CHAPTER 5

RESULTS AND DISCUSSIONS

The results and discussions of five sets of heat transfer experiments using various liquids and varying flow rates are presented in this chapter.

5.1. Equal water/water flow rates.

In this set of experiments all of the fluids used is tap water set at equal flow rates. Thus it is reasonable to assume that the flim heat transfer coefficient of the cold fluid essentially equals that of the hot one, and that heat transfer resistances caused by fouling is negligible [23].

The overall heat transfer coefficient U is obtained directly from the average heat transfer rate and the log mean temperature difference. That is

$$U = \frac{Q_{average} \; \Delta T_{lm}}{A} \qquad (5-1)$$

Based on the above definition and assumptions the film heat transfer coefficient may be calculated as

$$U = \frac{1}{\frac{2}{h} + \frac{x_p}{k_p}} \tag{5-2}$$

The experimental data obtained are analyzed to obtain the average heat transfer rate ($Q_{average}$), log meen temperature difference (ΔT_{lm}), Nusselt number (Nu), Reynolds number (Re), Prandtl number (Pr) and overall heat transfer coefficients (U) with the aid of program 1, as illustated in appendix A1. In short, program 1 uses the physical properties of water (shown in appendix B1) and calculates, for each section of the plate heat exchanger, $Q_{average}$, ΔT_{lm}, Nu, Pr and U from the inlet and outlet temperatures, and the flow rates of the respective section.

The heat transfer correlation used in this study is a relationship between Nu, Re and Pr as follows:

$$Nu = k\ Re^{a}\ Pr^{b} \tag{5-3}$$

Rearranging eqn. (5-3) we obtain

$$\frac{Nu}{Pr^{b}} = k\ Re^{a} \tag{5-4}$$

Afer taking the logarithm we obtain

$$\log(\ Nu/Pr^{b}\ ) = \log k + a \log Re \tag{5-5}$$

Equation (5-5) indicates that $\log(Nu/Pr^b)$ is linearly related to log Re. If the value of b is known a priori, the linear regression analysis method can be used to estimate the best values of parameters (constants) a and log k (or k). The optimal value of b is estimated by the trial-and-error method, in which the assumed value of b is varied essentially continuously to see which value of b yields the best fit to the experimental data by performing the linear regression analysis for each assumed value of b. More specifically, the experimental data expressed in terms of Nu, Re and Pr with the aid of program 1 are next used to estimate the values of constants (parameters) a, b and k of equation (5-5) through the linear regression method shown in program 2 (appendix A2). Program 2 thus estimates the optimal values of the constants a, b, and k, using the sum of least square, $\in$ as the optimization criteria.

In one approach, the value of b is set equal to 0.4 in advance, so as to be the same as several correlations found in the literature [4]. The typical correlation found in the literature is

$$Nu_{the} = 0.2\ Re^{0.67}\ Pr^{0.4} \qquad (5\text{-}6)$$

where Nu_{the} is the Nusselt number.

In a more general approach, the coefficient b is estimated simultaneously along with k and a. In this case, the estimated value of b can be quite different from that of the various correlations found in the literature. Table 5.1 lists, as function of Re and Pr, the experimental value of Nu(Nu_{exp}), the theoretical value of Nu given by correlation (5-6) (Nu_{the} or Nu(the)), the

Table 5.1 Experimental and estimated values of the Nusselt number.

System: Equal water/water flow rates.

T10(°C)	Flow(LPM)	Section	Re	Pr	Nu(exp)	Nu(o)	Nu(of)	Nu(the)	Nu(to)	Nu(tof)
98		3	409.05	4.89	23.01	17.73	17.63	21.21	12.91	20.62
	2	1	638.27	3.00	15.73	13.81	19.43	23.50	12.97	21.65
		2	846.65	2.00	9.84	10.33	19.89	24.14	12.09	21.50
		3	602.90	4.99	32.47	26.39	22.94	27.72	18.37	25.72
	3	1	944.89	3.04	22.74	20.52	25.31	30.75	18.47	27.03
		2	1255.46	2.02	16.20	15.31	25.92	31.58	17.19	26.83
		3	795.83	5.04	32.52	34.95	27.67	33.54	23.59	30.09
	4	1	1240.75	3.09	30.82	27.24	30.49	37.14	23.71	31.60
		2	1658.75	2.04	19.33	20.23	31.25	38.19	22.05	31.38
		3	987.16	5.08	41.31	43.44	31.99	38.37	28.63	33.99
	5	1	1545.09	3.11	35.27	33.83	35.30	43.11	28.80	35.72
		2	2058.52	2.05	29.08	25.13	36.13	44.27	26.76	35.44
		3	1193.74	5.04	50.27	51.52	36.14	44.01	33.56	37.61
	6	1	1832.83	3.14	45.74	40.47	39.69	48.56	33.72	39.42
		2	2430.47	2.09	29.60	30.14	40.58	49.30	31.32	39.08
		3	1364.49	5.15	59.74	60.36	39.82	48.56	38.35	40.84
	7	1	2097.30	3.21	48.78	47.45	43.75	53.61	38.56	42.82
		2	2792.87	2.12	33.76	35.18	44.75	55.01	35.78	42.45
		3	1443.17	5.23	74.41	65.00	41.56	50.72	40.74	42.57
	7.5	1	2251.40	3.21	55.44	50.63	45.81	56.17	40.95	44.49
		2	3001.42	2.11	36.34	37.51	46.36	57.65	37.99	44.11

Table 5.1 (continued)

T10(°C)	Flow(LPM)	Section	Re	Pr	Nu(exp)	Nu(o)	Nu(of)	Nu(the	Nu(to)	Nu(tof)
85		3	383.85	5.24	18.61	18.37	17.38	20.91	12.90	20.47
	2	1	566.71	3.41	15.12	14.75	18.93	22.86	12.95	21.37
		2	725.19	2.35	10.44	11.18	19.19	23.24	12.01	21.09
		3	572.84	5.28	24.18	27.18	22.69	27.41	18.36	25.58
	3	1	850.06	3.41	23.58	21.75	24.72	30.00	18.43	26.70
		2	1091.61	2.35	18.55	16.46	25.09	30.53	17.10	26.37
		3	763.78	5.28	32.71	35.79	27.42	33.23	23.58	29.97
	4	1	1128.87	3.43	31.54	28.69	29.86	36.33	23.67	31.26
		2	1441.81	2.37	30.37	21.79	30.26	36.93	21.96	30.86
		3	954.73	5.28	41.51	44.32	31.77	38.59	28.64	33.88
	5	1	1399.64	3.46	39.07	35.66	34.52	42.11	28.72	35.31
		2	1789.64	2.39	26.96	27.05	34.99	42.60	26.64	34.85
		3	1139.65	5.31	59.96	52.97	35.79	43.56	33.57	37.44
	6	1	1169.23	3.48	44.62	30.27	30.73	37.42	24.68	32.06
		2	2136.83	2.40	31.87	32.27	39.41	48.30	31.20	38.49
		3	1308.96	5.41	60.10	62.05	39.51	48.16	38.43	40.71
	7	1	1923.54	3.52	52.87	49.62	42.89	52.50	38.44	42.37
		2	2468.63	2.42	37.61	37.59	43.52	53.42	35.67	41.85
		3	1402.45	5.41	64.90	66.28	41.34	50.43	40.81	42.28
	7.5	1	2048.27	3.55	59.44	53.21	44.82	54.91	40.82	43.99
		2	2614.86	2.45	41.64	40.35	45.41	55.78	37.84	43.39

Table 5.1 (continued)

T10(°C)	Flow(LPM)	Section	Re	Pr	Nu(exp)	Nu(o)	Nu(of)	Nu(the)	Nu(to)	Nu(tof)
75		3	412.11	4.85	15.71	17.65	17.65	21.25	12.91	20.63
	2	1	552.98	3.50	18.08	14.91	18.81	22.71	12.93	21.29
		2	665.55	2.58	9.35	11.69	18.81	22.76	11.97	20.87
		3	616.61	4.86	18.42	26.05	23.05	27.86	18.36	25.78
	3	1	826.03	3.51	23.12	22.02	24.54	29.77	18.39	26.59
		2	996.23	2.59	13.20	17.25	24.56	29.85	17.04	26.07
		3	818.09	4.89	32.38	34.41	27.83	33.75	23.59	30.18
	4	1	1096.80	3.53	30.81	29.05	29.64	36.06	23.61	31.13
		2	1314.96	2.62	21.14	22.90	29.64	36.14	21.91	30.53
		3	1030.26	4.85	41.04	42.41	32.29	39.26	28.64	34.15
	5	1	1359.73	3.56	33.92	36.15	34.27	41.79	28.67	35.17
		2	1640.16	2.62	22.03	28.37	34.32	41.94	26.59	34.50
		3	1205.81	4.99	32.47	51.24	36.22	44.11	33.57	37.66
	6	1	1611.32	3.61	46.93	43.35	38.54	47.09	33.60	38.82
		2	1941.05	2.67	26.70	34.10	38.60	47.26	31.19	38.10
		3	1403.24	5.00	59.49	59.47	40.07	48.88	38.39	40.98
	7	1	1875.88	3.62	59.84	50.27	42.64	52.18	38.41	42.24
		2	2249.41	2.69	32.68	39.72	42.68	52.34	35.69	41.46
		3	1495.93	5.03	80.68	63.70	41.89	51.13	40.75	42.54
	7.5	1	1984.62	3.68	53.32	54.20	44.52	54.52	40.82	43.84
		2	2375.67	2.74	33.88	42.82	44.54	54.65	37.91	43.01

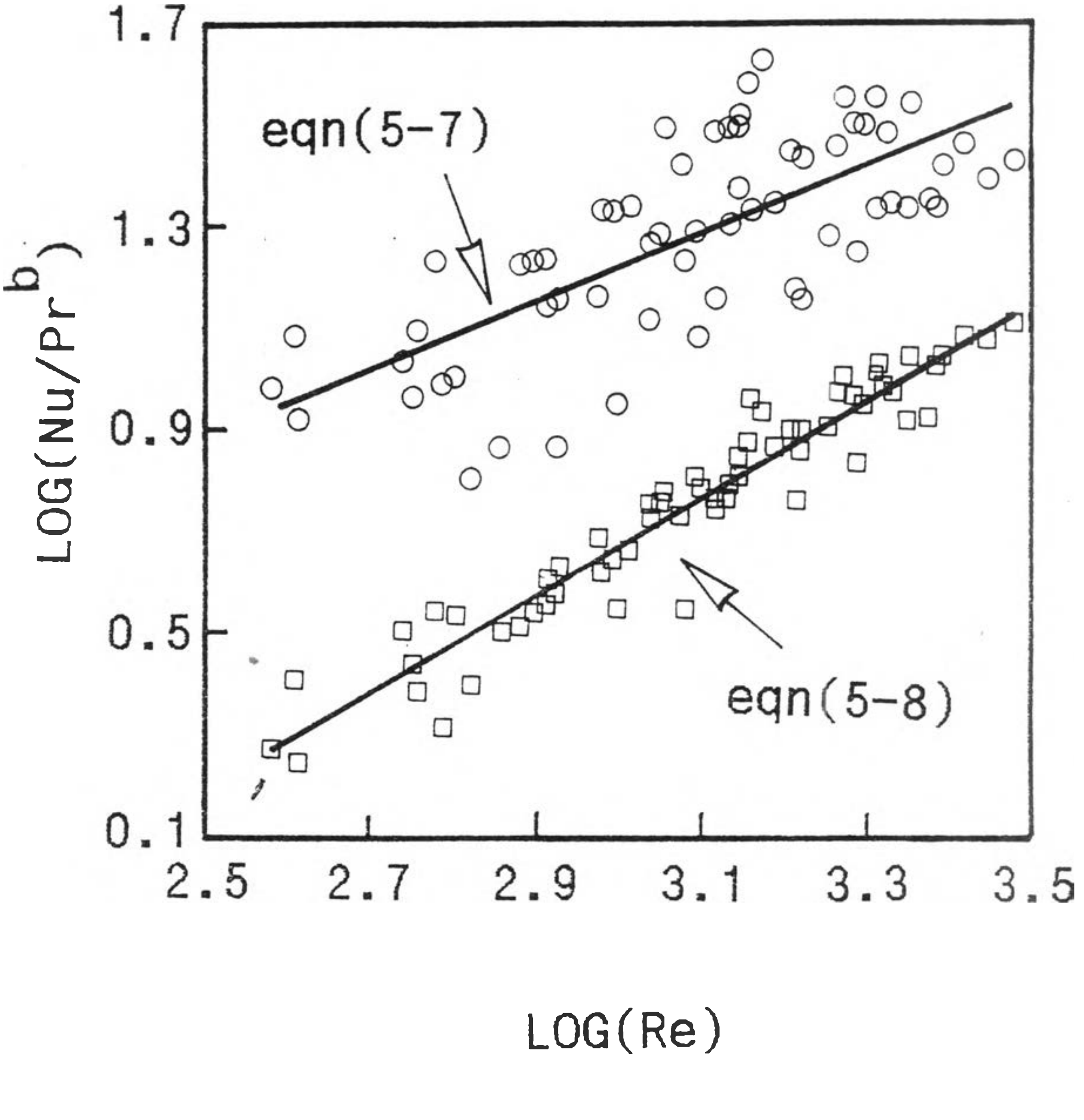

Figure 5.1 Experimental results for the case of equal water/water flow rates; (at hot water temperature ,T10 = 98, 85, and 75 °C , ○ : b = 0.4, □ : b = 1.39).

value of Nu predicted by correlation (5-7) (Nu_{of} or Nu(opt.f), and the value of Nu predicted by correlation (5-8) (Nu_o or Nu (o)). As explained later, correlation (5-7) is obtained by assuming that the exponent b in eqn.(5-5) must be equal to 0.4; whereas, correlation (5-8) is obtained without any assumption on the value of b. The meanings of Nu(to) and Nu(tof) in Table 5.1 will be explained later. Based on the 63 experimental data points listed in Table 5.1, in which Re = 383 - 3,006 and Pr = 2.11 - 5.41, the following correlations have been obtained.

Constrained linear regression analysis (b set at 0.4):

$$Nu_{of} = 0.18\ Re^{0.66}\ Pr^{0.4} \quad \text{with } \sigma = 0.147 \qquad (5\text{-}7)$$

Unconstrained linear regression analysis:

$$Nu_{o} = 0.006\ Re^{0.96}\ Pr^{1.38} \quad \text{with } \sigma = 0.062 \qquad (5\text{-}8)$$

where σ is the sample standard deviation equal to $\sqrt{\epsilon^2/n}$ where n is the number of experimental points.

Fig. 5.1 shows the experimental results obtained with equal flow rates of water and water streams. The horizontal axis is log (Re), and the vertical axis is log(Nu/Pr^b). The symbol ○ is for exponent b = 0.4, and □ for b = 1.38. Also shown in Fig. 5.1 are the two correlations obtained by constrained (b = 0.4) and unconstrained (b = 1.38 here) linear regression analysis. It is obvious that the latter case, i.e. eqn (5-8), fits the experimental data better than the former, i.e. eqn (5-7). The same conclusion is also obvious when one looks at Table 5.1

Figs. 5-2-5.4 graphically compare Nu_{exp}, the experimental value of Nu, with Nu_{the}, the theoretical value of Nu given by eqn (5-6), Nu_{of}, the value of Nu predicted by constrained correlation (5-7), and Nu_{o}, the value of Nu predicted by unconstrained correlation (5-8), respectively. Here again correlation (5-8) obviously fit the data best, since the relationship between Nu predicted and Nu_{exp} lies most closely to the dotted diagonol line.

In summary, it may be concluded that, for the case of equal flow rates of water and water streams, the correlation (5-8) gives the most reliable predictions of the water film heat transfer coefficient expressed in terms of Nu.

Table 5.2 lists the experimental value of the overall heat transfer coefficient, U_{exp}, the value of U, U_{of} or U (of), predicted by correlation (5-7), the value of U, U_{o} or U(o) predicted by correlation (5-8), and the theoretical value of U, U_{the} or U(the), given by correlation (5-6). Again it is obvious that correlation (5-8) gives the best fit for the overall heat transfer coefficient.

Figs 5.5-5.7 graphically compare respectively the pairs of U_{exp} and U_{the}, U_{exp} and U_{of}, and U_{exp} and U_{o}. As mentioned above, correlation (5-8) as represented by Fig. 5-7 gives the best fit for the overall heat transfer coefficient U.

5.2. Unequal water/water flow rates

In this set of experiments the flow rates of the hot and cold streams are generally different. The program 3, which is modified from program 1, as shown in appendix A3. With the aid of

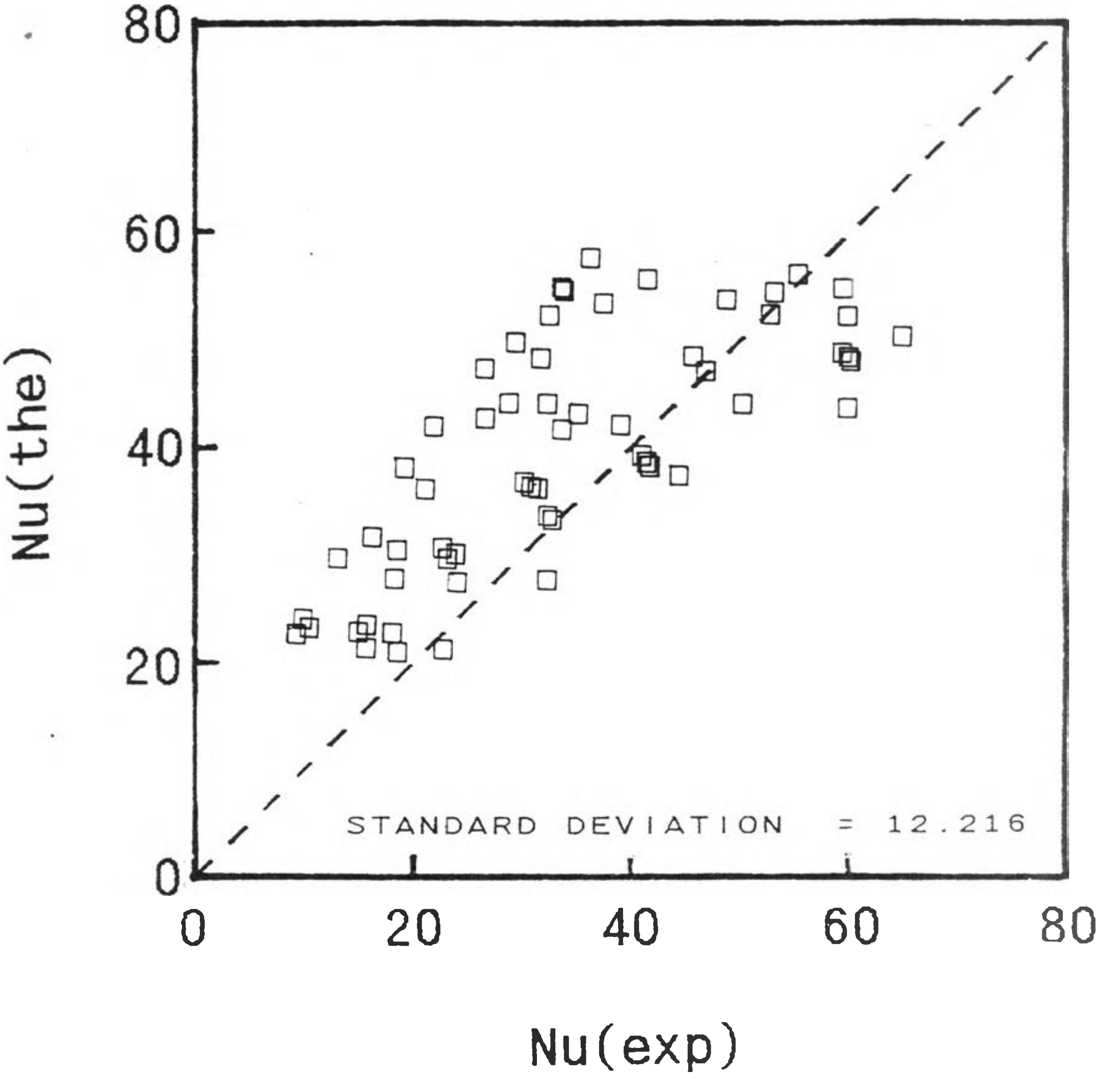

Figure 5.2 Comparison between Nu_{exp}, the experimental value of the Nusselt number and Nu_{the}, the theoretical value based on eqn(5-6) for the case of equal water/water flow rates.

