REFERENCES

ASHRAE Guide and Data Book. Fundamental and Equipment for 1965 and 1966.

Benedict, R.H. 1969. "Fundamental of Temperature, Pressure, and Flow Measurements." New York: John Wiley & Sons, Inc.

Bird, R.B., Stewart, W.E., and Lightfoot, E.N. 1960. "Transport Phenomena." New York: John Wiley & Sons, Inc.

Daugherty, R.L., and Franzini, J.B. 1965. "Fluid Mechanics with Engineering Applications." 6th ed. New York: McGraw-Hill, Inc.

Kays, W.M. 1968. "Convective Heat and Mass Transfer." New York: McGraw-Hill, Inc.

Kutateladze, S.S., and Borishanskii, U.M. 1966. "A Concise Encyclopedia of Heat Transfer." Pregamen Press Ltd. p. 107

Montgomery, S.R., and Wibulswas, P. 1967. "Laminar Flow Heat Transfer for Simultaneously Developing Velocity and Temperature Profiles in Ducts of Rectangular Cross Section." Appl. Sci. Res., 18: 247-59.

Montgomery, S.R., and Wibulswas, P. 1966. "Laminar Flow Heat Transfer in Ducts of Rectangular Cross Section." Proc. Third Int. Heat Transfer Conf., Vol I: 85-98.

Perry, J.H. 1950. "Chemical Engineers' Handbook." 3^{rd}ed. New York: McGraw-Hill Book Company, Inc.

Schlichting, Hermann. 1968. "Boundary-Layer Theory." New York: McGraw-Hill, Inc.

Shah, R.K., and London, A.L. 1971. "Laminar Flow Forced Convection Heat Transfer and Flow Friction in Straight and Curved Ducts - A Summary of Analytical Solutions." Technical Report No.75, Prepared under Contract Nonr 225(91), NR - 090 - 342, Department of Mechanical Engineering, Standford University.

Sparrow, E.M., and Haji - Sheikh, A. 1965. "Laminar Heat Transfer and Pressure Drop in Isosceles Triangular, Right Triangular, and Circular Sector Ducts." Tran. ASME, J. Heat Transfer, 87: 426-27.

Wibulswas, P. 1966. "Laminar Flow Heat Transfer in Non-Circular Ducts." Ph.D. Thesis, Department of Mechanical Engineering, London University.

Appendix A

Table of experimental results and specimen calculations

Table A-1 Experimental results for heat transfer with simultaneously developing velocity and temperature profiles in an equilateral triangular duct of z/d_h = 5.04 with constant wall temperature.

ΔH mm. H_2O	Re	Gz	$t_{w,o}$ °F	t_o °F	t_f °F	$t_{w,f}$ °F	Nu_l
10	528.26	76.90	157.031	102.721	117.643	156.383	6.23
15	639.58	93.12	157.207	99.913	117.521	156.559	8.61
20	729.18	106.14	157.072	99.071	117.193	156.667	9.99
25	806.40	117.41	157.274	98.284	116.737	156.842	11.18
30	881.73	128.39	157.166	97.554	116.239	156.761	12.12
35	950.12	138.31	157.041	97.371	115.911	156.667	12.92
40	1013.03	147.43	157.233	97.316	115.625	156.734	13.51
45	1074.84	156.53	157.193	97.019	115.212	156.869	14.14
50	1130.90	165.13	157.072	96.753	114.746	156.964	14.64
55	1188.20	173.04	157.395	96.494	114.492	157.112	15.20
60	1240.11	180.63	157.289	96.342	114.047	156.923	15.54
65	1291.17	188.04	157.099	96.446	113.764	156.815	15.85
70	1340.89	195.33	157.139	96.374	113.337	156.802	16.04

Table A-2 Experimental results for heat transfer with simultaneously developing velocity and temperature profiles in an equilateral triangular duct of z/d_h = 9.28 with constant wall temperature.

