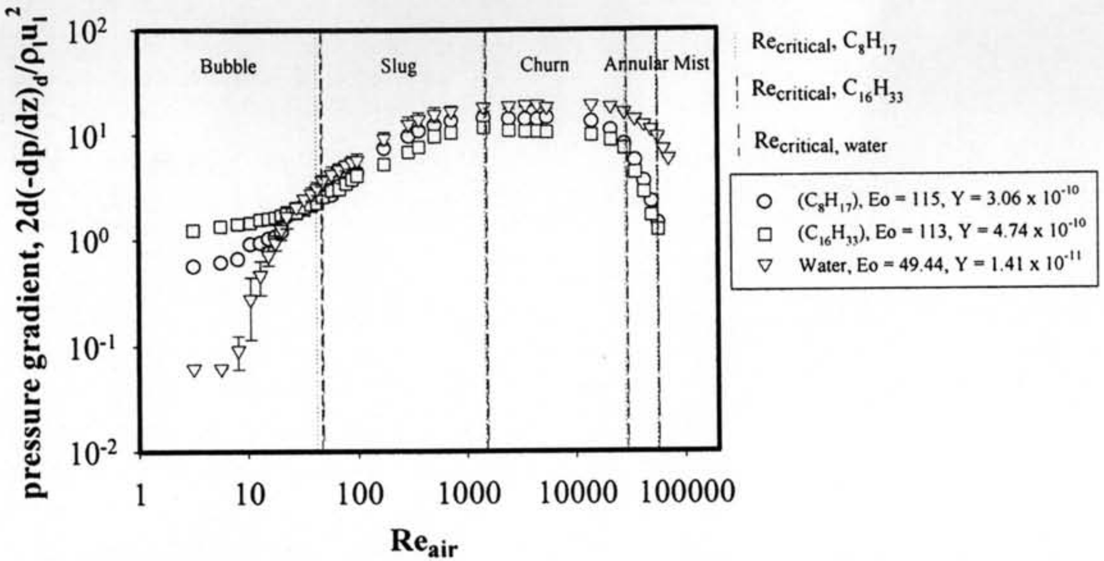


$(-dp/dz)_d$: Dynamic pressure gradient

C_8H_{17} : Octylbenzyldimethyl ammonium chloride surfactant (1CMC)

$C_{16}H_{33}$: Hexadecylbenzyldimethyl ammonium chloride surfactant (1CMC)

Figure M6 Comparison the dynamic pressure gradient from experiment between octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.



$(-dp/dz)_d$: Dynamic pressure gradient

ρ_l : Liquid density

u_l : Mean liquid velocity, (Liquid flow rate / Cross section area)

d : Pipe diameter

(C_8H_{17}) : Octylbenzyldimethyl ammonium chloride surfactant (1CMC)

$(C_{16}H_{33})$: Hexadecylbenzyldimethyl ammonium chloride surfactant (1CMC)

Figure M7 Comparison the dimensionless pressure gradient from experiment between octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC) by using pipe diameter of 19 mm.

Table M6 The critical Reynolds numbers $(Re_{air})_{critical}$ of various regimes by using octylbenzyldimethylammonium chloride solution (1 CMC) and hexadecylbenzyldimethylammonium chloride solution (1CMC)

Sample	$Re_{solution}$	Re_{air}(critical) for each flow regime					
		Bubble-Slug	Slug	Slug-Churn	Churn	Annular	Mist
Octylbenzyldimethylammonium chloride solution (1 CMC)	2749	33.21	43.46	369	2474	28510	57020
Hexadecylbenzyldimethylammonium chloride solution (1 CMC)	2741	38.33	48.59	369	2474	28510	57020

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