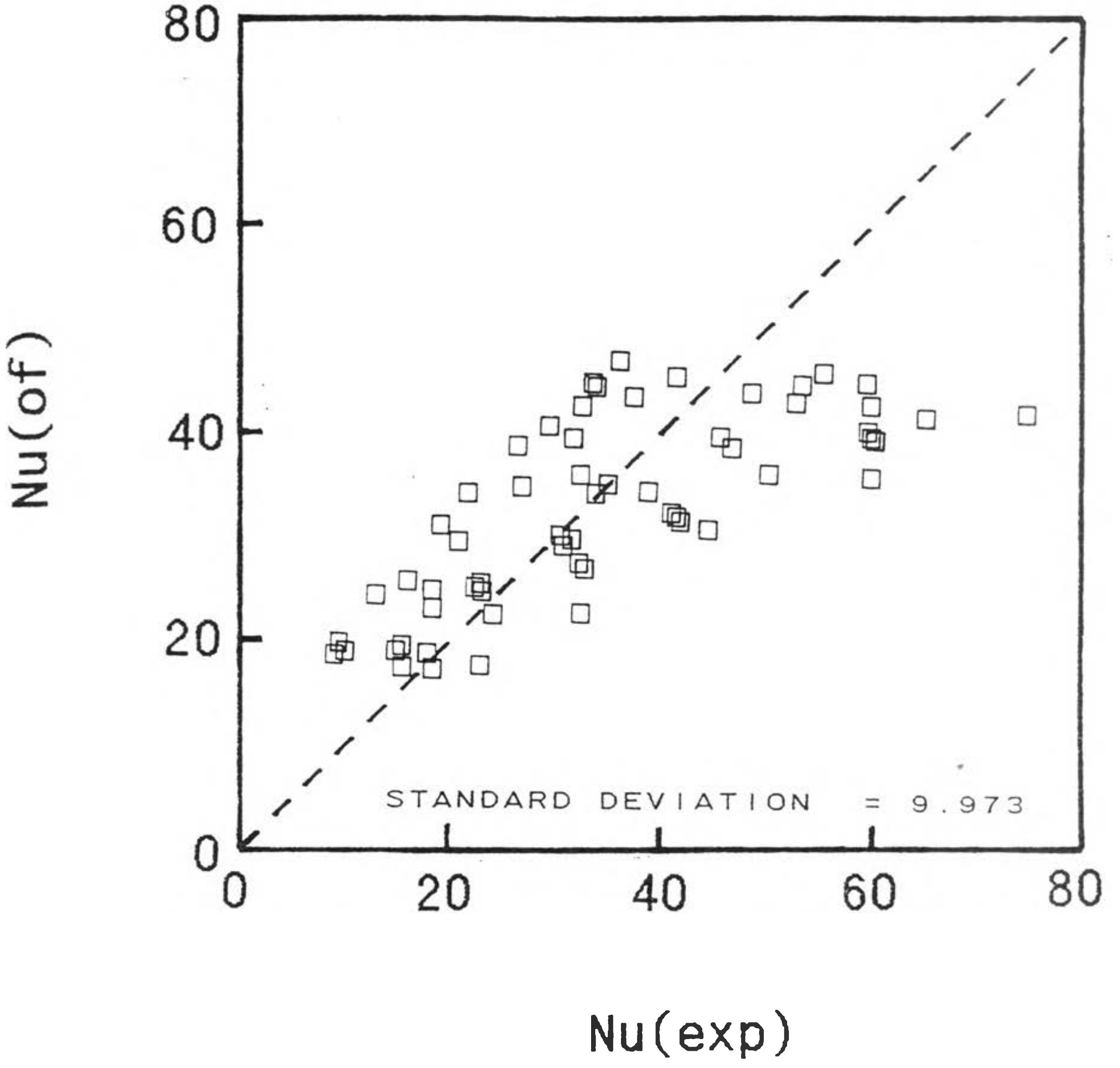

Figure 5.3 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-7) for the case of equal water/water flow rates.

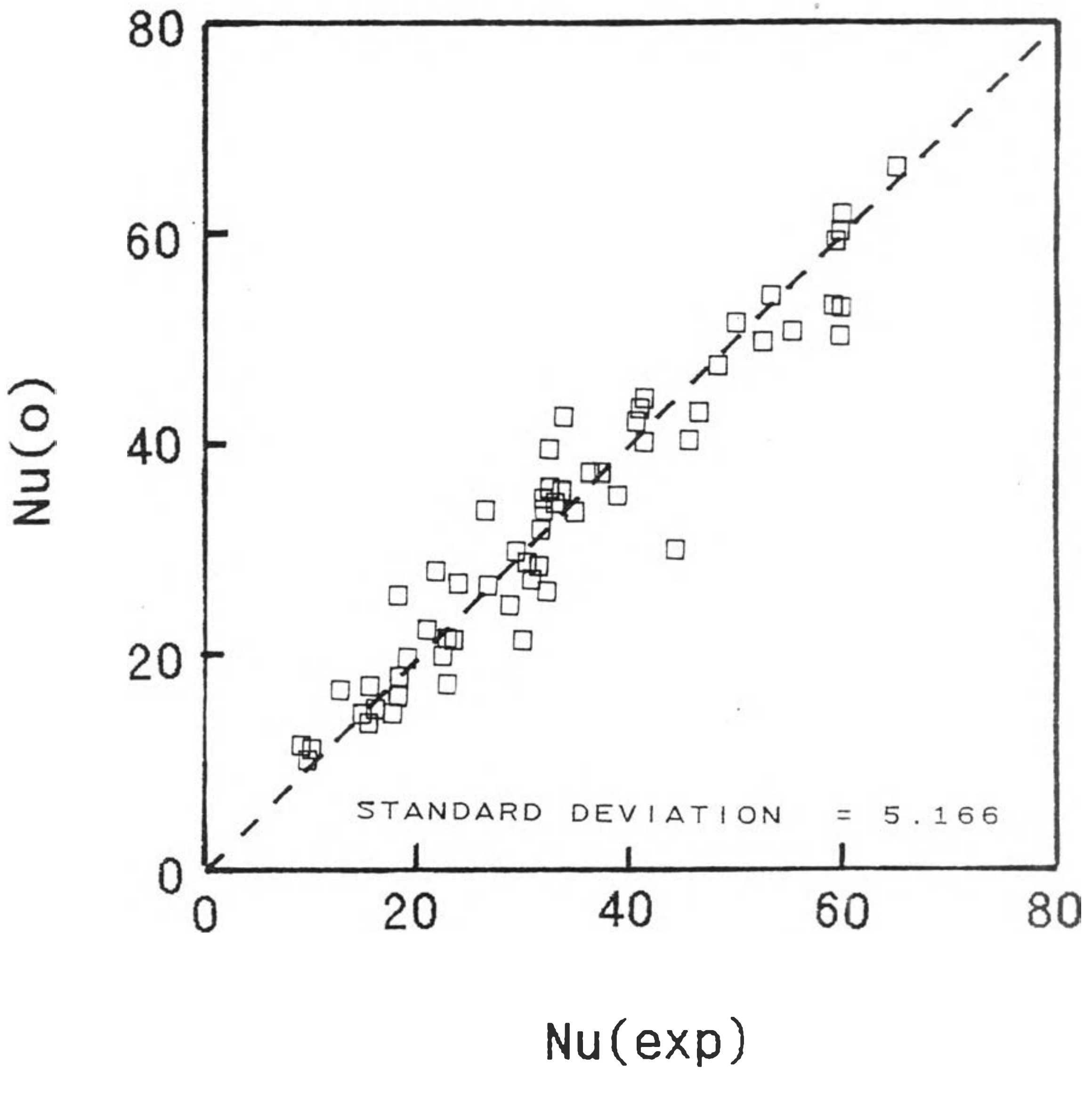

Figure 5.4 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-8) for the case of equal water/water flow rates.

Table 5.2 Experimental and estimated values of overall heat transfer coefficient.

System: Equal water/water flow rates.

T10(°C)	Flow(LPM)	Section	U(exp)	U(of)	U(o)	U(the)	U(tof)	U(to)
98		3	3236.88	1924.40	2894.26	2292.94	1959.17	1889.03
	7.5	1	2614.32	2209.62	2421.01	2642.56	2151.09	1992.25
		2	1832.65	2324.88	1893.02	2789.48	2199.38	1915.80
		3	2665.67	1844.57	2701.45	2207.12	1888.71	1781.21
	7	1	2327.17	2115.77	2279.18	2532.69	2074.27	1882.08
		2	1710.47	2227.29	1781.73	2673.66	2121.92	1810.44
		3	2284.36	1682.40	2336.70	2021.30	1746.58	1569.28
	6	1	2197.82	1930.57	1966.03	2319.26	1918.46	1657.95
		2	1512.66	2034.13	1539.87	2445.28	1964.61	1597.07
		3	1904.05	1498.29	1995.03	1799.14	1586.54	1348.64
	5	1	1728.76	1729.93	1662.01	2080.61	1749.21	1428.22
		2	1488.71	1825.73	1296.27	2197.31	1792.92	1376.10
		3	1523.24	1306.89	1630.31	1568.22	1415.66	1122.08
	4	1	1523.24	1505.73	1353.32	1813.17	1557.40	1185.52
		2	1008.44	1591.95	1052.37	1917.87	1598.11	1143.01
		3	1523.24	1089.46	1245.97	1311.33	1215.62	879.31
	3	1	1142.43	1259.41	1029.83	1520.44	1340.39	930.52
		2	850.87	1332.24	802.95	1605.79	1376.60	898.20
		3	1100.12	843.47	848.05	1017.46	981.40	622.85
	2	1	801.69	977.37	701.79	1179.22	1084.60	660.53
		2	523.61	1034.70	547.02	1245.42	1114.56	637.90

Table 5.2 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(of)	U(o)	U(the)	U(tof)	U(to)
85		3	2856.07	1898.30	2920.09	2272.51	1938.24	1875.25
	7.5	1	2759.36	2141.81	2505.42	2566.87	2104.84	1964.46
		2	2057.05	2235.04	2004.00	2678.81	2143.46	1888.03
		3	2665.67	1818.30	2750.56	2178.08	1869.72	1771.88
	7	1	2483.95	2056.21	2351.15	2465.77	2033.45	1857.67
		2	1873.37	2149.93	1876.51	2578.79	2073.53	1787.31
		3	2665.67	1657.77	2383.19	1989.68	1729.25	1560.90
	6	1	2129.10	1875.71	2041.01	2252.96	1881.69	1639.00
		2	1605.75	1959.91	1626.22	2354.90	1917.60	1575.58
		3	1904.05	1481.66	2023.30	1778.79	1574.38	1342.85
	5	1	1883.90	1677.54	1729.29	2017.54	1713.49	1410.58
		2	1371.37	1753.56	1375.49	2108.34	1746.73	1355.36
		3	1523.24	1287.73	1656.82	1545.83	1400.93	1114.83
	4	1	1542.58	1462.51	1408.33	1760.32	1527.57	1172.44
		2	1535.93	1529.25	1118.50	1839.08	1557.46	1126.84
		3	1142.43	1071.80	1274.07	1287.68	1202.40	874.02
	3	1	1170.24	1220.85	1079.47	1470.39	1313.81	920.64
		2	959.96	1279.07	852.79	1539.60	1341.05	884.37
		3	888.56	828.84	874.38	994.16	970.93	619.39
	2	1	762.43	943.89	741.27	1135.22	1060.73	653.10
		2	548.55	988.28	584.68	1188.16	1082.11	627.11

Table 5.2 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(of)	U(o)	U(the)	U(tof)	U(to)
75		3	3490.76	1940.39	2844.77	2321.53	1968.26	1891.50
	7.5	1	2493.40	2123.44	2541.34	2542.75	2093.41	1959.64
		2	1683.04	2179.64	2101.59	2607.70	2110.40	1877.62
		3	2665.67	1861.35	2673.43	2229.20	1900.46	1788.11
	7	1	2771.13	2039.62	2372.88	2447.20	2022.15	1851.02
		2	1629.02	2095.45	1960.76	2510.59	2039.87	1774.66
		3	1523.24	1692.46	2333.78	2028.53	1755.20	1575.68
	6	1	2222.69	1856.34	2070.04	2228.32	1868.95	1632.44
		2	1346.44	1907.55	1699.33	2289.28	1884.58	1562.49
		3	1904.05	1520.71	1962.79	1826.75	1603.16	1357.51
	5	1	1645.64	1661.70	1747.07	1998.52	1702.57	1404.40
		2	1122.03	1708.84	1428.25	2053.47	1717.40	1343.25
		3	1523.24	1316.28	1608.92	1583.79	1421.73	1124.01
	4	1	1504.59	1447.01	1419.80	1743.37	1515.90	1165.36
		2	1078.96	1486.30	1162.91	1787.94	1528.70	1114.72
		3	888.56	1098.82	1235.36	1321.90	1223.15	882.83
	3	1	1145.54	1209.30	1089.92	1456.28	1305.31	916.25
		2	684.73	1242.96	885.23	1495.95	1315.69	874.52
		3	761.20	849.04	848.65	1020.16	987.07	625.99
	2	1	904.27	935.11	746.71	1126.01	1053.61	649.70
		2	488.71	960.32	605.20	1155.61	1061.65	619.55

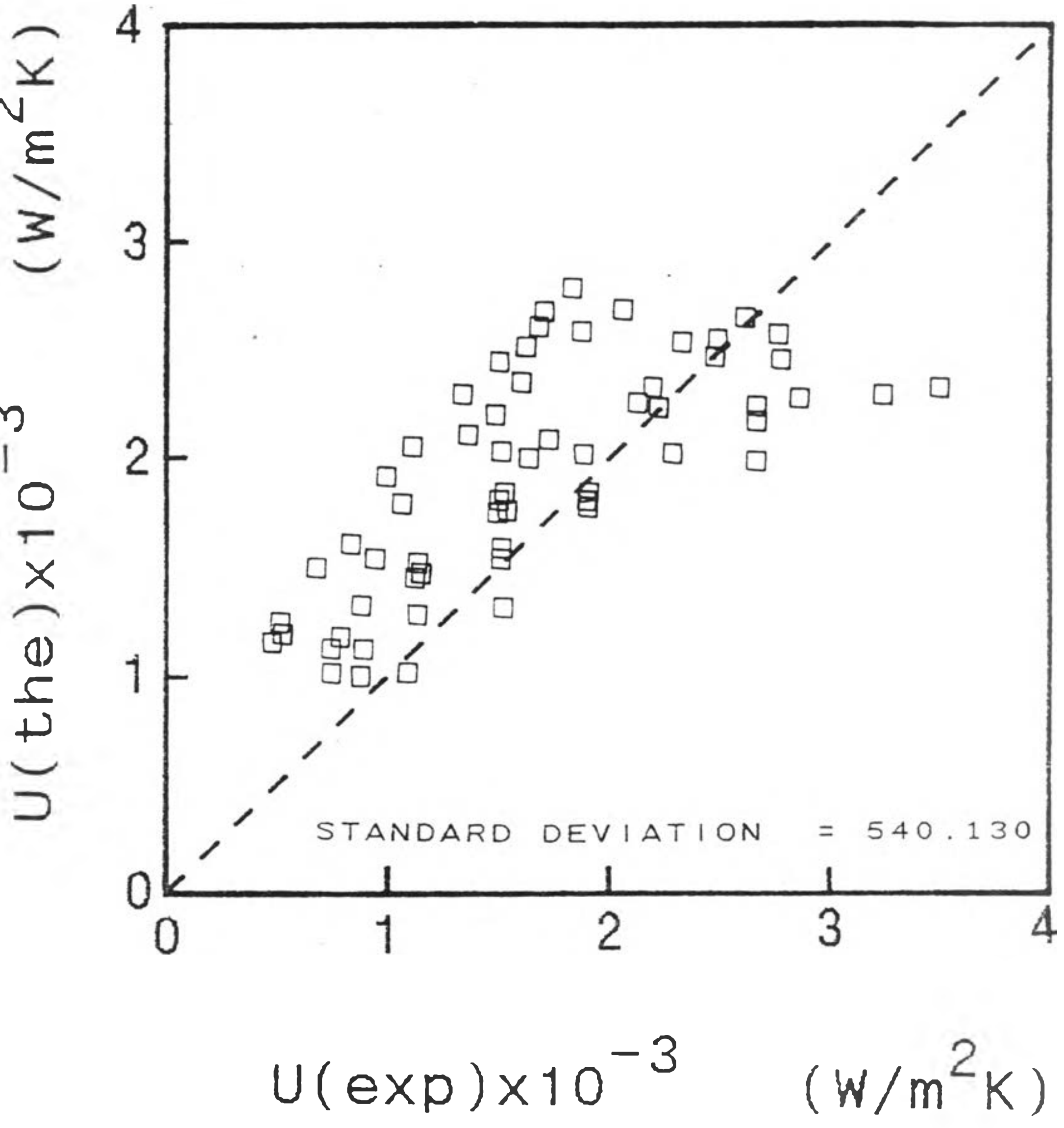

Figure 5.5 Comparison between the experimental value of the overall heat transfer coefficient and the theoretical value given by eqn(5-6) for the case of equal water/water flow rates.

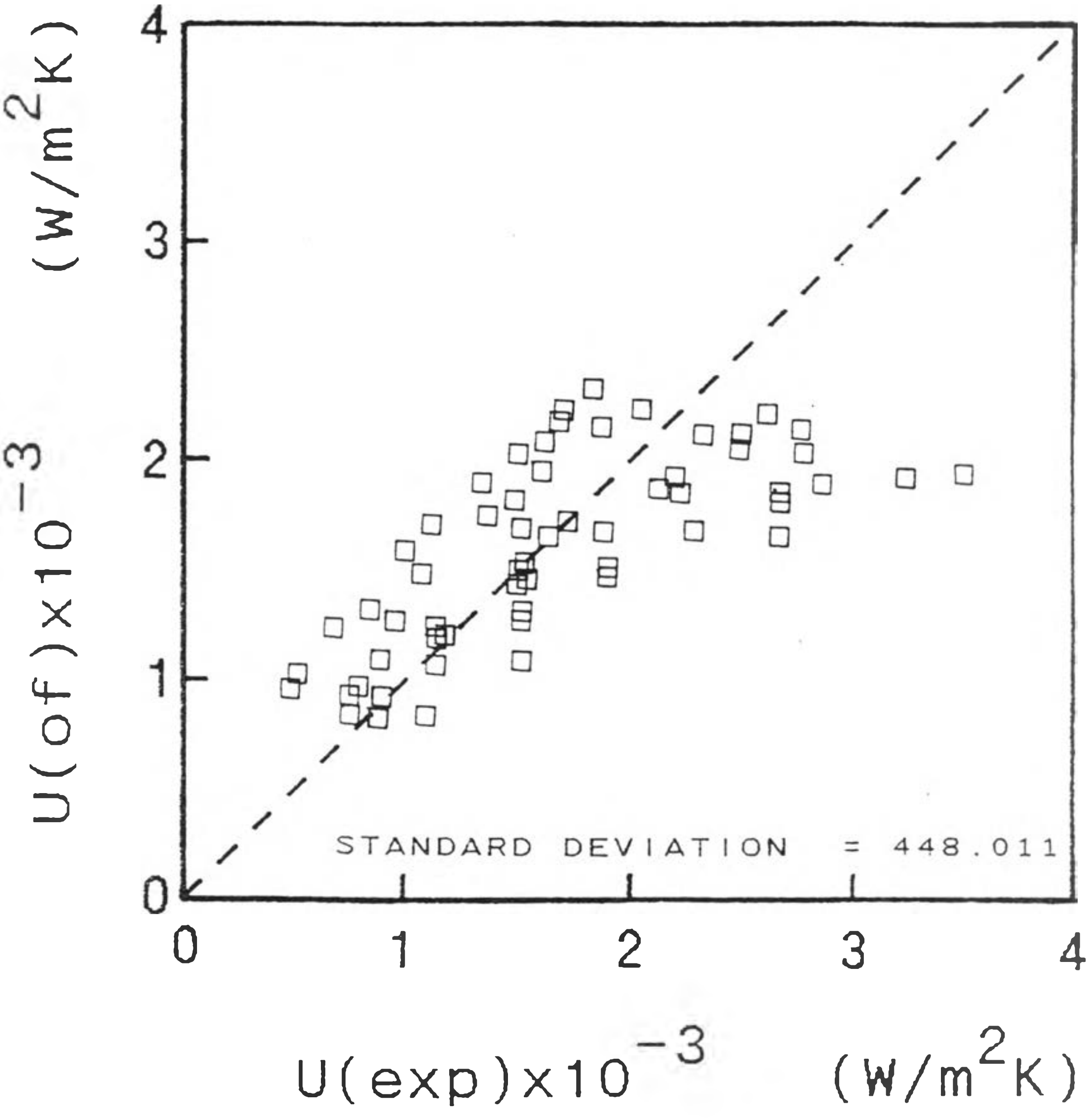

Figure 5.6 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn.(5-7) for the case of equal water/water flow rates.