ΔH mm. H_2O	Re	Gz	$t_{w,o}$ °F	t_o °F	t_f °F	$t_{w,f}$ °F	Nu_1
10	533.22	42.16	162.41	95.80	118.08	162.37	4.29
15	643.25	50.88	161.91	95.45	118.00	161.87	5.27
20	731.86	57.89	162.85	95.04	118.35	163.25	6.07
25	810.02	64.04	162.21	94.94	117.97	162.07	6.72
30	883.85	69.88	162.18	94.31	117.62	162.05	7.36
35	952.17	75.31	161.81	93.98	117.36	161.69	7.97
40	1013.67	80.35	161.02	93.53	117.27	162.02	8.55
45	1077.56	85.26	161.82	92.99	116.95	161.74	9.13
50	1138.00	90.01	161.97	91.90	116.50	161.89	9.74
55	1192.05	94.34	161.87	92.01	116.29	161.85	10.07
60	1242.98	98.35	161.93	92.02	116.24	161.95	10.46
65	1296.56	102.57	162.34	91.17	115.55	162.20	10.77
70	1346.87	106.59	163.05	91.19	115.43	162.92	10.98
75	1390.56	110.05	162.49	91.54	115.14	162.42	11.14
80	1437.18	113.72	162.61	91.56	114.82	162.68	11.27

<u>Table A-3</u> Experimental results for heat transfer with simultaneously developing velocity and temperature profiles in an equilateral triangular duct of $z/d_h = 12.35$ with constant wall temperature.

ΔH mm. H_2O	Re	Gz	$t_{w,o}$ ^oF	t_o ^oF	t_f ^oF	$t_{w,f}$ ^oF	Nu
10	543.59	32.32	156.32	88.69	115.83	156.40	4.15
15	662.02	39.37	156.41	88.36	115.72	156.49	5.07
20	752.98	44.78	156.25	88.12	115.65	156.32	5.80
25	835.41	49.69	156.79	87.55	115.31	156.45	6.28
30	905.34	53.84	157.15	87.69	114.91	156.90	6.72
35	973.18	57.88	157.07	87.58	114.44	156.75	7.11
40	1041.16	61.92	157.15	87.42	113.94	156.88	7.45
45	1095.51	65.15	156.90	87.49	113.62	156.61	7.72
50	1157.53	68.86	156.64	87.25	113.08	156.50	8.01
55	1214.18	72.42	156.68	87.18	112.88	156.46	8.36
60	1267.04	75.37	156.65	87.29	112.53	156.40	8.55
65	1316.41	78.31	156.82	87.47	112.23	156.53	8.67
70	1364.91	81.18	156.87	87.90	112.02	156.65	8.77

Table A-4 Experimental results for heat transfer with simultaneously developing velocity and temperature profiles in a right-angled isosceles triangular duct of z/d_h = 5.13 with constant wall temperature.

ΔH mm.H_2O	Re	Gz	$t_{w,o}$ °F	t_o °F	t_f °F	$t_{w,f}$ °F	Nu_1
10	463.77	66.28	157.328	106.389	120.063	157.444	5.17
15	559.01	79.90	157.357	106.111	120.460	157.530	6.55
20	637.72	91.16	157.201	104.231	120.345	157.166	8.27
25	705.15	100.81	157.496	104.188	120.513	157.663	9.19
30	769.24	109.99	157.178	103.654	120.241	157.403	10.17
35	827.19	118.25	157.588	104.252	120.345	157.594	10.62
40	882.42	126.15	157.276	104.017	120.000	157.415	11.24
45	935.93	133.71	157.357	103.767	119.714	157.721	11.76
50	987.01	141.11	157.478	103.568	119.259	157.461	12.14
55	1034.48	147.93	157.403	103.291	119.025	157.739	12.65
60	1080.03	154.45	157.519	102.863	118.528	157.600	13.03
65	1124.73	160.73	157.669	102.810	118.233	157.559	13.29
70	1168.37	167.06	157.484	102.800	118.040	157.478	13.65
75	1206.15	172.49	157.571	102.949	118.019	157.767	13.89
80	1247.14	178.25	157.461	102.731	117.595	157.652	14.10

Table A-5 Experimental results for heat transfer with simultaneously developing velocity and temperature profiles in a right-angled isosceles triangular duct of $z/d_h = 9.06$ with constant wall temperature.