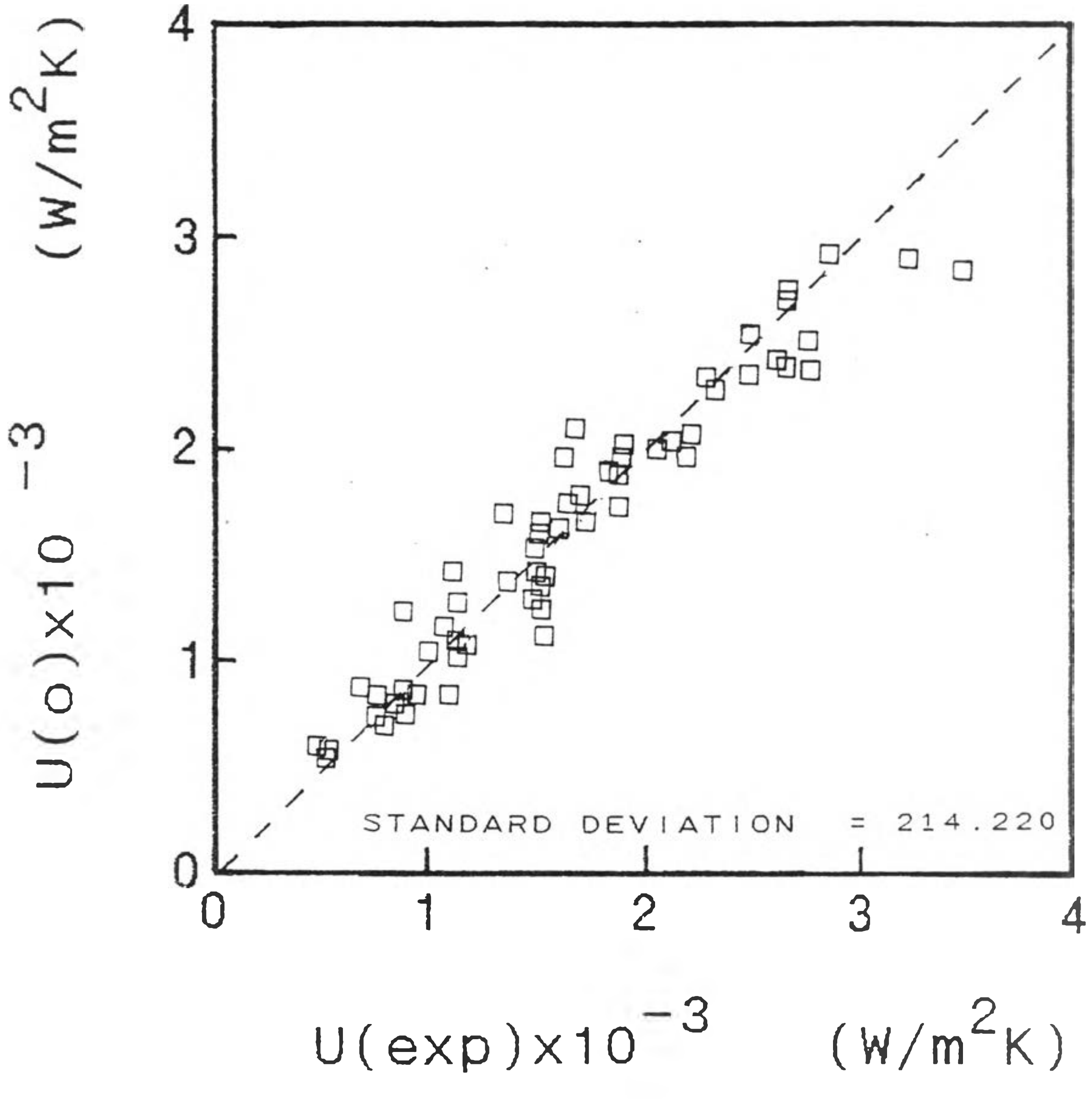

Figure 5.7 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-8) for the case of equal water/water flow rates.

this program, the experimental data are analyzed to obtain the same calculation of results as the program 1.

Tables 5.3.1-5.3.8 lists the experimental values of U_{exp} obtained for the case of unequal flow rates of water and water streams. By assuming that the theoretical correlation (5-6) as well as the two correlations (5-7) and (5-8) obtained earlier in this work are applicable to the present case, it is rather easy to calculate the values of U(the.), U(of), and U(o) based on correlations (5-6), (5-7) and (5-8), respectively. These values are listed also in Tables 5.3.1-5.3.8 for comparision with U_{exp}.

Figs. 5.8-5.15 graphically compare the U_{exp}, the experimental value of U, with respectively U_{the}, the theoretical value of U given by correlation (5-6), U_{of}, the value of U predicted by correlation (5-7), and U_{o}, the value of U predicted by correlation (5-8). It is obvious from an inspection of the figures as well as from comparing the corresponding standard deviations that correlation (5-8) gives the best fit for U_{exp}. Furthermore, it may be concluded that correlation (5-8), which is originally obtained for the case of equal flow rates of water and water streams, may be used to estimate quite satisfactorily the value of U for the case for the case of unequal flow rates. In fact the agreement is quite good in the range Re = 800-4,626 (turbulent flow region).

5.3. Equal syrup/syrup flow rates

In the previous experiments where water is used, the range of the values of the Reynolds number is wide, whereas the range of the values of the Prandtl number is fairly narrow. The liquid

Table 5.3.1 Experimental and estimated values of the overall heat transfer coefficient.
System: Unequal water/water flow rates.
Flow rate of product = 2,3,4,5,6,7 l/min
Flow rate of cooling water = Flow rate of hot water = 12 l/min

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
98		3	2919.543	2124.404	3266.383	2579.223
	7	1	2672.923	2109.835	2222.290	2567.788
		2	2210.813	2587.236	2198.818	3151.676
		3	2928.537	2006.780	3005.537	2436.201
	6	1	1896.517	1923.837	1936.073	2341.688
		2	1745.379	2462.008	2018.968	2999.850
		3	2126.676	1865.678	2712.506	2264.309
	5	1	1762.001	1721.828	1641.831	2095.659
		2	1239.219	2313.593	1811.692	2819.514
		3	1394.541	1711.333	2348.543	2076.163
	4	1	1449.495	1502.683	1337.087	1828.311
		2	1066.013	2131.149	1573.709	2597.257
		3	1080.769	1517.885	1924.318	1839.991
	3	1	1087.121	1263.305	1016.042	1535.939
		2	959.9585	1903.089	1291.742	2318.743
		3	886.4807	1262.805	1420.263	1528.144
	2	1	705.3326	981.2666	692.7902	1190.915
		2	771.6412	1596.362	957.1030	1943.112

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
85		3	3554.226	2582.253	3263.376	2582.253
	7	1	2482.316	2503.916	2303.328	2503.916
		2	1581.108	3037.351	2319.253	3037.351
		3	2393.662	2437.632	3002.801	2437.632
	6	1	2180.892	2284.656	2004.527	2284.656
		2	1675.563	2889.279	2130.826	2889.279
		3	2009.830	2270.764	2702.661	2270.764
	5	1	1982.985	2045.707	1699.806	2045.707
		2	1279.944	2714.654	1912.933	2714.654
		3	1910.495	2073.582	2351.576	2073.582
	4	1	1329.812	1786.260	1381.287	1786.260
		2	1196.831	2504.288	1657.351	2504.288
		3	1904.049	1826.662	1940.334	1826.662
	3	1	1114.942	1488.711	1064.227	1488.711
		2	850.8723	2225.544	1369.980	2225.544
		3	826.9120	1512.451	1438.451	1512.451
	2	1	760.0929	1153.733	726.9891	1153.733
		2	723.0856	1863.563	1015.135	1863.563

Table 5.3.1 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
75		3	3071.867	2101.295	3305.923	2550.816
	7	1	2373.715	2008.810	2373.658	2443.019
		2	1812.509	2418.160	2432.426	2943.206
		3	2157.923	1985.206	3041.270	2409.658
	6	1	2218.127	1831.155	2066.214	2227.043
		2	1450.007	2298.951	2232.117	2798.556
		3	2434.273	1852.683	2731.954	2248.299
	5	1	1901.632	1640.406	1749.720	1994.771
		2	1279.944	2158.478	2001.662	2627.765
		3	1634.373	1686.893	2389.701	2046.012
	4	1	1379.876	1428.092	1432.113	1735.723
		2	1020.375	1985.401	1742.858	2416.758
		3	1078.961	1486.177	1977.223	1800.800
	3	1	1023.955	1188.576	1107.473	1443.023
		2	1006.949	1765.495	1440.443	2148.011
		3	1586.708	1229.223	1472.892	1486.579
	2	1	727.4857	922.2148	757.0745	1117.441
		2	651.6081	1478.643	1069.105	1796.774

Table 5.3.2 Experimental and estimated values of the overall heat transfer coefficient.
System: Unequal water/water flow rates.
Flow rate of product = 2,3,4,5,6,7 l/min
Flow rate of cooling water = Flow rate of hot water = 9 l/min

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
98		3	3528.839	1966.199	2961.672	2387.720
	7	1	2489.062	2104.974	2229.591	2561.779
		2	1997.489	2389.794	1958.938	2912.838
		3	2894.155	1873.190	2734.026	2274.679
	6	1	2074.507	1921.582	1938.558	2338.904
		2	1518.479	2284.590	1811.759	2785.212
		3	1613.908	1752.807	2482.509	2128.009
	5	1	1778.624	1723.714	1639.033	2098.000
		2	1376.910	2157.744	1641.596	2630.969
		3	2639.573	1607.781	2186.153	1951.003
	4	1	1519.455	1503.495	1335.714	1829.324
		2	1139.629	1997.618	1443.666	2435.700
		3	1978.727	1429.600	1823.632	1733.260
	3	1	1149.998	1259.955	1020.764	1531.763
		2	872.6895	1794.168	1204.245	2186.977
		3	1143.815	1197.326	1371.788	1449.105
	2	1	718.0988	978.2666	697.0798	1187.166
		2	821.3548	1518.586	908.7449	1849.197

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
85		3	5204.403	1952.160	2984.059	2370.450
	7	1	2743.325	2049.148	2315.572	2492.805
		2	1994.718	2300.648	2071.241	2802.659
		3	3427.289	1858.035	2756.262	2256.033
	6	1	2154.296	1869.337	2015.027	2274.240
		2	1870.049	2198.574	1916.623	2678.764
		3	2005.599	1737.003	2507.708	2108.522
	5	1	1950.391	1674.069	1709.112	2036.435
		2	1520.973	2075.179	1737.464	2528.647
		3	3469.602	1587.822	2220.043	1926.353
	4	1	1595.775	1459.315	1395.196	1774.438
		2	1140.314	1921.356	1527.924	2341.039
		3	1650.176	1412.966	1848.747	1712.708
	3	1	1223.427	1223.200	1067.253	1486.028
		2	1047.227	1726.591	1273.328	2102.962
		3	1033.640	1184.904	1386.839	1433.760
	2	1	742.0354	949.6796	728.9667	1151.569
		2	872.6895	1460.040	961.0508	1776.307

Table 5.3.2 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
75		3	1734.801	1941.581	3007.911	2357.407
	7	1	2712.817	2000.930	2385.113	2433.296
		2	1595.775	2226.827	2178.191	2711.412
		3	2919.543	1846.882	2777.350	2242.280
	6	1	2124.375	1825.531	2076.891	2220.071
		2	1701.744	2127.843	2012.208	2591.275
		3	1548.627	1730.962	2517.496	2101.075
	5	1	1701.377	1636.558	1758.088	1989.981
		2	1329.173	2008.649	1819.036	2446.296
		3	2581.045	1590.291	2213.908	1929.411
	4	1	1563.859	1426.123	1433.991	1733.286
		2	1208.339	1857.435	1603.315	2261.804
		3	1294.753	1406.970	1862.734	1705.274
	3	1	1371.752	1190.399	1101.939	1445.316
		2	748.0196	1664.209	1343.817	2025.492
		3	1015.493	1178.687	1399.053	1426.042
	2	1	877.6763	924.3971	752.2841	1120.792
		2	756.3309	1409.276	1010.397	1713.194

Table 5.3.3 Experimental and estimated values of the overall heat transfer coefficient.
System: Unequal water/water flow rates.
Flow rate of product = 2,3,4,5,6,7 l/min
Flow rate of cooling water = Flow rate of hot water = 7.5 l/min

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
98		3	4157.175	1862.671	2759.048	2262.045
	7	1	2350.443	2093.735	2244.112	2547.907
		2	1832.648	2250.727	1814.225	2743.786
		3	1876.849	1768.686	2576.932	2147.647
	6	1	2154.296	1909.193	1954.249	2323.583
		2	1557.061	2156.623	1688.593	2629.569
		3	1722.711	1665.655	2346.003	2022.175
	5	1	1762.001	1713.783	1652.122	2085.686
		2	1265.399	2045.423	1538.108	2494.354
		3	3486.354	1526.529	2090.364	1852.253
	4	1	1519.455	1498.469	1342.605	1823.076
		2	1028.855	1905.361	1359.378	2323.593
		3	1599.274	1367.650	1754.925	1658.119
	3	1	1160.406	1257.259	1024.581	1528.403
		2	998.1386	1720.036	1144.545	2096.971
		3	1298.667	1153.467	1332.987	1396.055
	2	1	787.4803	976.1671	699.5954	1184.548
		2	890.1433	1465.097	874.2799	1784.385

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
85		3	2792.606	1843.919	2794.387	2238.930
	7	1	2454.554	2035.304	2330.364	2475.749
		2	2242.140	2165.458	1920.031	2638.263
		3	2246.778	1759.200	2592.410	2135.954
	6	1	1926.328	1856.946	2028.829	2258.938
		2	1658.110	2074.976	1786.979	2528.410
		3	1904.049	1663.947	2348.421	2020.067
	5	1	1695.511	1671.666	1711.137	2033.465
		2	1599.930	1966.174	1630.419	2396.037
		3	4887.061	1533.999	2079.320	1861.468
	4	1	1542.582	1462.990	1390.623	1778.999
		2	1236.310	1831.840	1440.013	2232.253
		3	1713.644	1373.928	1744.857	1665.873
	3	1	1053.211	1226.009	1063.071	1489.526
		2	906.2545	1653.715	1212.199	2014.446
		3	1091.711	1162.237	1321.546	1406.887
	2	1	743.2952	952.5332	725.5681	1155.122
		2	623.3496	1408.171	925.6291	1713.452

Table 5.3.3 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
75		3	3406.133	1871.191	2747.938	2272.518
	7	1	2593.134	2013.565	2362.907	2448.913
		2	1658.110	2110.070	2000.562	2569.689
		3	2284.859	1756.179	2597.673	2132.229
	6	1	2034.613	1855.805	2030.475	2257.528
		2	1870.049	2074.046	1788.199	2527.259
		3	3384.977	1664.692	2346.745	2020.981
	5	1	1695.511	1671.666	1711.137	2033.465
		2	1371.369	1967.700	1628.151	2397.929
		3	4887.061	1533.999	2079.320	1861.468
	4	1	1542.582	1462.990	1390.623	1778.999
		2	1236.310	1831.840	1440.013	2232.253
		3	1675.563	1376.490	1741.883	1669.033
	3	1	1089.746	1225.356	1064.227	1488.711
		2	1009.826	1651.288	1215.173	2011.422
		3	270.7982	1173.125	1303.249	1420.408
	2	1	743.2952	952.5332	725.5681	1155.122
		2	623.3496	1408.171	925.6291	1713.452

Table 5.3.4 Experimental and estimated values of the overall heat transfer coefficient.
System: Unequal water/water flow rates.
Flow rate of product = 2,3,4,5,6,7.5 l/min
Flow rate of cooling water = Flow rate of hot water = 7 l/min

T10(C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
98		3	1677.377	1892.862	2711.080	2299.200
	7.5	1	2584.067	2188.550	2376.734	2663.138
		2	1713.644	2242.135	1806.669	2733.195
		3	1692.488	1765.015	2457.650	2143.732
	6	1	2091.353	1920.459	1939.791	2337.517
		2	1648.413	2115.121	1634.234	2579.159
		3	1205.898	1658.804	2250.788	2014.309
	5	1	1795.247	1722.750	1640.188	2096.806
		2	1550.307	2007.093	1494.002	2447.765
		3	2792.606	1527.235	2007.545	1853.658
	4	1	1409.601	1504.348	1334.753	1830.382
		2	1252.566	1869.946	1326.488	2280.495
		3	1607.364	1368.816	1691.377	1660.052
	3	1	1067.174	1260.637	1019.955	1532.611
		2	872.6895	1690.961	1121.103	2061.597
		3	1455.615	1155.164	1292.669	1398.569
	2	1	718.0988	978.7435	696.2468	1187.764
		2	624.6619	1442.859	861.8663	1757.331

T10(C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
85		3	5490.010	1862.511	2759.711	2261.841
	7.5	1	2472.401	2122.580	2474.929	2581.744
		2	1982.251	2150.647	1918.016	2619.997
		3	2506.999	1740.799	2496.070	2113.886
	6	1	2053.510	1866.938	2018.014	2271.275
		2	1582.477	2034.260	1730.161	2478.926
		3	2834.918	1633.658	2289.227	1983.288
	5	1	1816.244	1672.866	1710.127	2034.947
		2	1517.137	1932.213	1579.077	2354.829
		3	1853.275	1509.685	2030.780	1832.020
	4	1	1469.792	1461.987	1391.561	1777.756
		2	1382.877	1799.411	1402.851	2192.833
		3	1269.366	1351.924	1714.402	1639.197
	3	1	1396.303	1225.648	1064.886	1489.066
		2	926.3935	1625.364	1188.007	1979.956
		3	1046.223	1142.952	1308.296	1383.487
	2	1	743.2952	950.3070	728.4034	1152.348
		2	523.6137	1387.088	912.3636	1687.831

Table 5.3.4 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
75		3	2729.138	1847.910	2784.049	2243.862
	7.5	1	2573.187	2074.502	2552.644	2522.421
		2	1620.709	2085.925	2021.101	2539.801
		3	3363.821	1743.861	2492.349	2117.652
	6	1	2004.692	1830.126	2068.967	2225.762
		2	1701.744	1973.169	1813.180	2403.210
		3	1523.239	1641.381	2279.378	1992.804
	5	1	1607.508	1640.657	1751.067	1995.068
		2	1171.897	1871.435	1652.182	2279.479
		3	2157.923	1517.629	2021.520	1841.802
	4	1	1595.775	1432.165	1423.281	1740.804
		2	1119.951	1741.105	1468.538	2120.480
		3	1269.366	1358.691	1706.217	1647.537
	3	1	1140.979	1199.992	1091.104	1457.224
		2	901.7792	1574.339	1241.827	1916.556
		3	846.2444	1149.769	1300.106	1391.897
	2	1	809.2859	932.9008	746.4842	1130.712
		2	639.9723	1342.259	954.6102	1632.075

Table 5.3.5 Experimental and estimated values of the overall heat transfer coefficient.
System: Unequal water/water flow rates.
Flow of product flow rate = 2,3,4,5,7,7.5 l/min
Flow rate of cooling water = Flow rate of hot water = 6 l/min

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
98		3	1904.049	1774.747	2566.717	2155.094
	7.5	1	2309.884	2166.782	2408.543	2636.276
		2	1650.521	2119.032	1681.315	2583.085
		3	3236.884	1736.936	2501.332	2109.118
	7	1	2280.628	2081.416	2261.552	2532.694
		2	1545.907	2083.135	1635.222	2539.578
		3	2506.999	1562.147	2159.176	1896.314
	5	1	1728.756	1703.462	1664.149	2072.903
		2	1368.744	1904.552	1407.642	2322.572
		3	1929.437	1447.040	1930.921	1755.850
	4	1	1552.254	1494.044	1347.744	1817.583
		2	1047.227	1785.856	1254.727	2177.920
		3	2284.859	1300.453	1643.665	1576.687
	3	1	1097.095	1252.370	1031.075	1522.312
		2	985.6258	1622.829	1069.311	1978.550
		3	976.1792	1105.523	1268.000	1338.164
	2	1	731.3969	973.5812	703.0824	1181.319
		2	558.5213	1393.605	830.1877	1697.425

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
85		3	1618.442	1784.607	2553.208	2167.235
	7.5	1	2208.438	2122.255	2474.109	2581.350
		2	1639.737	2046.097	1766.005	2492.772
		3	1421.690	1747.852	2486.515	2122.557
	7	1	2579.054	2043.807	2322.000	2486.220
		2	1509.239	2014.377	1716.991	2454.369
		3	1320.141	1575.078	2142.253	1912.256
	5	1	1839.574	1671.921	1711.737	2033.775
		2	1520.973	1839.721	1482.671	2242.033
		3	1946.362	1457.278	1917.714	1768.477
	4	1	1372.366	1457.197	1396.879	1771.816
		2	1093.770	1719.485	1325.770	2095.380
		3	1713.644	1314.678	1625.578	1594.250
	3	1	974.5626	1222.154	1067.570	1484.734
		2	942.5047	1559.560	1133.104	1899.761
		3	1269.366	1112.120	1260.230	1346.294
	2	1	726.4976	949.1985	729.8111	1150.967
		2	535.2495	1338.527	880.6604	1628.756

Table 5.3.5 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
75		3	1618.442	1736.801	2643.712	2108.260
	7.5	1	2543.266	2060.437	2583.635	2505.021
		2	1396.303	1980.993	1863.746	2412.040
		3	779.7537	1694.732	2586.754	2057.002
	7	1	2550.580	1974.435	2436.678	2400.525
		2	1230.951	1945.236	1815.919	2368.636
		3	1294.753	1535.200	2214.323	1862.982
	5	1	1617.938	1618.432	1785.955	1967.516
		2	1210.856	1779.320	1558.640	2167.052
		3	3173.416	1426.210	1972.320	1730.061
	4	1	1329.812	1418.155	1448.176	1723.374
		2	954.1405	1665.883	1386.224	2028.809
		3	2157.923	1277.471	1687.521	1548.221
	3	1	1390.165	1185.858	1108.687	1439.667
		2	748.0196	1508.870	1187.793	1836.735
		3	1114.486	1090.305	1292.163	1319.314
	2	1	803.2068	922.0702	756.4692	1117.269
		2	436.3447	1296.076	922.5602	1575.906

Table 5.3.6 Experimental and estimated values of the overall heat transfer coefficient.
System: Unequal water/water flow rates.
Flow rate of product = 2,3,4,6,7,7.5 l/min
Flow rate of cooling water = Flow rate of hot water = 5 l/min

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
98		3	1904.049	1669.174	2341.835	2026.466
	7.5	1	2720.071	2180.609	2386.373	2653.353
		2	1570.841	1999.603	1503.587	2437.698
		3	2157.923	1640.061	2281.879	1991.151
	7	1	2440.495	2092.439	2245.314	2546.313
		2	1535.933	1966.669	1468.125	2397.750
		3	2030.986	1570.195	2149.780	1906.217
	6	1	2336.670	1911.436	1950.885	2326.363
		2	1376.910	1894.494	1384.755	2310.143
		3	2877.230	1381.965	1793.107	1676.779
	4	1	1707.479	1499.191	1340.749	1823.983
		2	965.0919	1696.553	1155.982	2069.063
		3	1904.049	1245.120	1544.754	1509.529
	3	1	1196.831	1257.906	1023.452	1529.211
		2	942.5047	1549.897	994.8343	1889.752
		3	1142.429	1067.686	1205.014	1292.452
	2	1	681.2732	976.7285	699.2530	1185.243
		2	632.6999	1339.669	784.0606	1631.909

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
85		3	1428.037	1664.763	2347.279	2021.040
	7.5	1	2273.979	2108.395	2499.626	2564.225
		2	1439.937	1907.582	1610.948	2323.563
		3	1396.303	1633.966	2289.334	1983.644
	7	1	2278.179	2027.212	2340.203	2465.772
		2	1190.031	1883.548	1562.750	2294.631
		3	1100.117	1561.523	2161.944	1895.518
	6	1	2266.939	1857.426	2030.045	2259.521
		2	1418.120	1816.338	1471.618	2213.088
		3	1713.644	1378.155	1797.396	1672.080
	4	1	1314.614	1456.142	1397.713	1770.511
		2	1122.029	1629.214	1226.237	1985.245
		3	1523.239	1246.117	1543.829	1510.755
	3	1	1835.141	1228.037	1062.382	1492.034
		2	1710.471	1493.373	1049.755	1819.313
		3	729.8858	1066.369	1206.596	1290.832
	2	1	702.1410	950.7891	727.5545	1152.951
		2	673.2176	1286.974	831.2103	1566.163

Table 5.3.6 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
75		3	1428.037	1642.714	2391.442	1993.802
	7.5	1	2393.662	2060.437	2583.635	2505.021
		2	1386.036	1848.650	1696.218	2250.424
		3	1650.176	1613.775	2329.025	1958.701
	7	1	2151.949	1978.812	2423.812	2405.962
		2	1365.502	1822.268	1650.543	2218.534
		3	2030.986	1547.364	2188.581	1878.023
	6	1	2004.692	1808.558	2102.099	2199.084
		2	1178.130	1757.174	1552.537	2139.586
		3	1777.113	1367.072	1813.701	1658.385
	4	1	1342.328	1419.004	1446.329	1724.434
		2	1000.684	1574.512	1288.260	1917.239
		3	1904.049	1235.881	1557.782	1498.099
	3	1	1334.927	1193.344	1097.239	1448.983
		2	785.4205	1438.655	1106.920	1751.222
		3	1332.834	1057.431	1217.583	1279.766
	2	1	738.0460	926.1685	751.2081	1122.368
		2	727.2412	1243.509	872.4449	1512.042

Table 5.3.7 Experimental and estimated values of the overall heat transfer coefficient.
System: Unequal water/water flow rates.
Flow rate of product = 2,3,5,6,7,7.5 l/min
Flow rate of cooling water = Flow rate of hot water = 4 l/min

T10(^{o}C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
98		3	924.8242	1552.063	2055.954	1883.694
	7.5	1	2521.894	2160.172	2423.551	2628.088
		2	1571.328	1812.293	1341.453	2208.247
		3	856.8224	1513.166	2027.514	1836.247
	7	1	2361.021	2074.886	2275.222	2524.603
		2	1438.121	1792.978	1306.570	2185.069
		3	825.0883	1453.704	1922.124	1764.034
	6	1	2067.254	1892.651	1978.614	2303.106
		2	1369.535	1730.817	1241.467	2109.628
		3	888.5566	1384.784	1789.489	1680.244
	5	1	1795.247	1699.181	1668.185	2067.611
		2	1047.227	1661.198	1153.532	2025.152
		3	1618.442	1174.189	1420.480	1423.227
	3	1	1213.928	1248.621	1034.781	1517.656
		2	916.3240	1442.823	917.0240	1758.631
		3	1583.744	1011.633	1131.418	1224.385
	2	1	718.0988	972.4792	704.3498	1179.946
		2	595.4822	1260.938	733.7628	1535.694

T10(^{o}C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
85		3	507.7466	1526.791	2094.596	1852.511
	7.5	1	2426.908	2095.320	2522.380	2548.082
		2	1191.375	1746.857	1418.242	2126.993
		3	507.7466	1500.749	2048.500	1820.920
	7	1	2327.172	2014.112	2366.328	2449.557
		2	1283.939	1722.333	1386.223	2097.322
		3	761.6199	1445.302	1934.350	1753.671
	6	1	1977.921	1842.610	2047.908	2241.219
		2	1151.950	1668.959	1308.038	2032.759
		3	1078.961	1377.397	1798.667	1671.131
	5	1	1635.669	1656.225	1728.258	2014.362
		2	1105.406	1601.955	1217.459	1951.430
		3	1692.488	1168.593	1426.741	1416.317
	3	1	1232.032	1216.309	1075.417	1477.464
		2	779.6026	1390.758	966.9779	1693.719
		3	1142.429	1010.480	1132.770	1222.957
	2	1	789.0221	947.5519	731.9753	1148.916
		2	644.4476	1214.871	774.2733	1478.204

Table 5.3.7 (continued)

T10(^{o}C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
75		3	507.7466	1519.538	2107.609	1843.623
	7.5	1	2318.860	2055.354	2595.612	2498.729
		2	1254.995	1697.240	1485.489	2065.371
		3	507.7466	1493.594	2061.313	1812.089
	7	1	2234.085	1975.515	2433.346	2401.368
		2	1399.389	1674.064	1452.523	2037.334
		3	507.7466	1431.829	1960.371	1737.000
	5	1	2222.686	1804.056	2110.810	2193.506
		2	1108.829	1617.760	1377.806	1969.066
		3	1078.961	1363.347	1823.202	1653.751
	4	1	1720.445	1618.250	1784.801	1967.301
		2	1209.298	1550.629	1283.138	1887.552
		3	2284.859	1161.469	1438.325	1407.494
	3	1	1107.069	1188.411	1106.653	1442.828
		2	952.0249	1345.748	1012.751	1637.692
		3	1184.742	1000.460	1146.398	1210.555
	2	1	854.8795	922.5538	755.3178	1117.875
		2	581.7930	1173.944	812.5814	1427.220

Table 5.3.8 Experimental and estimated values of the overall heat transfer coefficient.
System: Unequal water/water flow rates.
Flow rate of product = 2,4,5,6,7,7.5 l/min
Flow rate of cooling water = Flow rate of hot water = 3 l/min

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
98		3	380.8099	1373.621	1747.023	1665.415
	7.5	1	2633.029	2140.608	2452.835	2603.951
		2	1151.013	1610.302	1113.504	1960.865
		3	380.8099	1349.709	1719.833	1636.371
	7	1	2380.364	2058.989	2300.387	2504.958
		2	1179.561	1591.312	1092.704	1937.947
		3	544.0142	1310.477	1632.125	1589.006
	6	1	2023.733	1888.395	1985.977	2297.830
		2	1125.744	1549.737	1041.172	1887.790
		3	1396.303	1254.678	1534.275	1521.293
	5	1	1673.829	1700.245	1667.280	2068.925
		2	952.0249	1494.231	978.2829	1820.545
		3	1269.366	1180.753	1412.868	1431.321
	4	1	1343.110	1488.702	1354.301	1810.949
		2	973.7378	1420.120	900.8772	1730.416
		3	1533.995	944.0753	1019.653	1142.310
	2	1	776.1270	974.5938	701.5095	1182.587
		2	523.6137	1165.606	655.3458	1419.185

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
85		3	380.8099	1373.621	1747.023	1665.415
	7.5	1	2411.263	2093.879	2523.871	2546.310
		2	1003.661	1553.302	1177.218	1889.981
		3	380.8099	1352.666	1714.601	1640.039
	7	1	2349.074	2015.237	2363.222	2450.957
		2	1211.415	1535.097	1154.090	1868.020
		3	380.8099	1304.783	1638.929	1581.981
	6	1	2097.975	1840.247	2050.856	2238.301
		2	1031.868	1491.755	1101.059	1815.645
		3	550.0588	1248.762	1541.510	1513.983
	5	1	1818.714	1657.772	1728.026	2016.267
		2	839.4442	1439.367	1032.240	1752.240
		3	973.1810	1181.029	1412.688	1431.664
	4	1	1308.535	1449.613	1405.402	1762.414
		2	959.9585	1366.611	953.3753	1663.713
		3	3554.226	941.2050	1023.258	1138.755
	2	1	771.2913	945.2050	734.5829	1145.996
		2	548.5477	1118.637	695.9299	1360.532

Table 5.3.8 (continued)

T10(°C)	Flow(LPM)	Section	U(exp)	U(o)	U(of)	U(the)
75		3	380.8099	1358.028	1773.992	1646.154
	7.5	1	2646.838	2049.357	2611.601	2491.300
		2	967.3767	1503.124	1241.819	1827.592
		3	380.8099	1349.062	1718.330	1635.620
	7	1	2059.547	1973.067	2439.038	2398.835
		2	1155.866	1487.306	1214.310	1808.595
		3	380.8099	1298.336	1647.682	1574.029
	5	1	1855.088	1801.574	2115.143	2190.432
		2	1088.824	1446.135	1157.561	1758.868
		3	380.8099	1237.866	1558.126	1500.508
	4	1	1715.458	1619.293	1782.761	1968.597
		2	954.8250	1392.822	1089.431	1694.249
		3	602.9491	1168.931	1426.597	1416.719
	4	1	1356.408	1417.987	1447.181	1723.176
		2	935.0245	1323.591	1001.041	1610.122
		3	1184.742	936.1114	1028.299	1132.468
	2	1	877.5763	926.9959	751.0153	1123.391
		2	593.4288	1083.151	727.0571	1316.325

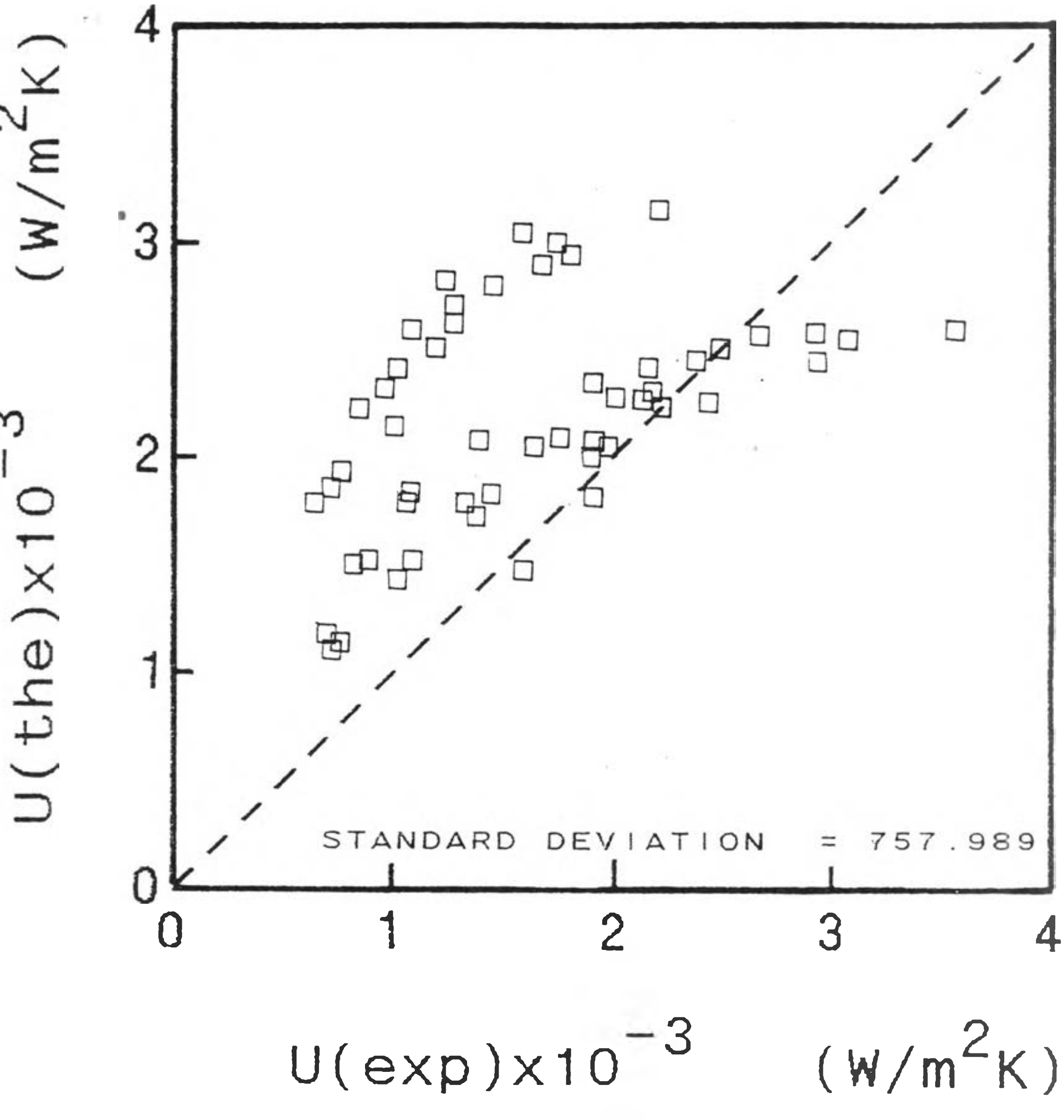

Figure 5.8(a) Comparison between the experimental value of U and the theoretical value given by eqn(5-6) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7 LPM.,

Flow rate of cooling water = Flow rate of hot water = 12 LPM.

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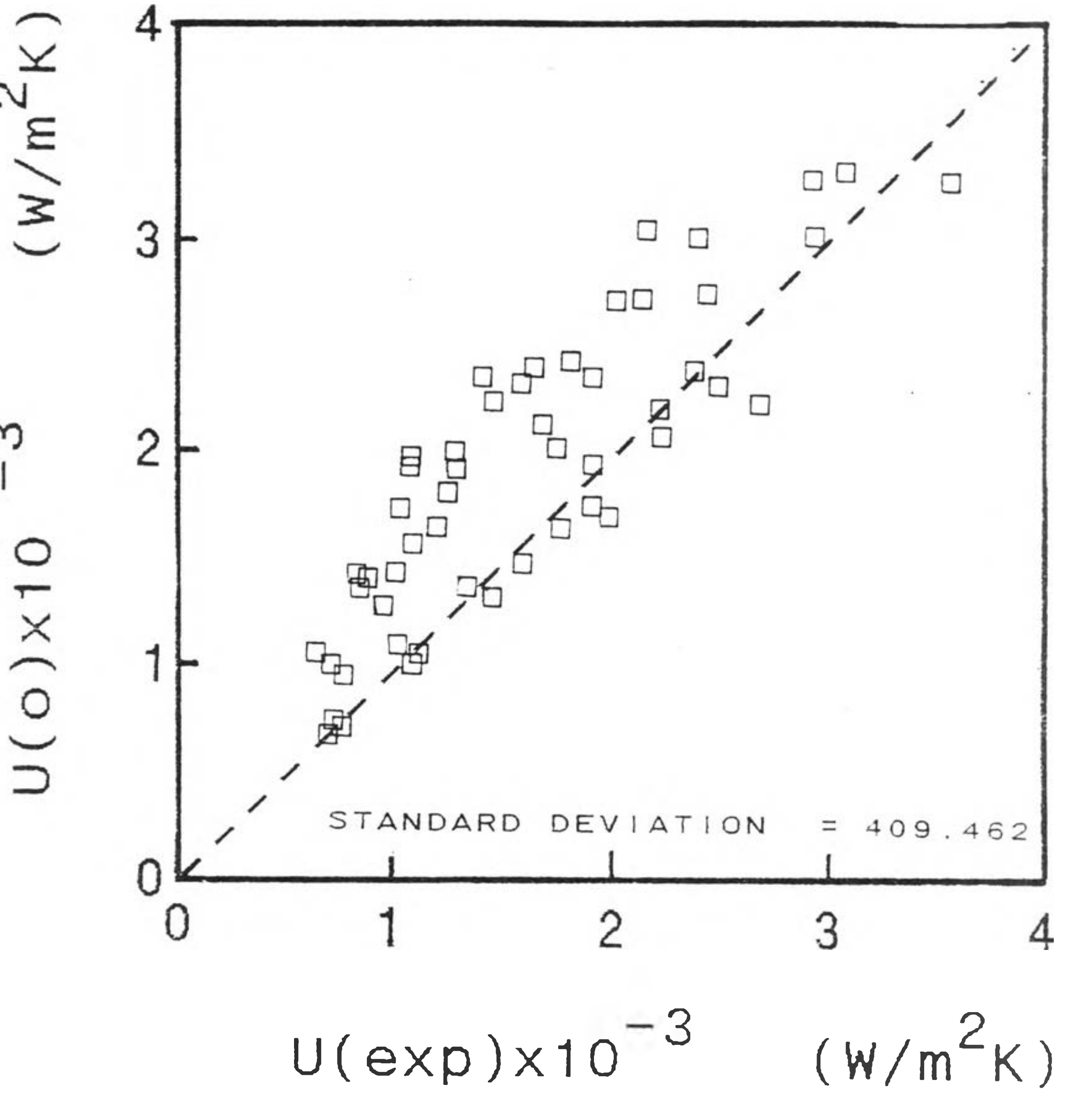

Figure 5.8(c) Comparison between the experimental value of U and the value estimated from eqn(5-8) for the case of unequal water/water flow rates ;

Flow rate of product = 2,3,4,5,6,7 LPM.,

Flow rate of cooling water = Flow rate of hot water = 12 LPM.

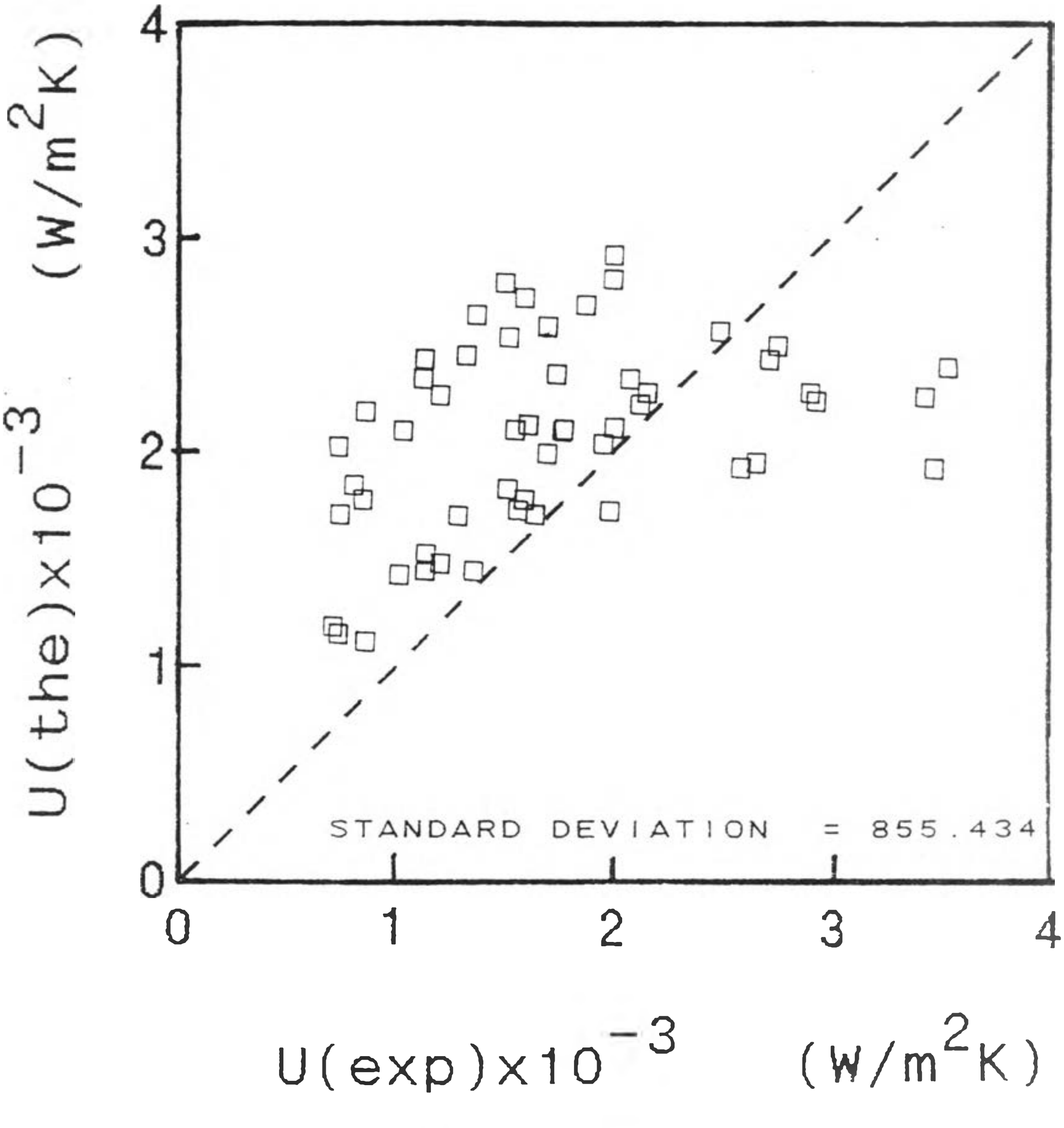

Figure 5.9(a). Comparison between the experimental value of U and the theoretical value given by eqn(5-6) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7 LPM.,

Flow rate of cooling water = Flow rate of hot water = 9 LPM.