ΔH mm. H_2O	Re	Gz	$t_{w,o}$ ^oF	t_o ^oF	t_f ^oF	$t_{w,f}$ ^oF	Nu_1
10	470.47	38.12	154.74	99.37	116.88	155.11	3.60
15	567.00	45.87	153.88	99.48	116.94	154.20	4.43
20	648.42	52.46	153.72	97.45	116.91	154.01	5.47
25	715.74	57.91	153.82	97.97	116.82	154.09	5.97
30	781.26	63.21	153.52	96.88	116.17	153.68	6.57
35	841.19	68.06	153.35	96.93	115.99	153.45	7.01
40	899.18	72.75	153.81	95.89	115.84	153.86	7.68
45	953.07	77.21	153.79	95.91	115.64	153.94	8.03
50	1004.50	81.27	153.82	95.65	115.34	154.07	8.38
55	1052.24	85.25	154.09	95.62	115.13	154.22	8.64
60	1097.49	88.91	154.27	95.71	114.92	154.44	8.82
65	1142.12	92.40	154.33	95.84	114.59	154.53	8.93
70	1187.14	96.18	154.15	95.58	114.10	154.16	9.15
80	1227.40	99.45	154.26	95.50	113.70	154.57	9.23

Table A-6 Experimental results for heat transfer with simultaneously developing velocity and temperature profiles in a right-angled triangular duct of $z/d_h = 12.14$ with constant wall temperature.

ΔH mm.H_2O	Re	Gz	$t_{w,o}$ ^oF	t_o ^oF	t_f ^oF	$t_{w,f}$ ^oF	Nu_l
10	470.21	28.43	158.12	96.88	118.81	158.13	3.15
15	567.96	34.32	158.52	95.71	118.70	158.39	3.92
20	647.17	39.13	158.28	94.46	118.78	158.10	4.70
25	715.07	43.23	158.32	94.87	118.78	158.39	5.12
30	779.10	47.11	158.60	94.81	118.86	158.26	5.60
35	838.87	50.72	158.59	94.72	118.74	158.34	6.00
40	893.84	54.04	158.71	95.06	118.73	158.43	6.30
45	947.57	57.30	158.86	94.89	118.55	158.45	6.64
50	998.81	60.39	158.30	94.96	118.27	158.35	6.93
55	1045.62	63.22	158.73	95.50	118.03	158.31	7.00
60	1091.74	66.01	158.76	94.94	117.63	158.66	7.26
65	1137.97	68.80	158.52	94.71	117.11	158.50	7.44
70	1181.14	71.41	158.57	95.20	117.01	158.82	7.51
80	1221.75	73.87	158.59	94.78	116.35	159.01	7.59

Table A-7 Experimental results for heat transfer with simultaneously developing velocity and temperature profiles in an equilateral triangular duct of higher Reynolds numbers with constant wall temperature.

z/d_h	ΔH mm.H_2O	Re	Gz	$t_{w,o}$ °F	t_o °F	t_f °F	$t_{w,f}$ °F	Nu_1
5.04	30	1939.2	282.6	157.788	94.524	109.348	156.694	19.22
	40	2231.0	325.2	157.355	93.853	108.632	156.977	21.58
	50	2487.7	362.6	157.355	93.636	108.205	157.126	23.41
	60	2719.6	396.5	157.045	93.506	107.372	157.045	24.41
	70	2929.8	427.1	157.274	93.203	106.806	157.126	25.51
	80	3132.3	456.6	157.126	93.290	106.410	157.193	26.25
	90	3317.5	483.6	157.207	93.011	105.881	157.139	27.04
	100	3481.1	507.5	157.220	92.857	105.331	157.099	27.36
	110	3635.9	530.1	157.409	92.452	104.870	157.247	28.14
	115	3717.3	542.0	157.031	92.294	104.541	156.937	28.39

Table A-7 (continued)

z/d_h	ΔH mm.H_2O	Re	Gz	$t_{w,o}$ °F	t_o °F	t_f °F	$t_{w,f}$ °F	Nu_l
12.35	30	1957.6	116.5	155.99	90.50	110.75	155.95	10.77
	40	2294.1	136.5	156.14	89.57	109.85	156.21	12.17
	50	2508.7	149.2	156.18	89.71	109.48	156.33	13.15
	60	2795.6	166.4	156.14	89.41	108.68	156.29	13.90
	70	3011.1	179.1	156.45	89.23	108.18	156.45	14.57
	80	3222.7	191.8	156.63	88.78	107.61	156.65	15.31
	90	3412.4	203.1	156.65	88.63	107.06	156.67	15.76
	100	3576.3	212.7	156.67	88.88	106.94	156.70	16.18
	110	3672.6	218.6	156.77	88.46	106.19	156.80	16.41
	115	3751.6	223.2	156.59	88.47	105.89	156.68	16.47