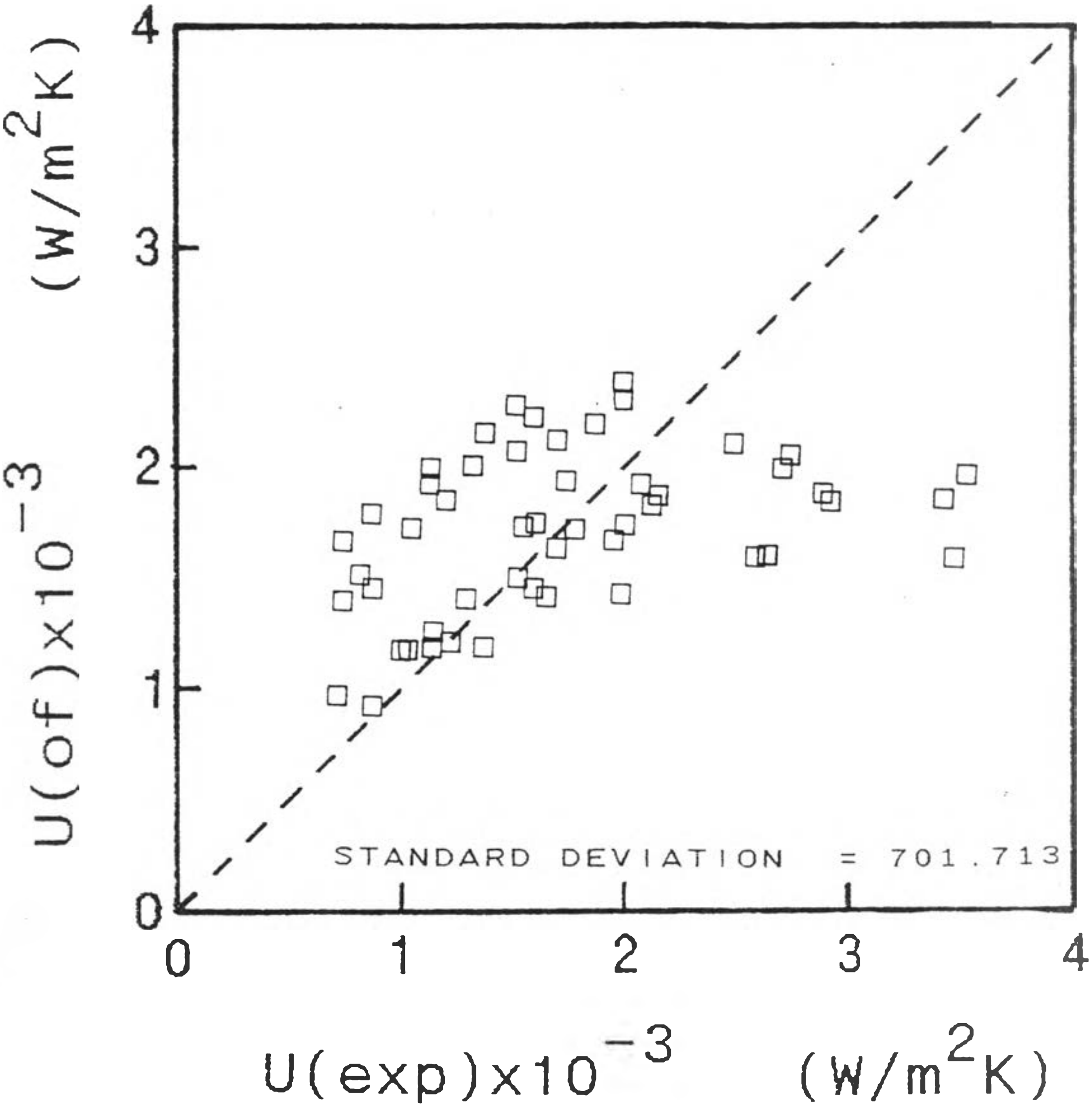

Figure 5.9(b) Comparison between the experimental value of U and the value estimated from eqn(5-7) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7 LPM.,

Flow rate of cooling water = Flow rate of hot water = 9 LPM.

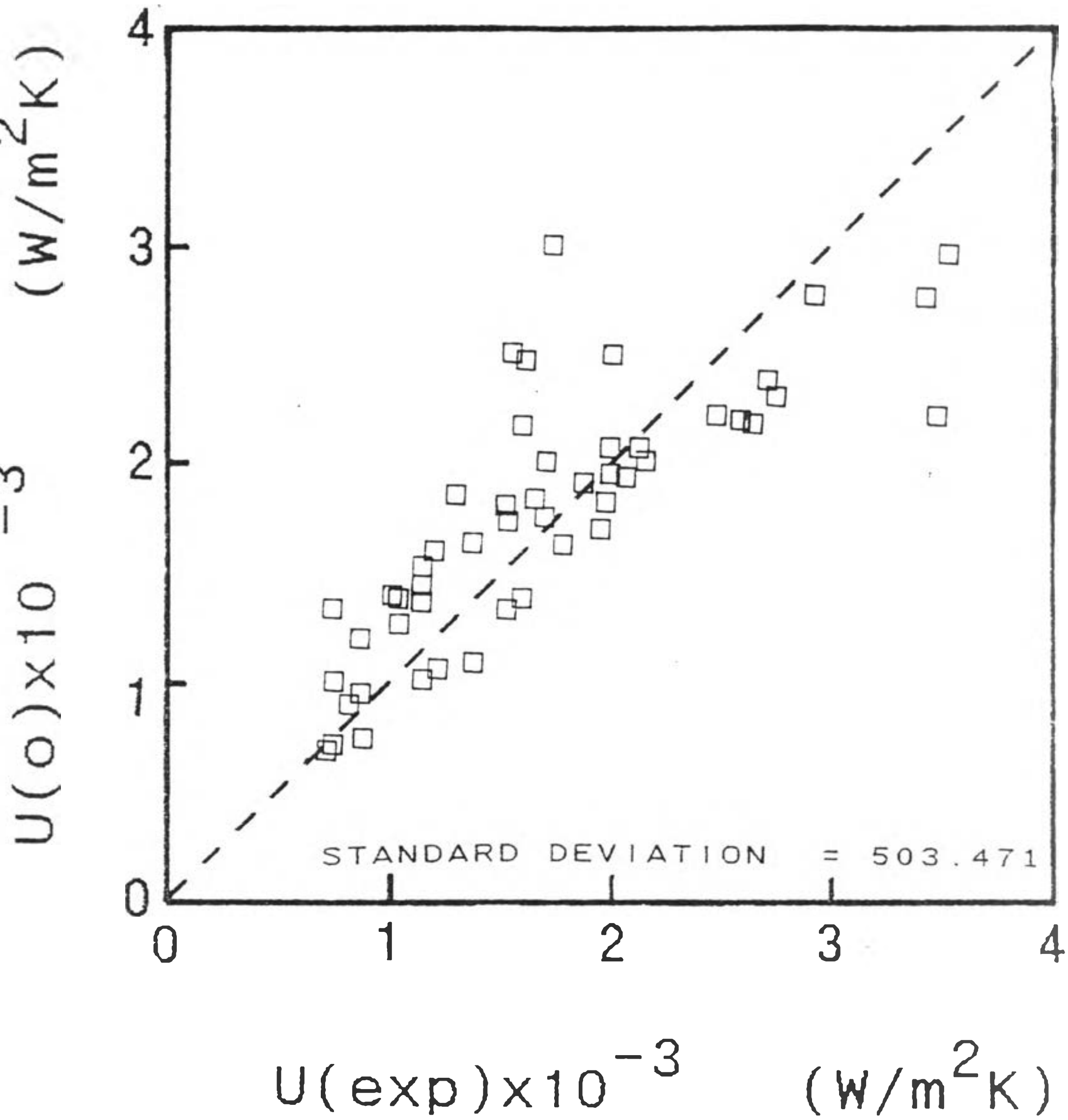

Figure 5.9(c) Comparison between the experimental value of U and the value estimated from eqn(5-8) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7 LPM.,

Flow rate of cooling water = Flow rate of hot water = 9 LPM.

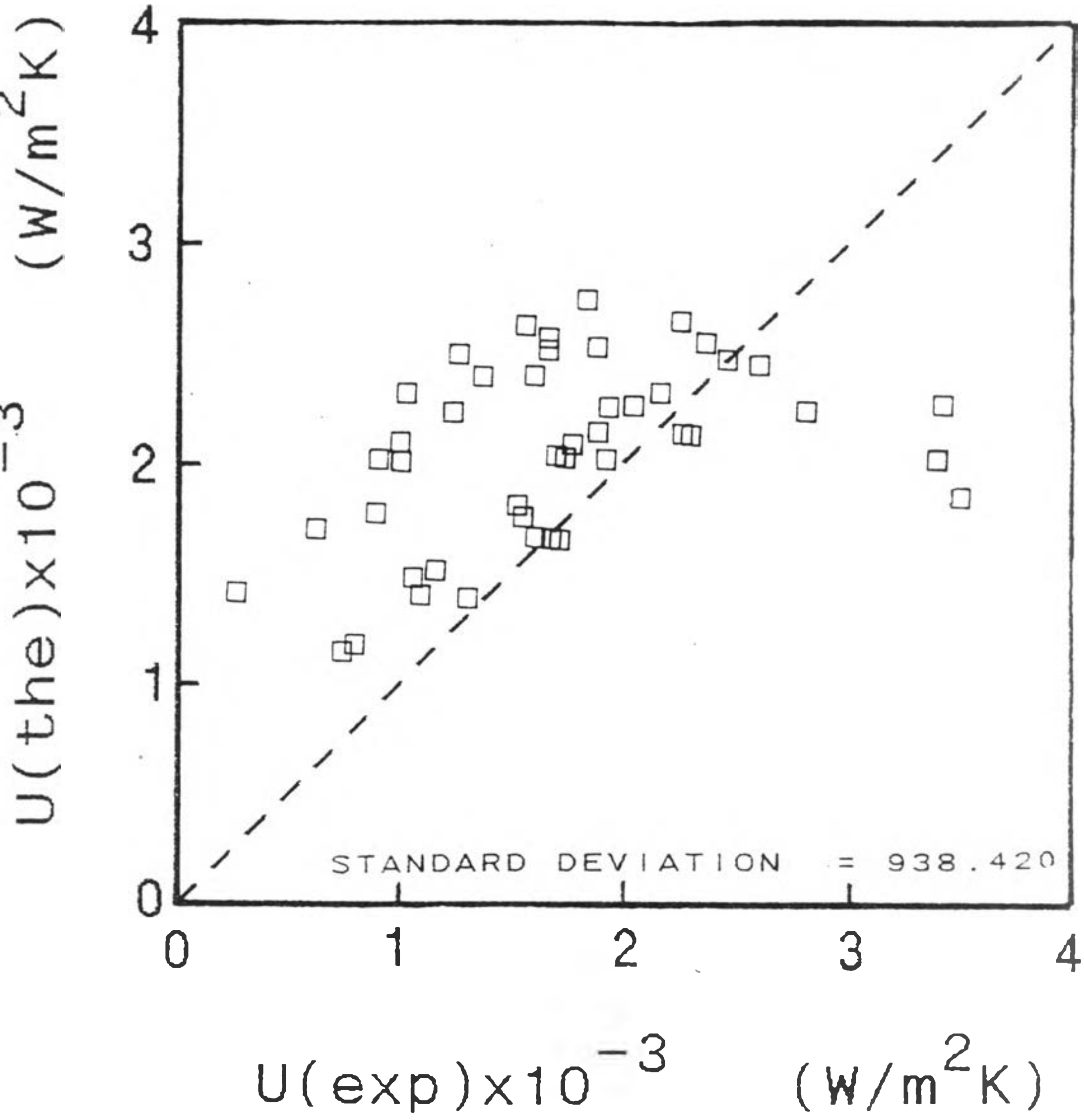

Figure 5.10(a) Comparison between the experimental value of U and the theoretical value given by eqn(5-6) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7 LPM.,

Flow rate of cooling water = Flow rate of hot water = 7.5 LPM.

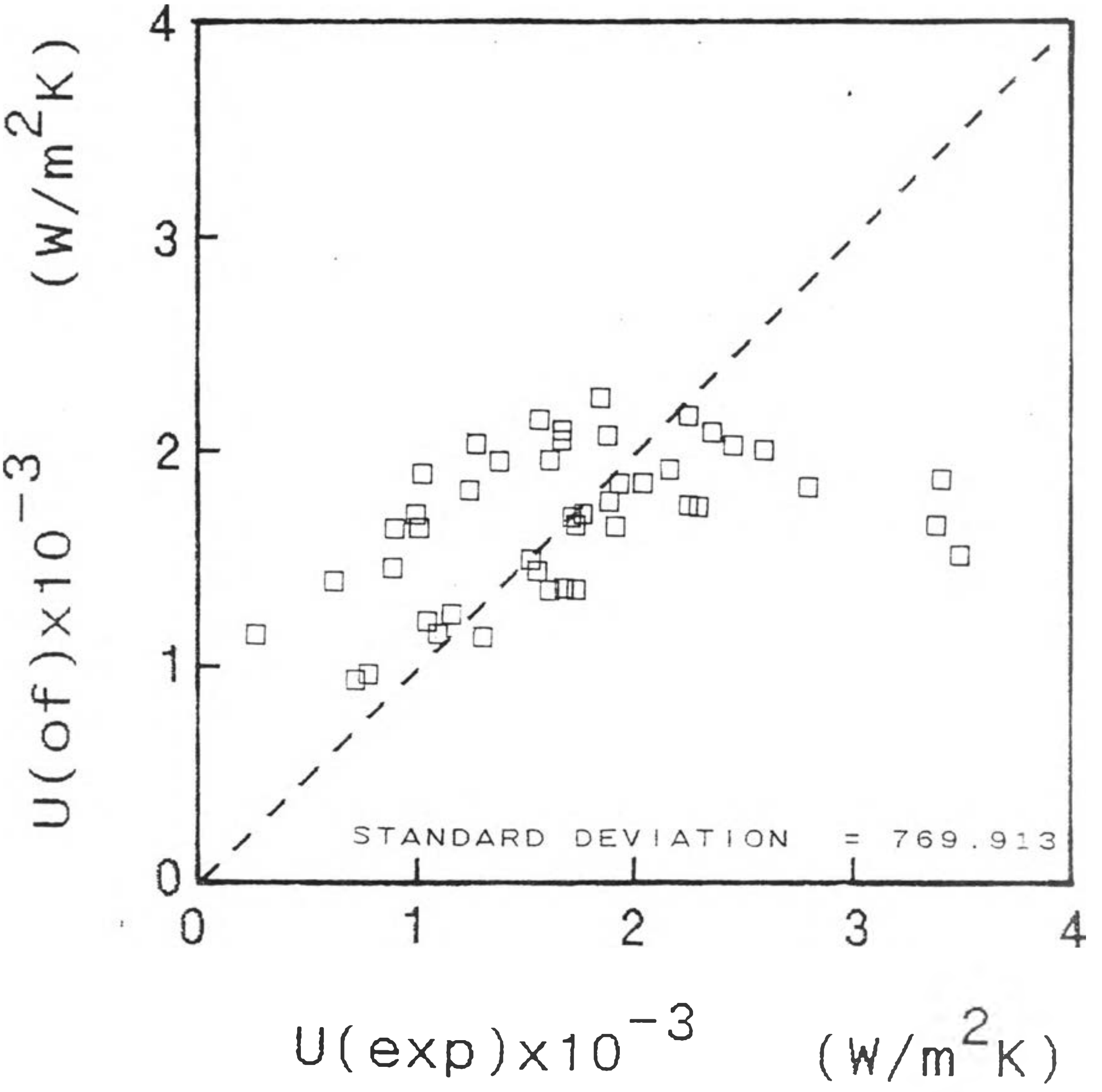

Figure 5.10(b) Comparison between the experimental value of U and the value estimated from eqn(5-7) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7 LPM.,

Flow rate of cooling water = Flow rate of hot water = 7.5 LPM.

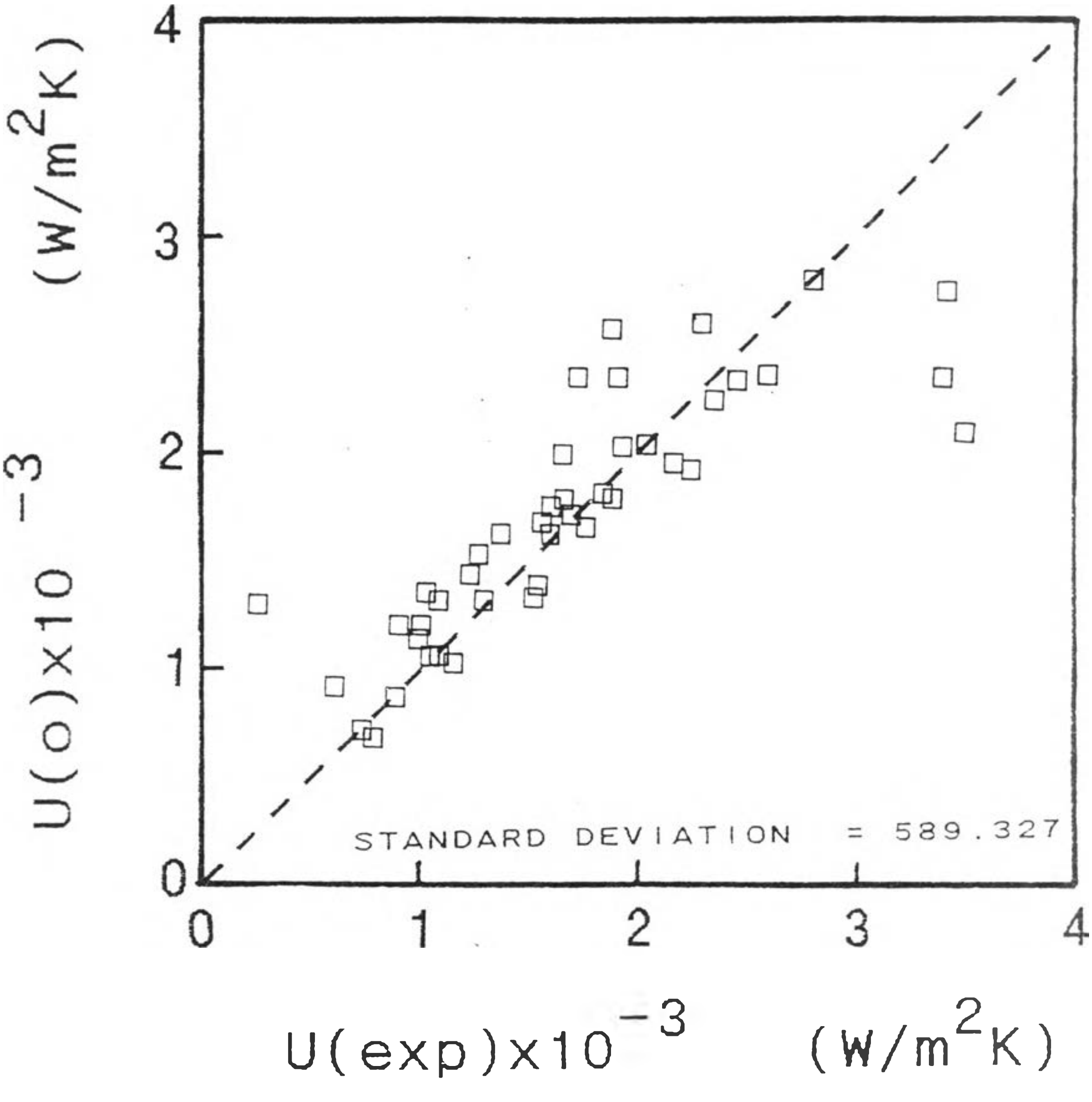

Figure 5.10(c) Comparison between the experimental value of U and the value estimated from eqn(5-8) for the case of unequal water/water flow rates;
Flow rate of product = 2,3,4,5,6,7 LPM.,
Flow rate of cooling water = Flow rate of hot water = 7.5 LPM.

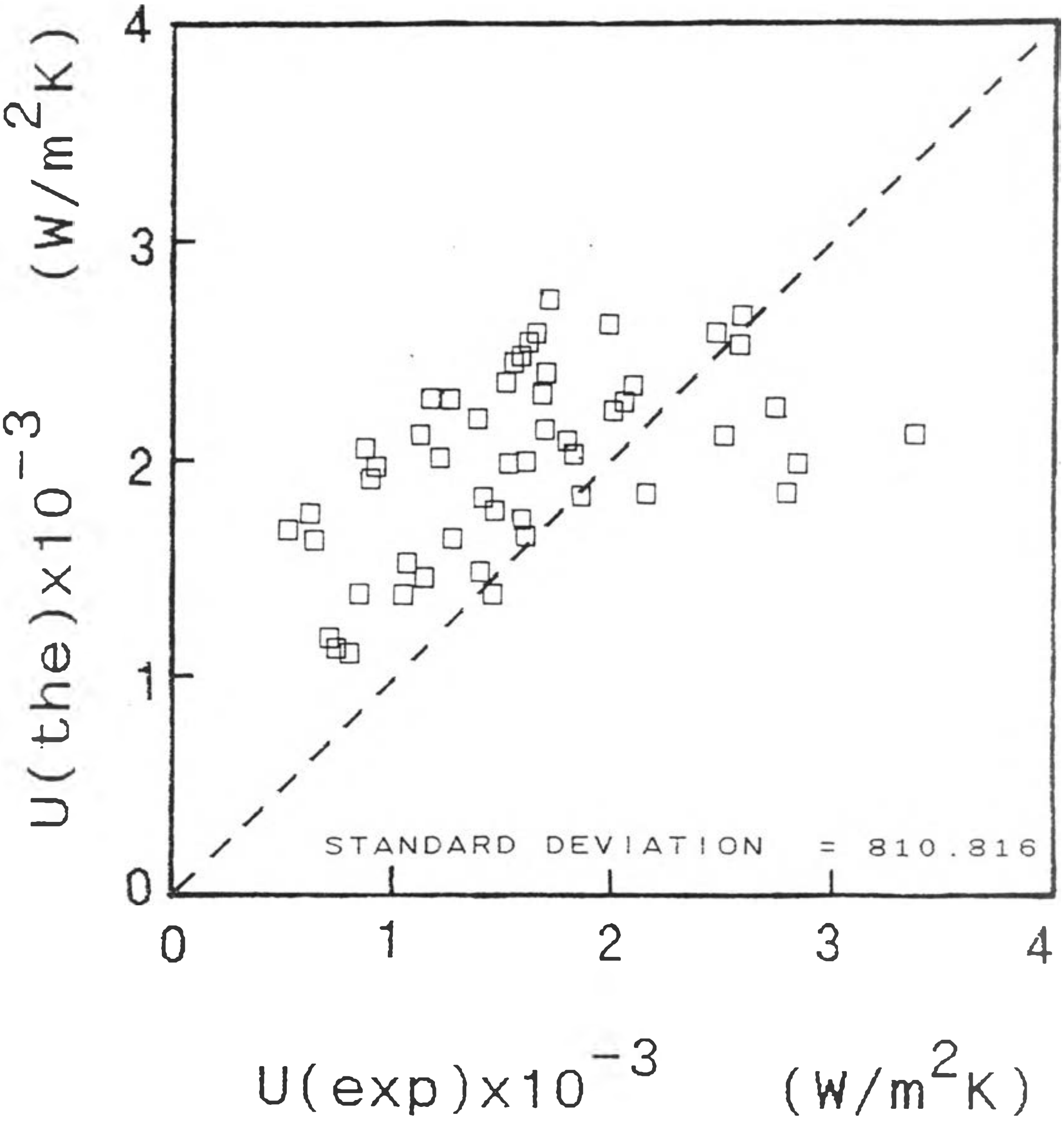

Figure 5.11(a) Comparison between the experimental value of U and the theoretical value given by eqn(5-6) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 7 LPM.

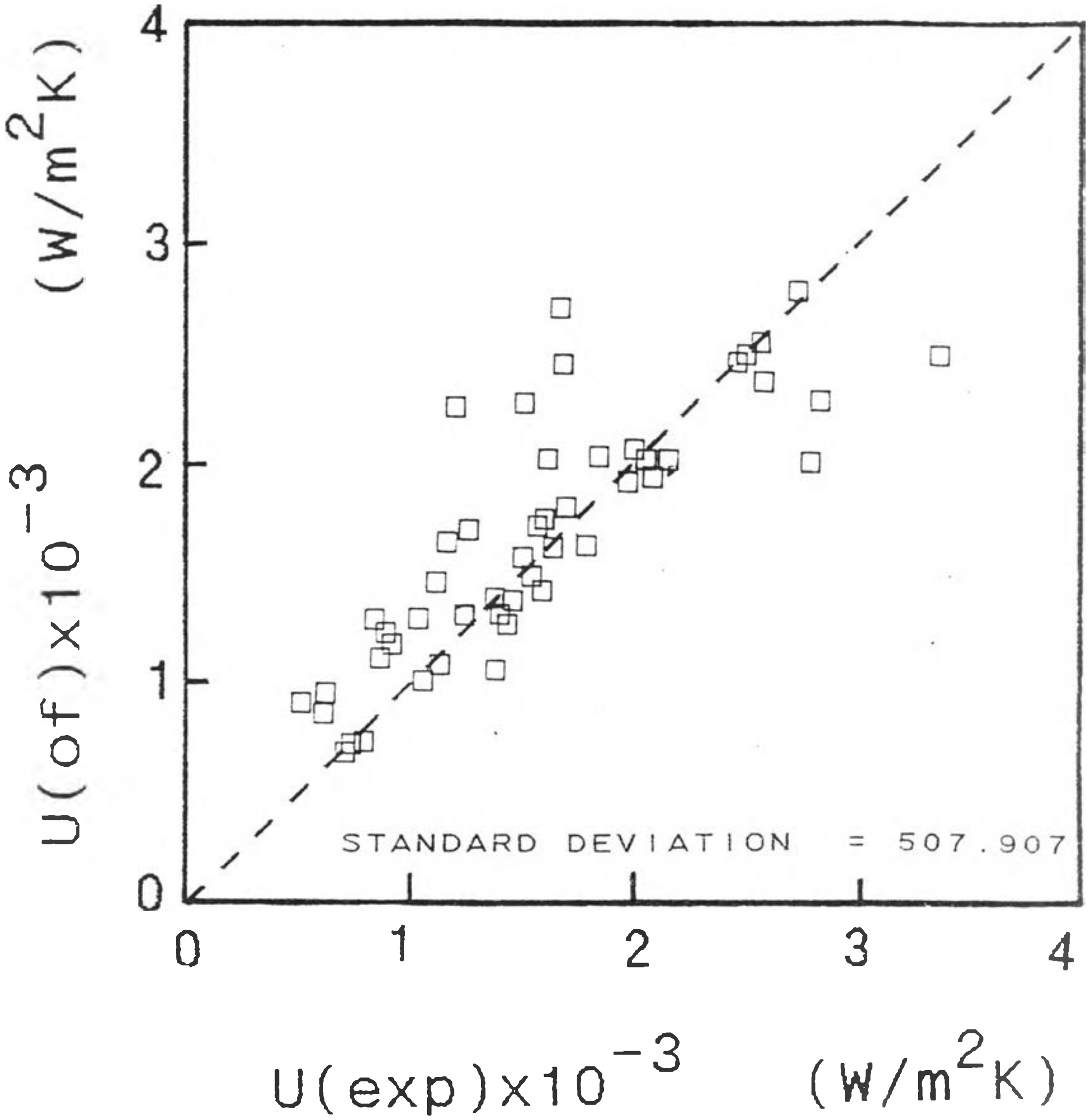

Figure 5.11(b) Comparison between the experimental value of U and the value estimated from eqn(5-7) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 7 LPM.

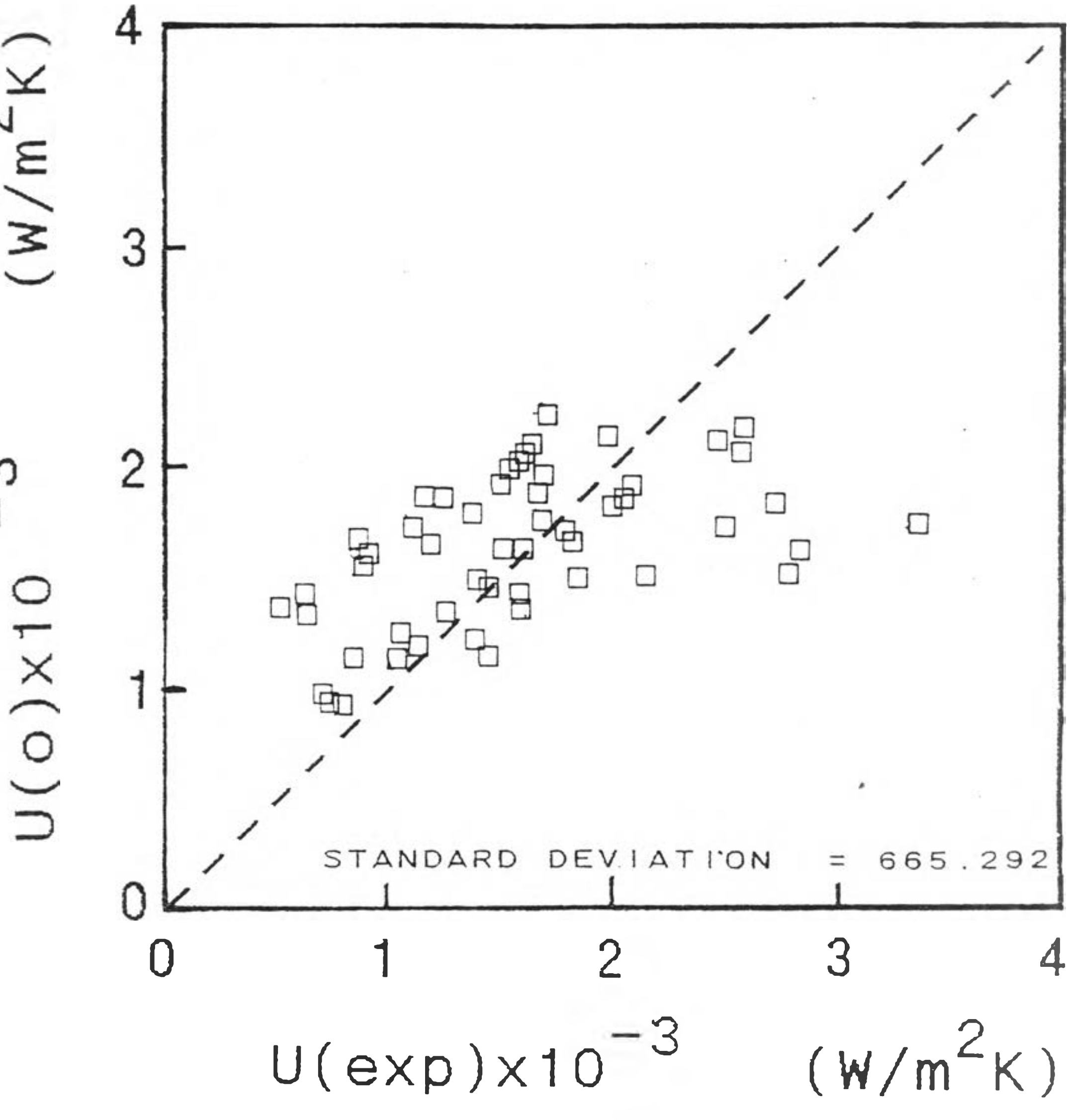

Figure 5.11(c) Comparison between the experimental value of U and the value estimated from eqn(5-8) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,6,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 7 LPM.

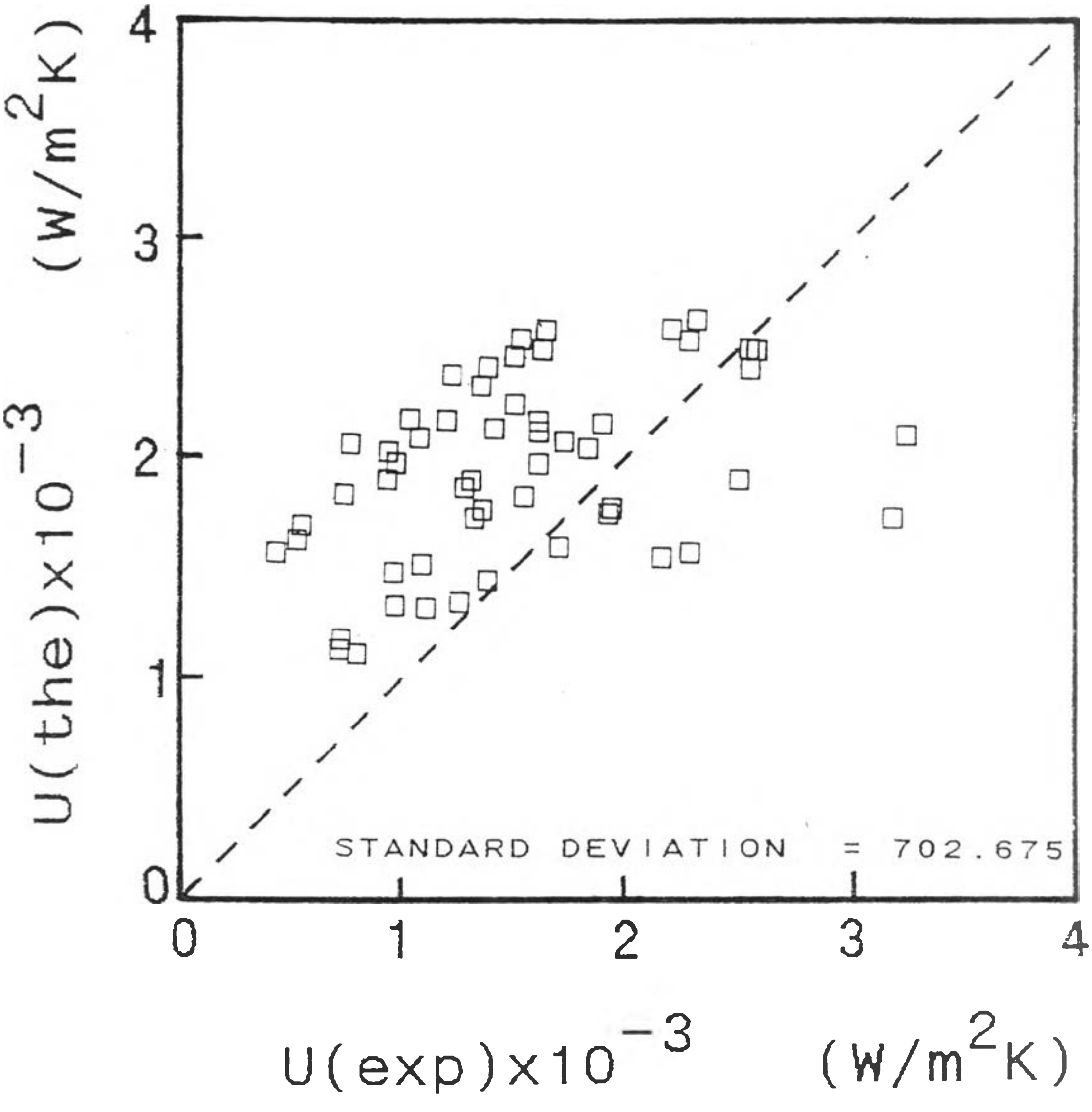

Figure 5.12(a) Comparison between the experimental value of U and the theoretical value given by eqn(5-6) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,7,7.5 LPM.,

Flow rate ofcooling water = Flow rate of hot water = 6 LPM.

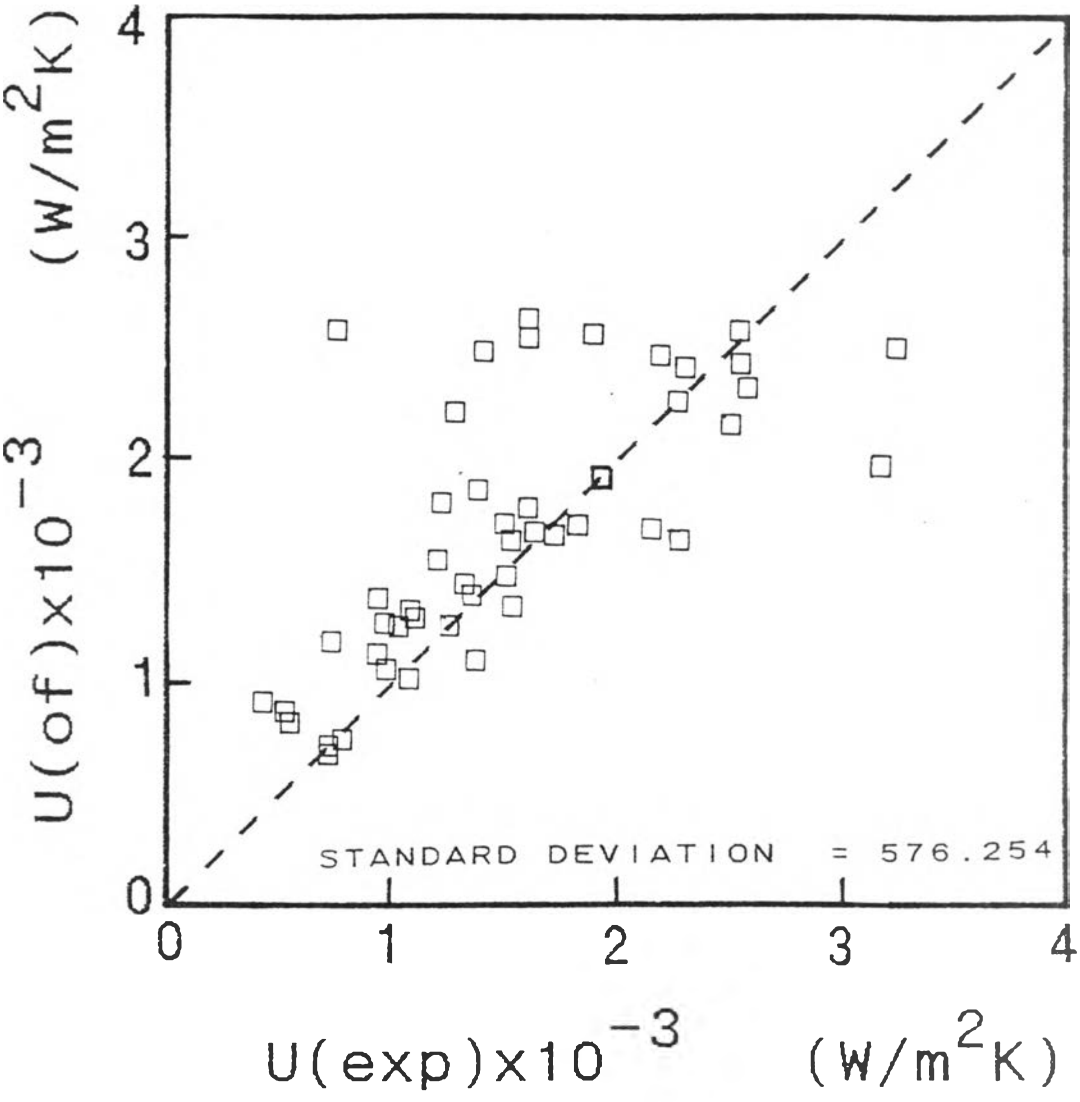

Figure 5.12(b) Comparison between the experimental value of U and the value estimated from eqn(5-7) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 6 LPM.

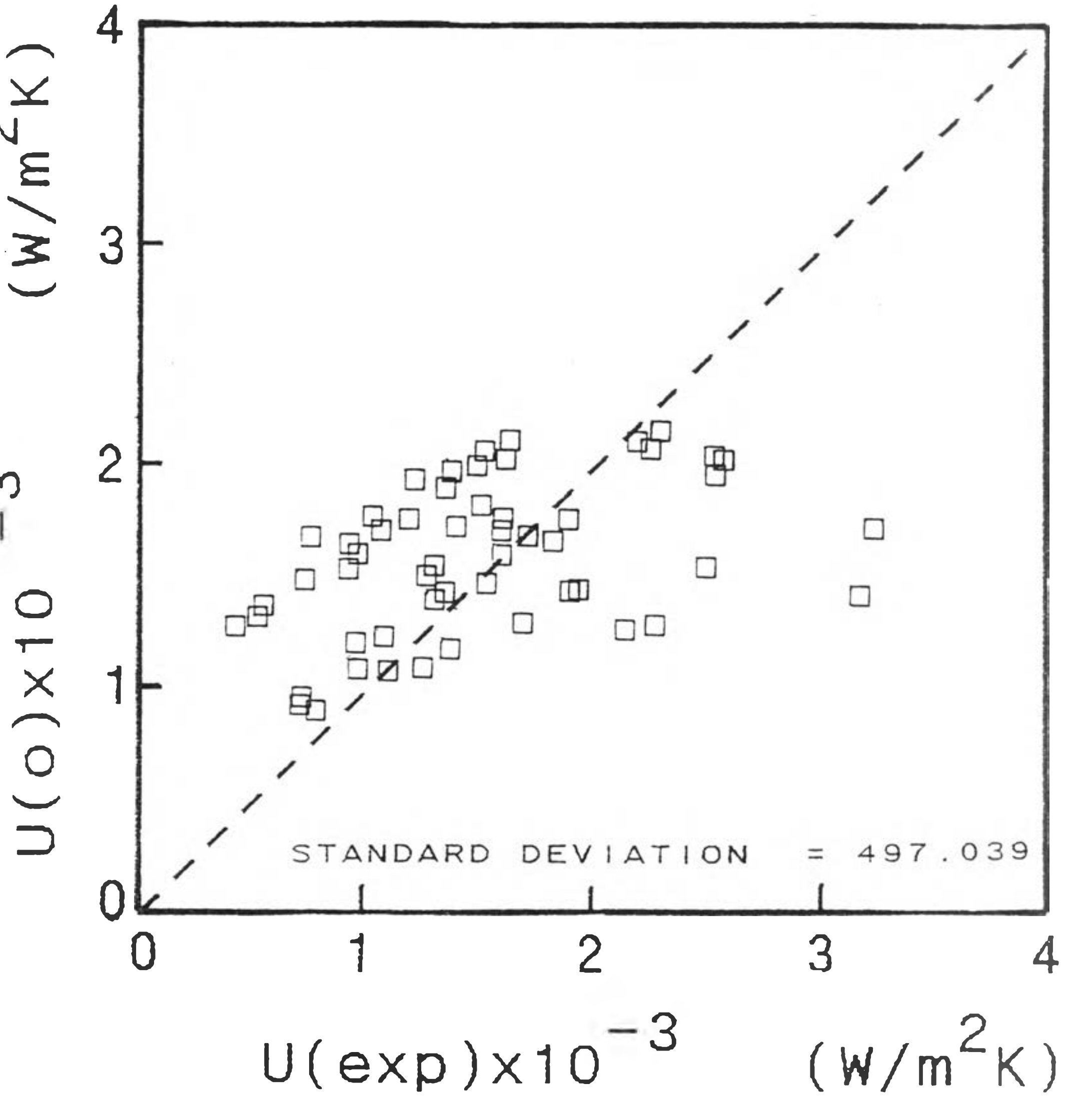

Figure 5.12(c) Comparison between the experimental value of U and the value estimated from eqn(5-8) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,5,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 6 LPM.