Table A-8 Experimental results for heat transfer with simultaneously developing and temperature profiles in a right-angled isosceles triangular duct of higher Reynolds numbers with constant wall temperature.

z/d_h	ΔH mm.H_2O	Re	Gz	$t_{w,o}$ °F	t_o °F	t_f °F	$t_{w,f}$ °F	Nu_1
5.13	30	1718.5	246.0	157.715	94.048	109.466	157.987	17.01
	40	1974.0	282.6	157.901	94.026	108.942	158.219	18.74
	50	2198.6	314.8	157.906	93.853	108.547	158.398	20.42
	60	2405.1	344.4	157.953	93.702	108.141	158.369	21.83
	70	2588.9	370.8	157.785	93.636	107.756	158.311	22.94
	80	2757.3	396.2	158.005	93.766	107.500	158.456	23.73
	90	2929.0	419.4	158.022	93.874	107.137	158.444	24.20
	100	3072.8	440.1	157.982	93.571	106.624	158.490	24.81
	110	3204.7	459.0	158.010	93.831	106.496	158.624	25.09
	115	3275.1	469.1	158.045	93.701	106.186	158.519	25.20

Table A-8 (continued)

z/d_h	ΔH mm.H_2O	Re	Gz	$t_{w,o}$ °F	t_o °F	t_f °F	$t_{w,f}$ °F	Nu_1
12.14	30	1726.5	104.4	157.316	89.417	110.085	157.652	9.45
	40	1982.1	119.9	157.542	89.483	109.658	157.929	10.51
	50	2207.7	133.6	157.825	89.279	109.145	158.165	11.40
	60	2415.3	146.2	157.924	89.416	108.771	158.347	12.09
	70	2603.1	157.5	157.149	89.192	108.098	157.564	12.79
	80	2780.4	168.3	157.270	89.258	107.714	157.706	13.27
	90	2940.5	178.0	157.276	89.498	107.500	157.672	13.68
	100	3086.4	186.8	157.056	89.279	106.976	157.483	14.08
	110	3218.4	194.8	157.114	89.558	106.784	157.544	14.24
	115	3289.7	199.1	156.981	89.401	106.528	157.449	14.49

Sample of calculation

For an equilateral triangular duct of $z/d_h = 5.04$

At a differential pressure, $\Delta H = 25$ mm. H_2O.

Available data

Perimeter, P	= 5.07825	in.
Cross sectional area, A_c	= 1.239	$in.^2$
Total length, L	= 4.92	in.
Volume rate of flow, V	= 1608	litres/h.
Initial bulk temperature, t_o	= 98.284	deg.F.
Final bulk temperature, t_f	= 116.737	deg.F.
Initial wall temperature, $t_{w,o}$	= 157.274	deg.F.
Final wall temperature, $t_{w,f}$	= 156.842	deg.F.

Hydraulic diameter, $d_h = 4A_c/P = \frac{4 \times 1.239}{5.07825} = 0.97593$ in.

Mean velocity of the air, $w_b = \frac{144V}{28.316A_c} = \frac{144 \times 1608}{28.316 \times 1.239}$

$= 6600.02$ ft/h.

Logarithmic mean temperature difference,

$$\Delta t_1 = \frac{(t_{w,o}-t_o) - (t_{w,f}-t_f)}{\ln\frac{(t_{w,o}-t_o)}{(t_{w,f}-t_f)}}$$

$$= \frac{(157.274 - 98.284) - (156.842 - 116.737)}{\ln\frac{(157.274 - 98.284)}{(156.842 - 116.737)}}$$

$= 48.423$ deg.F.

Average wall temperature, $t_w = \frac{t_{w,o} + t_{w,f}}{2}$

$= \frac{157.274 + 156.842}{2}$

$= 157.058$ deg.F.

Since $\Delta t_1 = (t_w - t_b)_1$

Thus the bulk temperature, $t_b = t_w - \Delta t_1$

$= 157.058 - 48.423$

$= 108.635$ deg.F.

The values C_p, μ, k and ρ are estimated from the bulk temperature, $t_b = 108.635$ deg.F, that is

$C_p = 0.25$ Btu/lb-°F,

$\mu = 0.04647$ lb/ft-h,

$k = 0.01583$ Btu/h-ft^2-°F/ft,

and $\rho = 0.06981$ lb/ft^3.

Thermal diffusivity, $\alpha = k/\rho C_p = \frac{0.01583}{0.06981 \times 0.25}$

$= 0.907$

Prandtl number, $Pr = C_p\mu/k = \frac{0.25 \times 0.04647}{0.01583}$

$= 0.7338$

Reynolds number, $Re = \frac{d_h w_b \rho}{\mu}$

$= \frac{0.97593 \times 6600.02 \times 0.06981}{12 \times 0.04647}$

$= 806.40$

$$\text{Graetz number, } G_z = \frac{R_e P_r}{(z/d_h)}$$

$$= \frac{806.40 \times 0.7338}{5.04}$$

$$= 117.41$$

From eq. (8) in section 1.3, Nusselt number

$$Nu_1 = \frac{1}{4} \cdot \frac{w_b d_h^2}{\propto L} \cdot \frac{(t_f - t_c)}{\Delta t_1}$$

$$= \frac{1}{4} \cdot \frac{6600.02(0.97593)^2 12}{0.907 \times 4.92 \times 144} \cdot \frac{(116.737-98.284)}{48.423}$$

$$= 11.18$$

Appendix B

Air flow measurements

B-1 Air flow measurement using an orifice meter

There are several types of fluid flow-measuring device such as orifice meter, flow nozzle, venturi tube, for instance, they are however based on the same principle. Detailed informations on such device may be found elsewhere in the literature.[1] Many investigators are often faced with the question of which type of flow-measuring device should be suited for their purposes. In this investigation the orifice was selected because it had the merit that it could be installed in a pipeline with a minimum of trouble and expense. In addition, it was easy and convenient to construct all components. In view of the fact that the flow of air fell well with Reynolds number not more than 4000, the effect of frictional resistance offered by it would not be so important to consider. And the pressure difference between the orifice plate was also small relative to the total pressure, therefore, the compressibility of air could be ignored.

For an orifice the flow equation, which may be found in many fluid mechanics text books, is derived from the two

---

[1]See, for example, Howard S. Beam, Fluid Meter: Their Theory and Application (6th ed., The American Society of Mechanical Engineers, N.Y., 1971).

principle equations, namely, the continuity and energy equations. The following expressions may be obtained, i.e.,

$$V = \frac{CA_0}{\sqrt{1 - (D_0/D_1)^2}} \sqrt{2g_0(P_1/\gamma + Z_1 - P_2/\gamma - Z_2)} \qquad \text{....(B-1)}$$

where V = Volume rate of flow,

C = Coefficient,

A_0 = Area of the orifice,

D_0 = Diameter of the orifice,

D_1 = Diameter of the pipe,

P_1 = Upstream pressure,

P_2 = Downstream pressure,

Z_1 = Upstream elevation,

Z_2 = Downstream elevation,

γ = Specific weight,

g_0 = Acceleration of gravity.

For a given meter all dimensions are known and constant. Though C varies with the rate of flow, the variation is very small and eq.(B-1) for a particular meter will reduce to the following form,

$$V = K\sqrt{(P_1/\gamma + Z_1) - (P_2/\gamma + Z_2)} \qquad \text{....(B-2)}$$

where K = constant.

It is convenient to express the terms $(P_1/\gamma+Z_1)$ - $(P_2/\gamma+Z_2)$ as (H_1-H_2) or ΔH, the different head. Hence eq.(B-2) becomes

$$V = K\sqrt{\Delta H} \qquad \text{....(B-3)}$$

It is of some interest to concluded that the volume rate of flow varies directly as the square root of the different head.