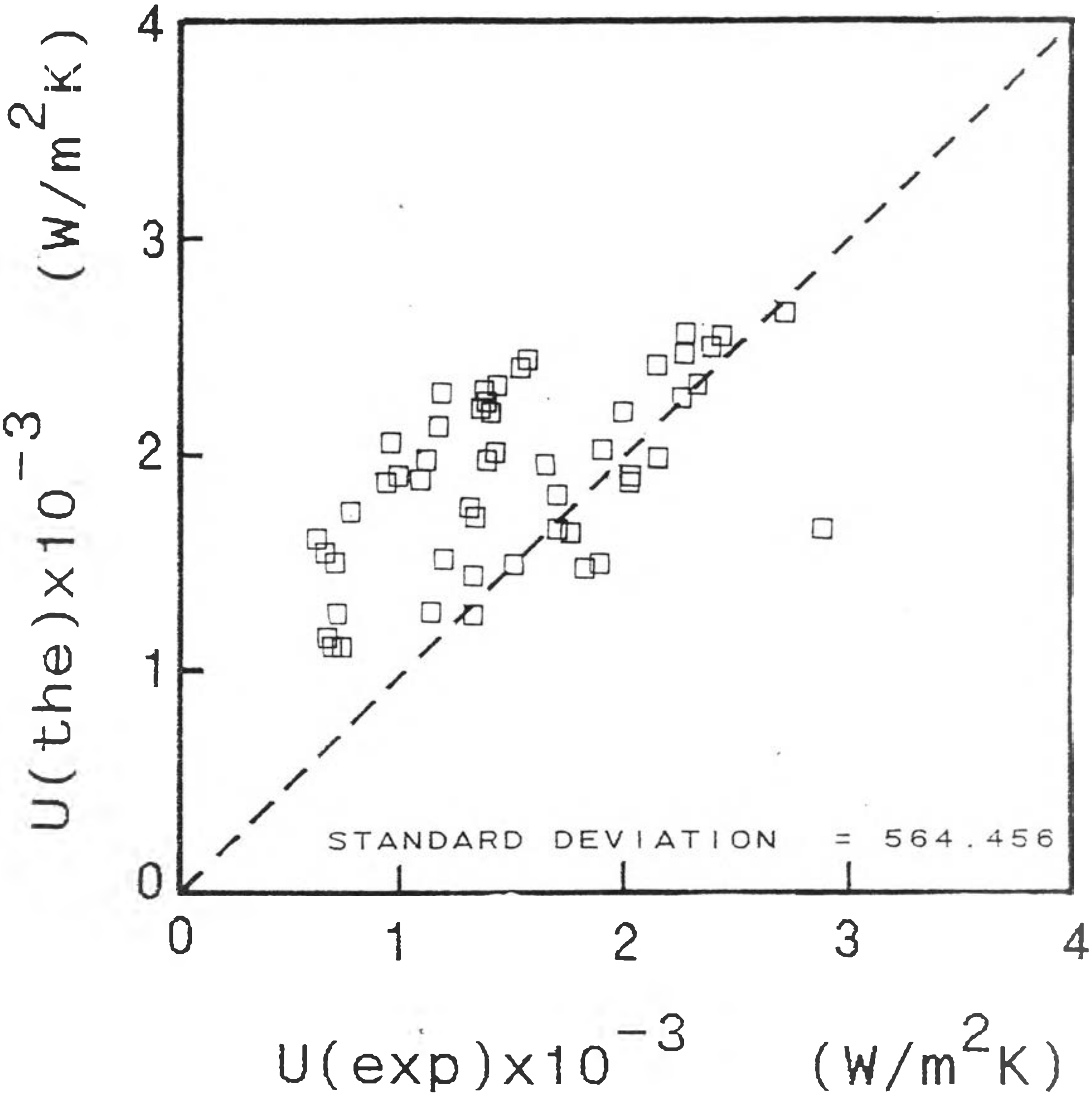

Figure 5.13(a) Comparison between the experimental value of U and the theoretical value given by eqn(5-6) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 5 LPM.

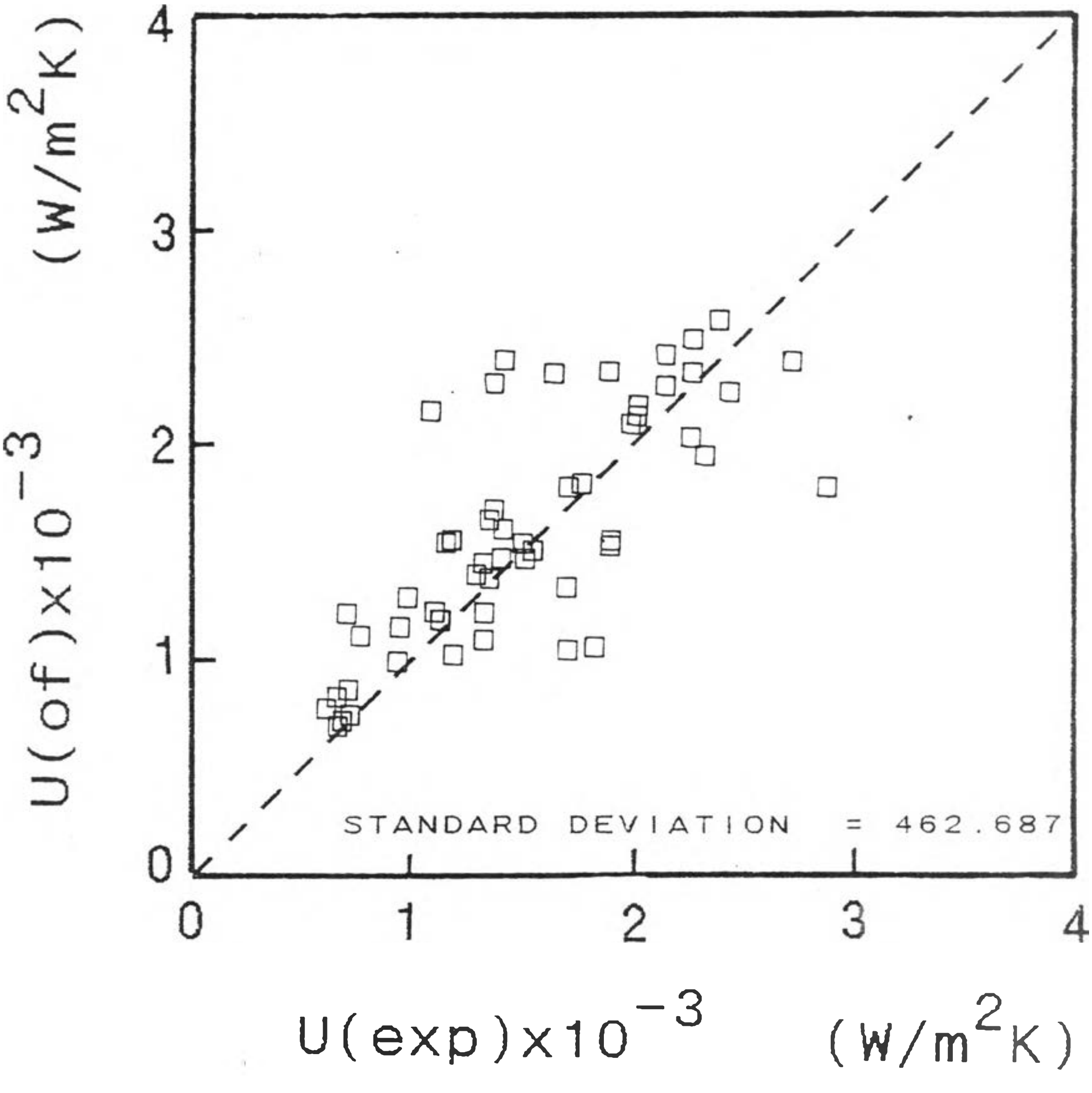

Figure 5.13(b) Comparison between the experimental value of U and the value estimated from eqn(5-7) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 5 LPM.

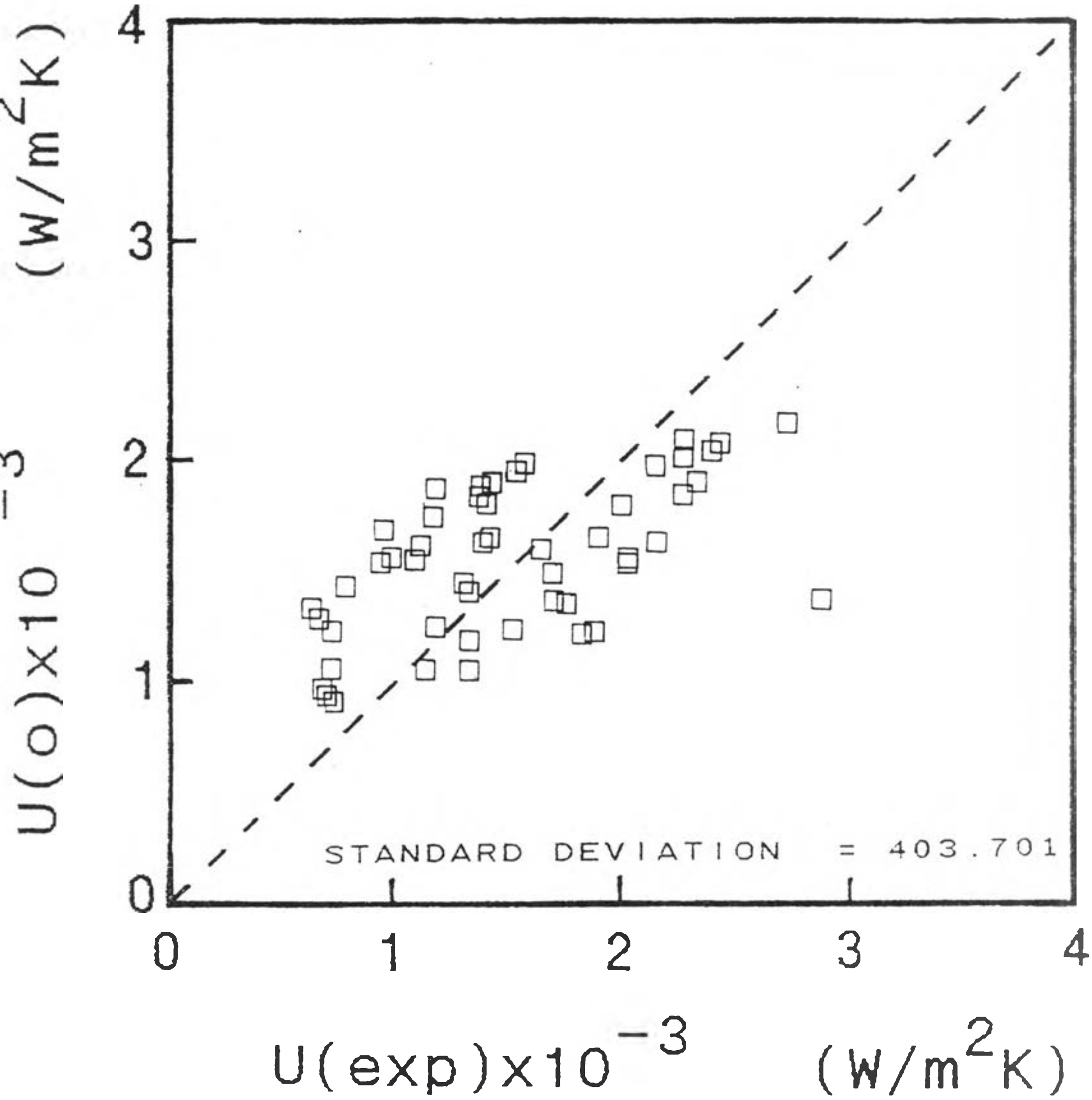

Figure 5.13(c) Comparison between the experimental value of U and the value estimated from eqn(5-8) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,4,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 5 LPM.

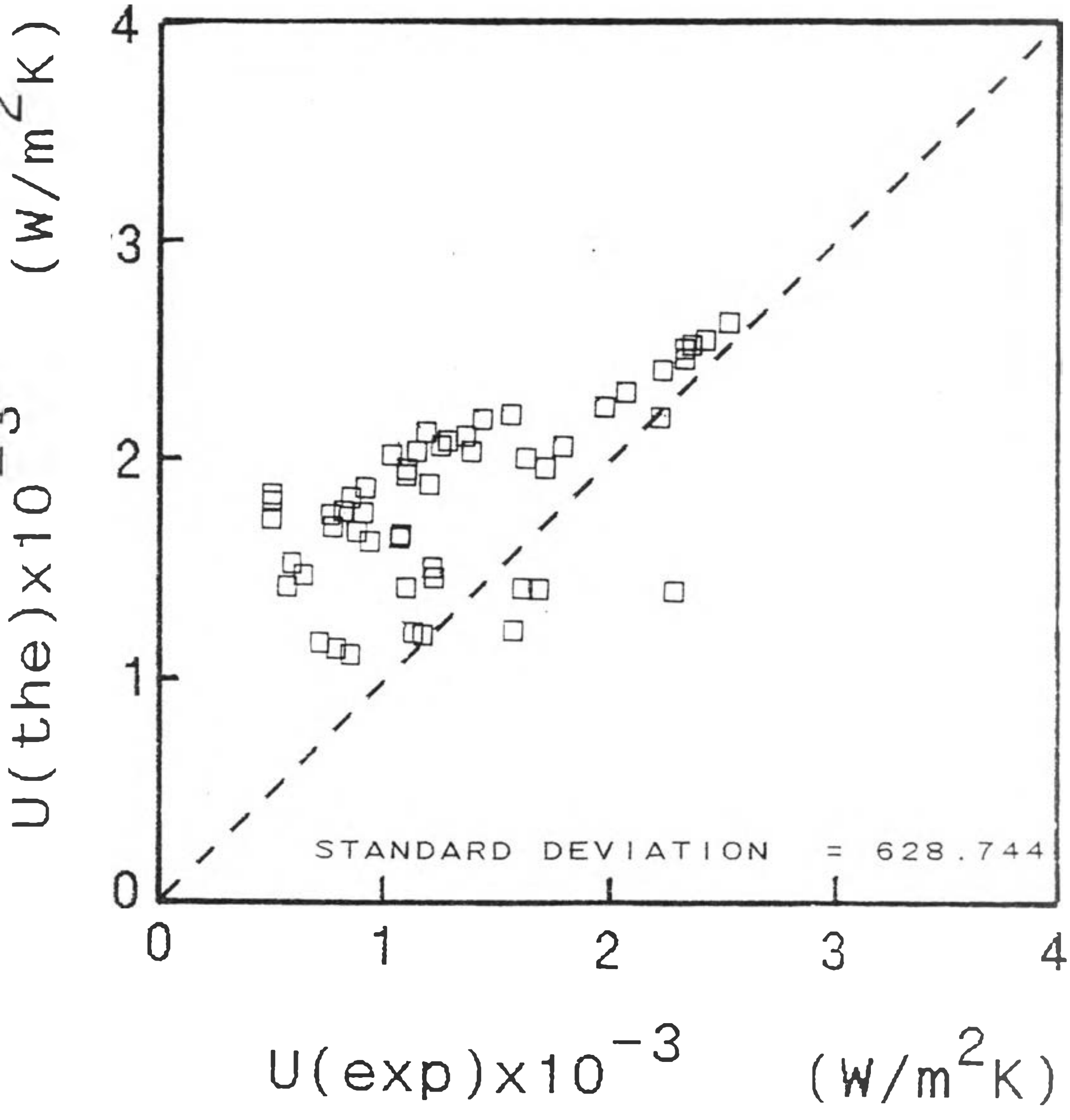

Figure 5.14(a) Comparison between the experimental value of U and the theoretical value given by eqn(5-6) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,5,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 4 LPM.

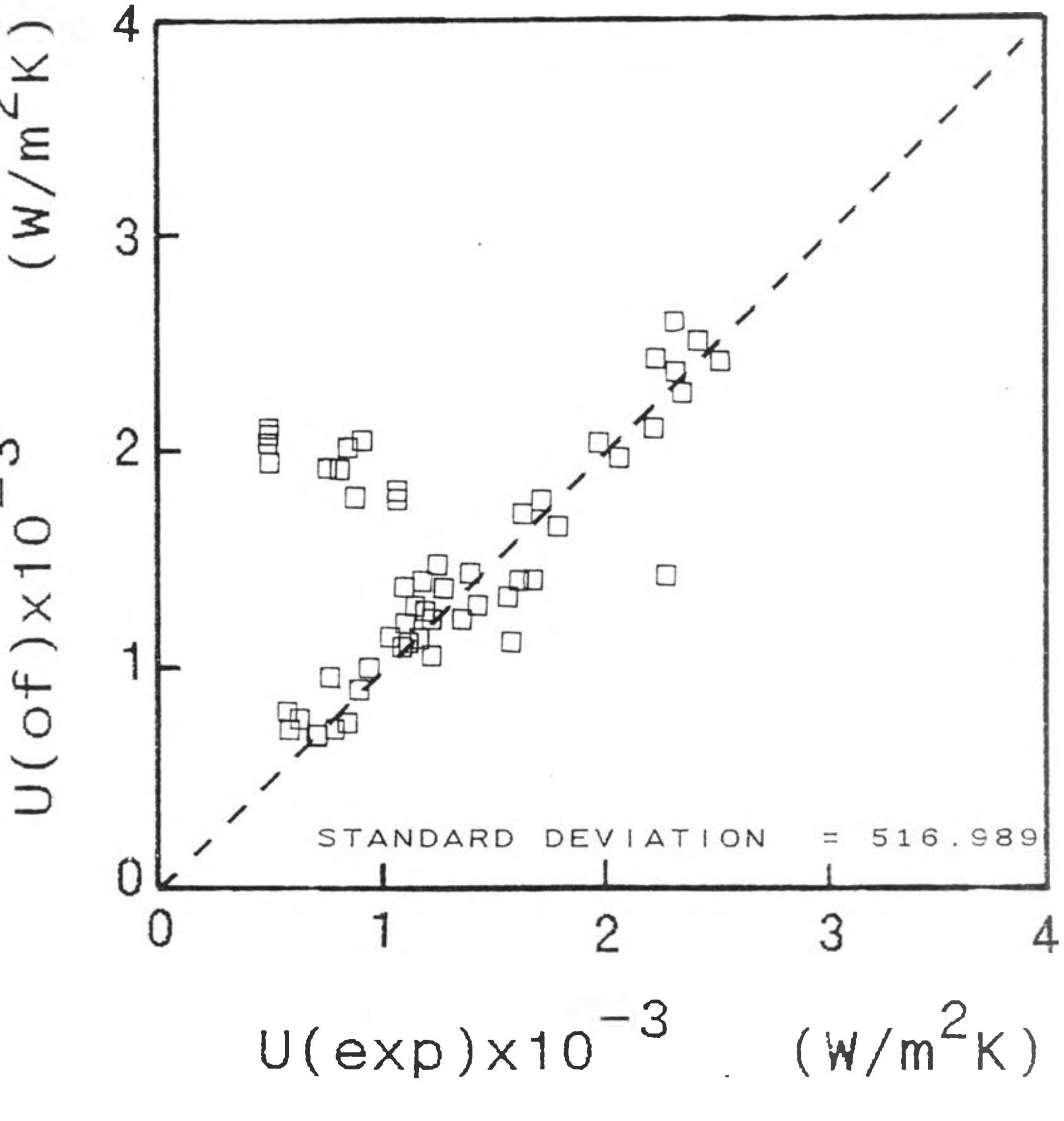

Figure 5.14(b) Comparison between the experimental value of U and the value estimated from eqn(5-7) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,5,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 4 LPM.