The orifice has been calibrated against standard gas meter with various measurable flow rates. Detailed informations may be found in Chapter II. The results obtained are presented graphically in Figs.B-1 and B-2

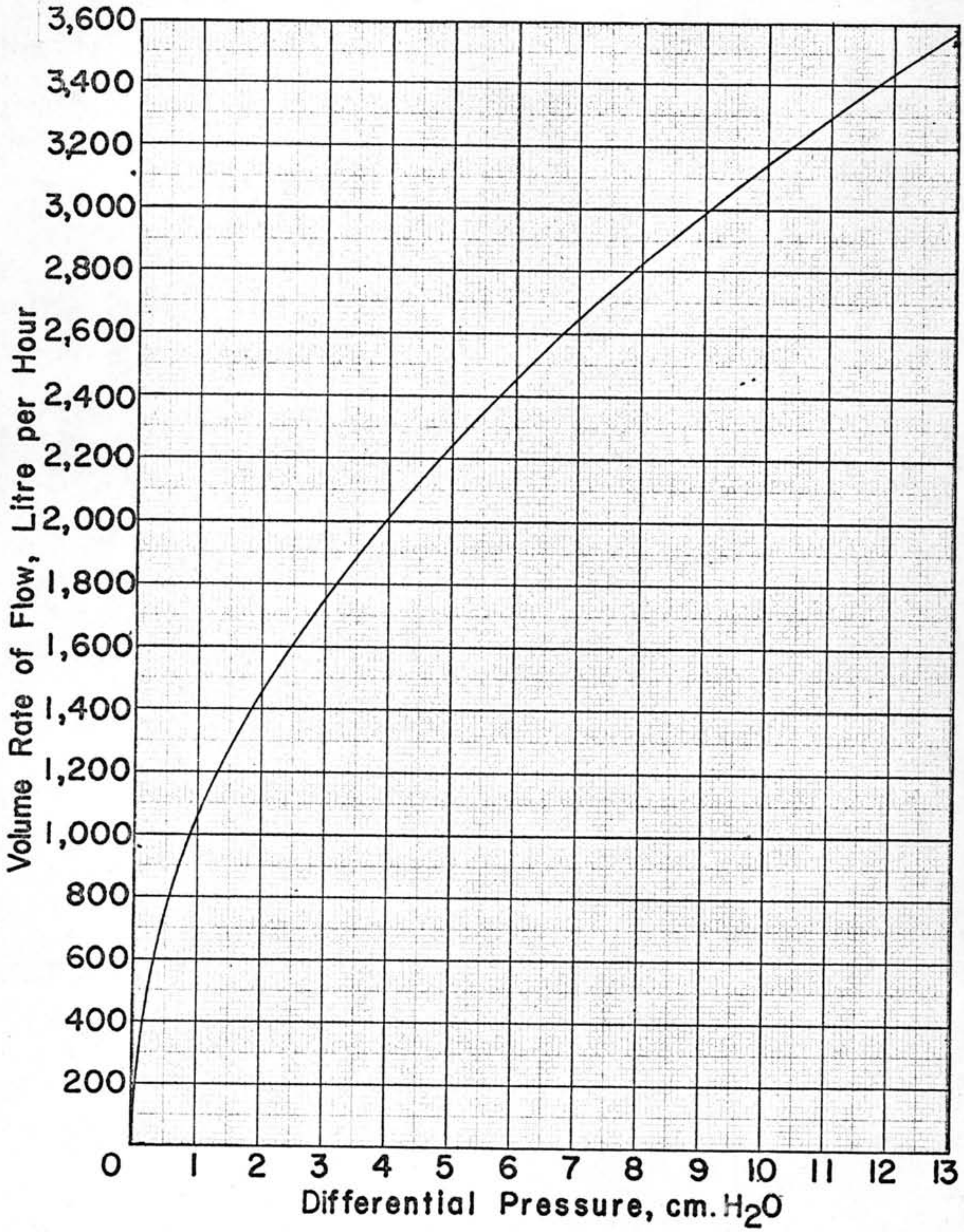

Fig.B-1 Orifice Meter Calibration Curve for Laminar Region.

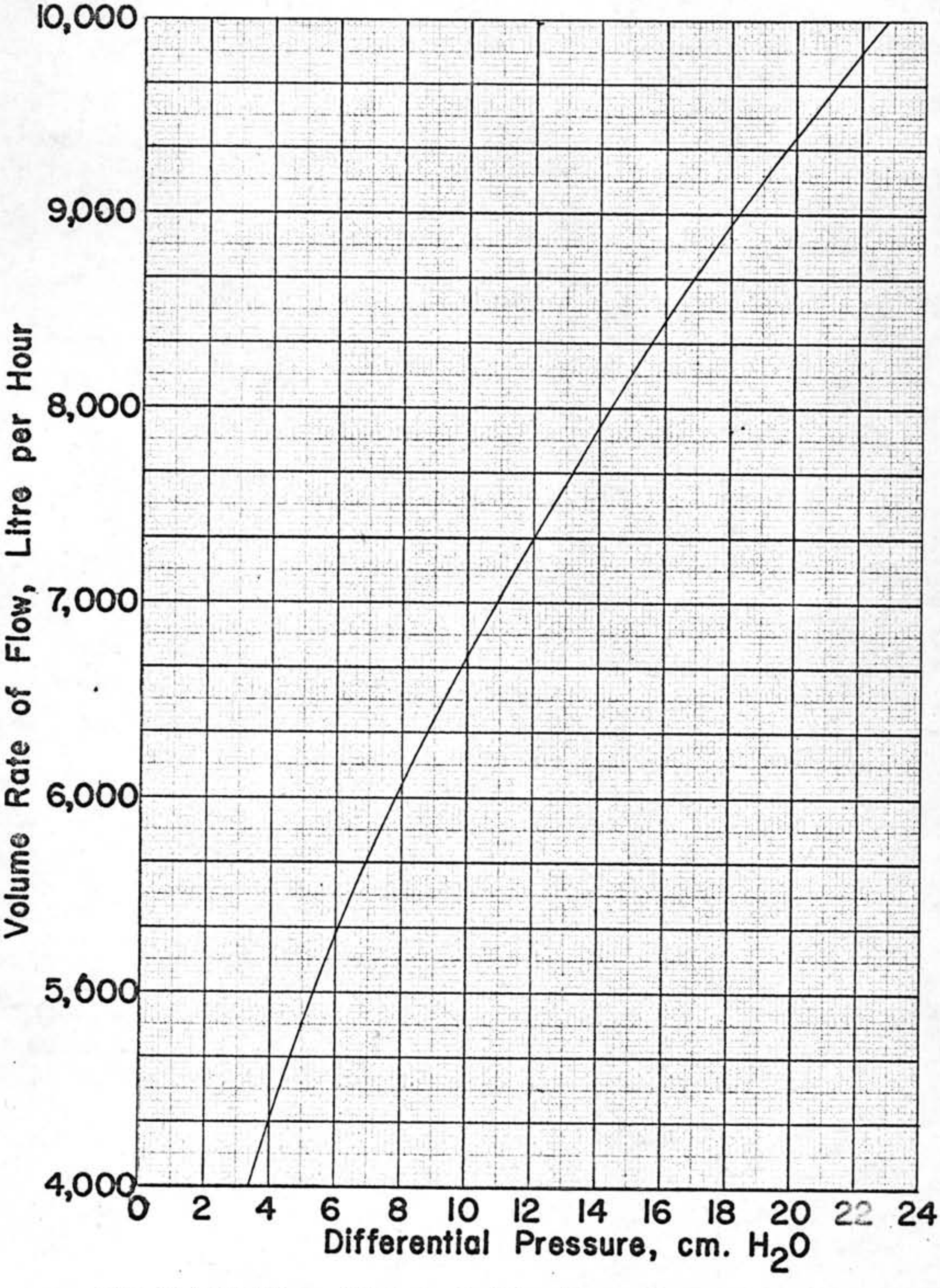

Fig. B-2 Orifice Meter Calibration Curve for Transition Region.

VITA

Name of student	Mr. Peerapong Tangsirimonkol
Qualification	Bachelor of Engineering
Institute	Chulalongkorn University
Graduated Year	1972
Office	Mahaguna Distillery, Co. Ltd, Department of Engineering, Unit of Boiler
Position	Assistant Engineer