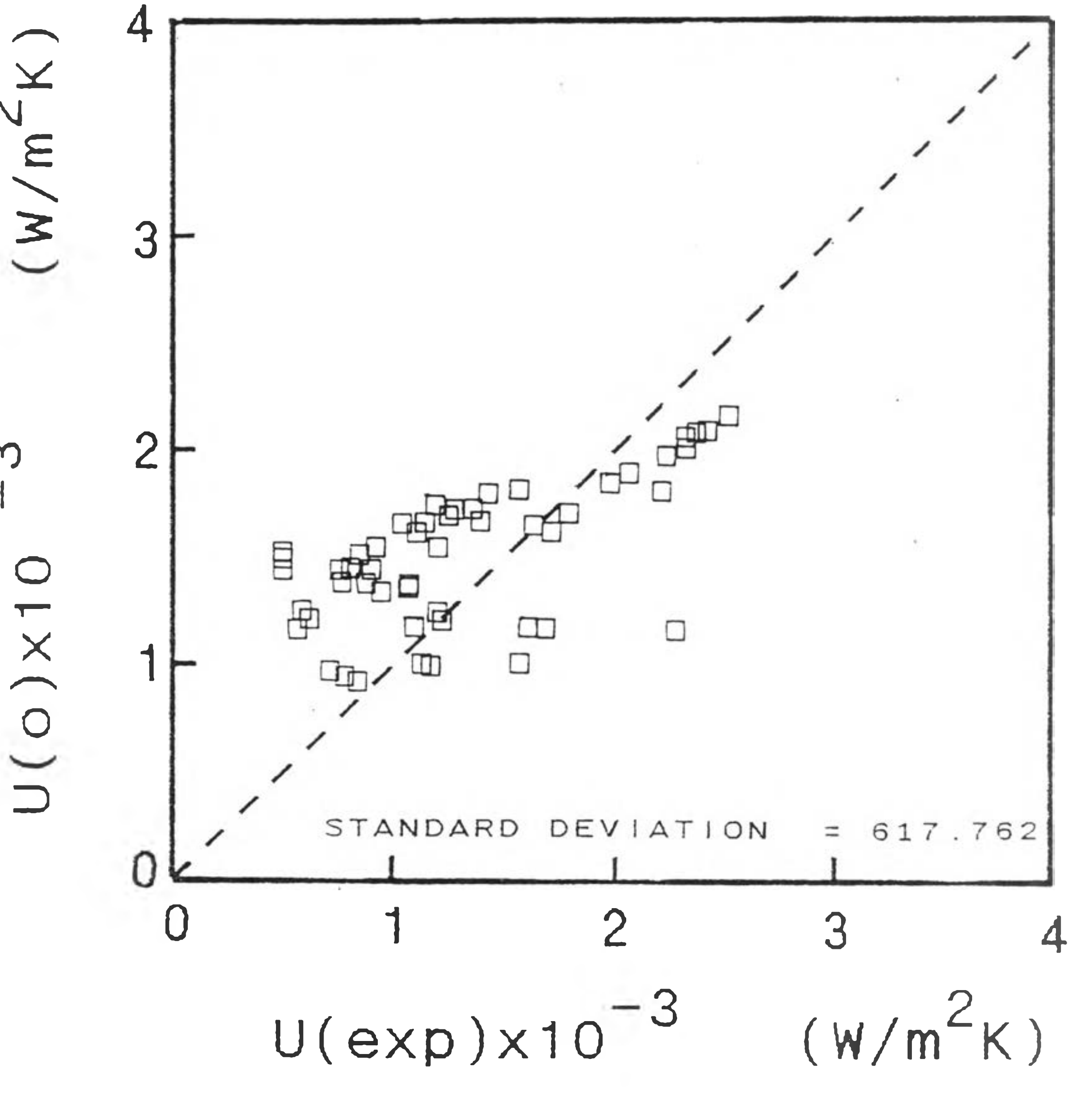

Figure 5.14(c) Comparison between the experimental value of U and the value estimated from eqn(5-8) for the case of unequal water/water flow rates;

Flow rate of product = 2,3,5,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 4 LPM.

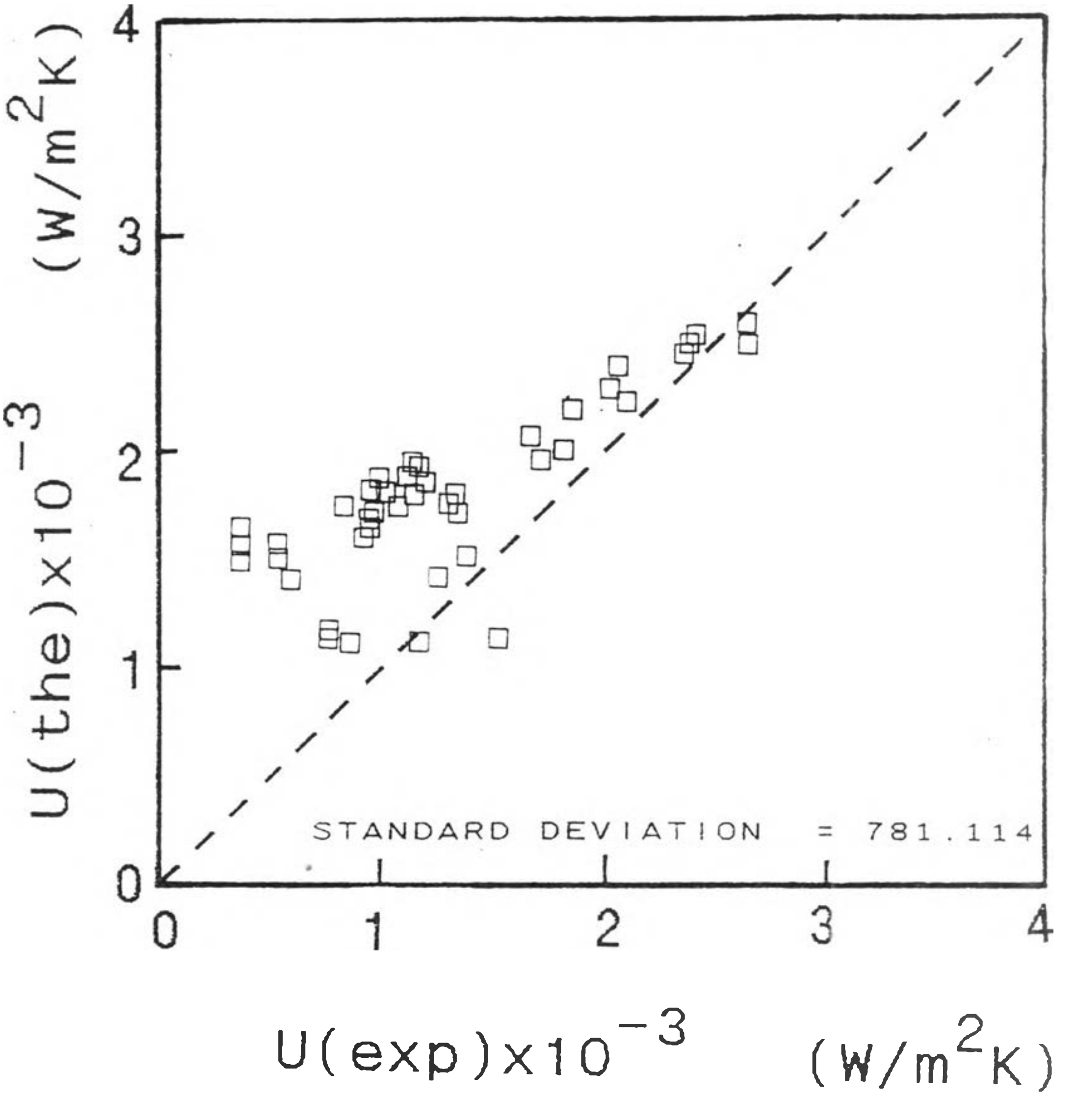

Figure 5.15(a) Comparison between the experimental value of U and the theoretical value given by eqn(5-6) for the case of unequal water/water flow rates;

Flow rate of product = 2,4,5,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 3 LPM.

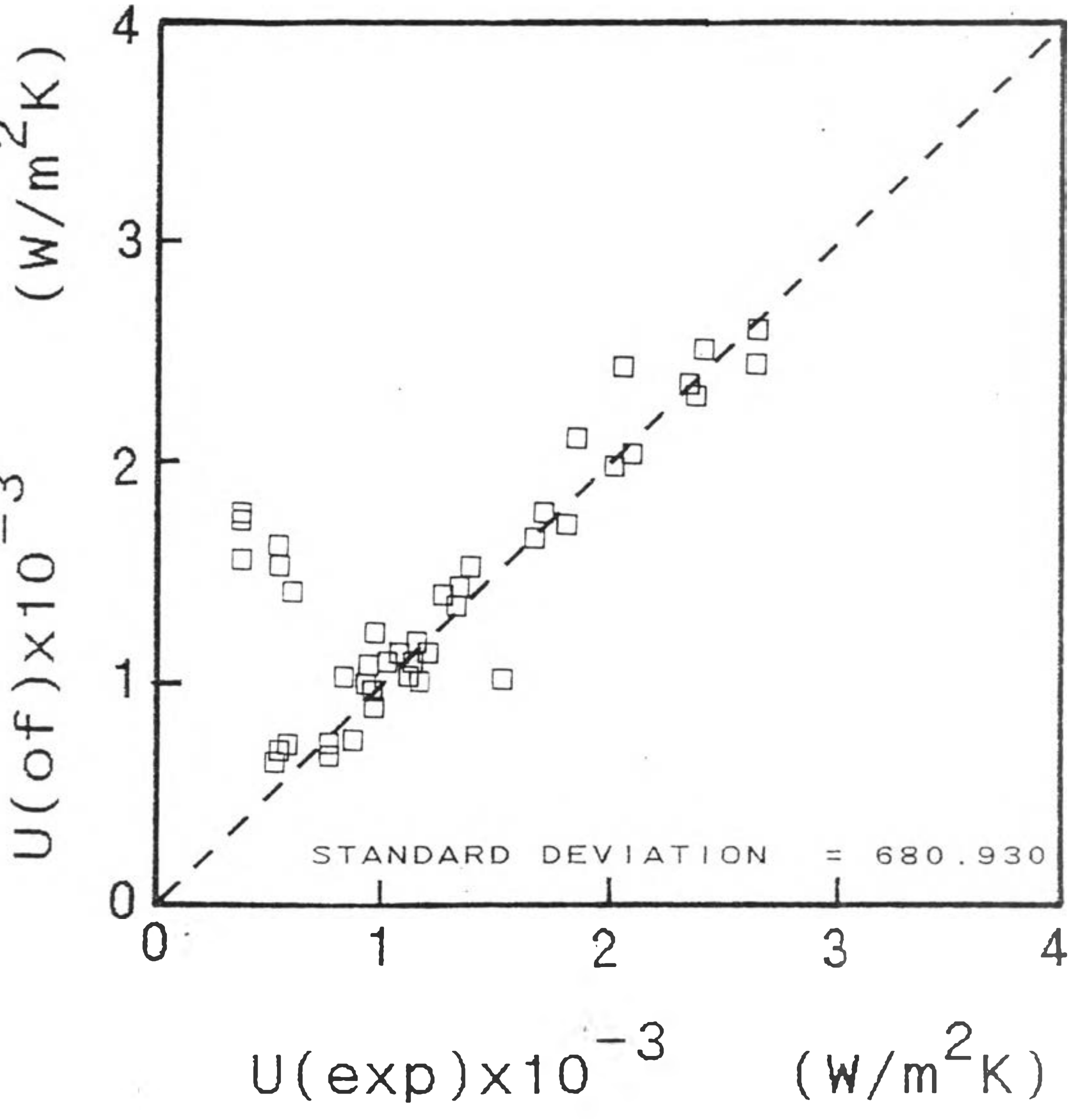

Figure 5.15(b) Comparison between the experimental value of U and the value estimated from eqn(5-7) for the case of unequal water/water flow rates;

Flow rate of product = 2,4,5,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 3 LPM.

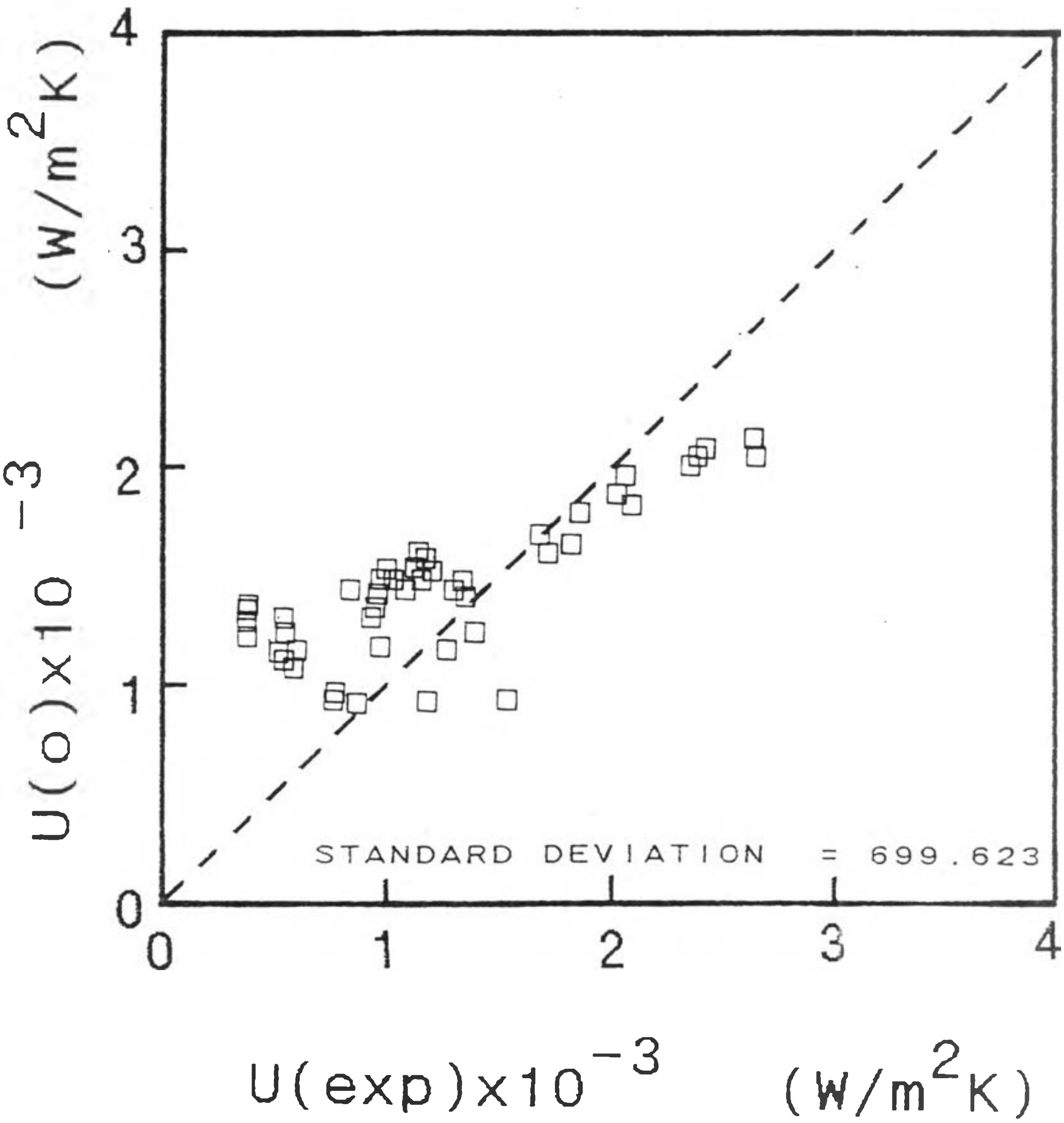

Figure 5.15(c) Comparison between the experimental value of U and the value estimated from eqn(5-8) for the case of unequal water/water flow rates;

Flow rate of product = 2,4,5,6,7,7.5 LPM.,

Flow rate of cooling water = Flow rate of hot water = 3 LPM.

product is changed here to a sugar syrup of various concentrations in order to increase the range of the Prandtl number.

The Nusselt number and the overall heat transfer coefficient are obtained from the experimental results in the same manner as in the case of equal water/water flow rates. Program 4 (shown in appendix A4) which calculates the physical properties of the syrup (viscosity, thermal conductivity and specific heat as presented in appendix B) is very handy. The inputs to program 4 are the inlet and outlet temperatures, flow rates, densities, and concentrations of solute and percent brix. Table 5.4 lists, as function of Re and Pr, Nu(exp), Nu(the), the value of Nu predicted by correlation (5-9) (Nu_{sof} or Nu(sof)), and the value of Nu predicted by correlation (5-10) (Nu_{so} or Nu(so)). The meanings of Nu(to) and Nu(tof) in Table 5.4 will be explained later. Program 2 is again used to estimate the optimal values of the constants for the heat transfer correlation. This particular set of experiments contains 42 experimental points with the Reynolds number ranging between 140 and 1,189 and the Prandlt number ranging between 5.12 and 17.45. The correlations obtained may be summarized as follow.

Constrained linear regression analysis (b set at 0.4):

$$Nu_{sof} = 0.15\ Re^{0.75}\ Pr^{0.4} \text{ with } \sigma = 0.069 \qquad (5\text{-}9)$$

Unconstrained linear regression analysis:

$$Nu_{so} = 0.07\ Re^{0.8}\ Pr^{0.54} \text{ with } \sigma = 0.067 \qquad (5\text{-}10)$$

Table 5.4 Experimental and estimated values of the Nusselt number.

System: syrup/syrup (concentration 20 wt%)

T10(°C)	Flow(LPM)	Re	Pr	Nu(exp)	Nu(the)	Nu(so)	Nu(sof)	Nu(to)	Nu(tof)
98	2	410.09	5.12	19.56	21.62	20.81	21.93	13.41	21.03
	3	615.34	5.12	23.69	28.37	28.81	29.38	19.10	26.30
	4	808.54	5.21	28.63	34.28	36.16	36.00	24.53	30.76
	5	993.16	5.31	37.34	39.65	43.06	42.06	29.77	34.70
	6	1188.95	5.32	43.12	44.77	49.81	47.93	34.89	38.35
85	2	373.77	5.66	18.82	21.15	20.39	21.35	13.37	20.80
	3	553.61	5.73	27.01	27.67	28.14	28.48	19.02	25.96
	4	727.05	5.83	31.49	33.43	35.31	34.89	24.43	30.36
	5	897.32	5.92	36.94	38.70	42.10	40.83	29.66	34.27
	6	1071.26	5.95	44.29	43.68	48.66	46.49	34.76	37.87
75	2	331.87	6.43	18.65	20.56	19.88	20.63	13.33	20.51
	3	498.99	6.41	61.72	27.00	27.49	27.63	18.95	25.63
	4	670.75	6.36	35.49	32.80	34.68	34.08	24.36	30.06
	5	829.69	6.43	43.56	38.00	41.37	39.90	29.57	33.94
	6	995.76	6.43	45.44	42.93	47.88	45.51	34.67	37.53

System: syrup/syrup (concentration 30 wt%)

T10(°C)	Flow(LPM)	Re	Pr	Nu(exp)	Nu(the)	Nu(so)	Nu(sof)	Nu(to)	Nu(tof)
98	2	272.07	8.02	17.63	19.64	19.10	19.53	13.31	20.08
	3	402.50	8.14	25.11	25.68	26.34	26.04	18.94	25.05
	4	524.91	8.34	29.89	30.98	33.01	31.84	24.32	29.28
	5	650.72	8.42	35.55	35.90	39.39	37.31	29.53	33.08
	6	774.18	8.49	44.41	40.48	45.48	42.43	34.59	36.52
85	2	240.79	9.12	19.28	19.07	18.57	18.83	13.24	19.77
	3	358.19	9.21	24.14	24.97	25.65	25.17	18.85	24.69
	4	467.98	9.41	33.06	30.13	32.14	30.77	24.19	28.85
	5	579.97	9.50	38.60	34.92	38.36	36.05	29.37	32.59
	6	690.01	9.59	43.97	39.37	44.31	41.01	34.42	36.00
75	2	220.68	10.02	16.15	18.67	18.22	18.36	13.20	19.56
	3	320.54	10.38	19.89	24.31	25.04	24.37	18.79	24.37
	4	424.76	10.44	30.33	29.44	31.46	29.92	24.11	28.52
	5	521.55	10.65	35.93	34.04	37.47	34.95	29.27	32.17
	6	622.01	10.71	50.36	38.41	43.28	39.77	34.27	35.53

Table 5.4 (continued)

System: syrup/syrup (concentration 40 wt%)

T10(°C)	Flow(LPM)	Re	Pr	Nu(exp)	Nu(the)	Nu(so)	Nu(sof)	Nu(to)	Nu(tof)
98	2	181.14	12.56	16.45	17.88	17.57	17.43	13.26	19.21
	3	272.68	12.53	22.12	23.49	24.35	23.38	18.89	24.03
	4	353.60	12.91	27.52	28.28	30.46	28.54	24.25	28.06
	5	435.05	13.12	35.69	32.72	36.28	33.35	29.42	31.66
85	2	158.55	14.44	17.18	17.31	17.04	16.75	13.17	18.88
	3	234.94	14.66	20.44	22.65	23.53	22.37	18.76	23.58
	4	306.21	15.01	27.61	27.31	29.46	27.33	24.07	27.54
	5	376.55	15.27	36.04	31.59	35.08	31.93	29.20	31.07
75	2	140.07	16.47	16.57	16.80	16.57	16.15	13.10	18.59
	3	203.96	17.01	22.66	21.88	22.77	21.44	18.64	23.15
	4	270.31	17.16	23.05	26.49	28.65	26.35	23.97	27.12
	5	332.14	17.45	33.58	30.64	34.10	30.77	29.05	30.58

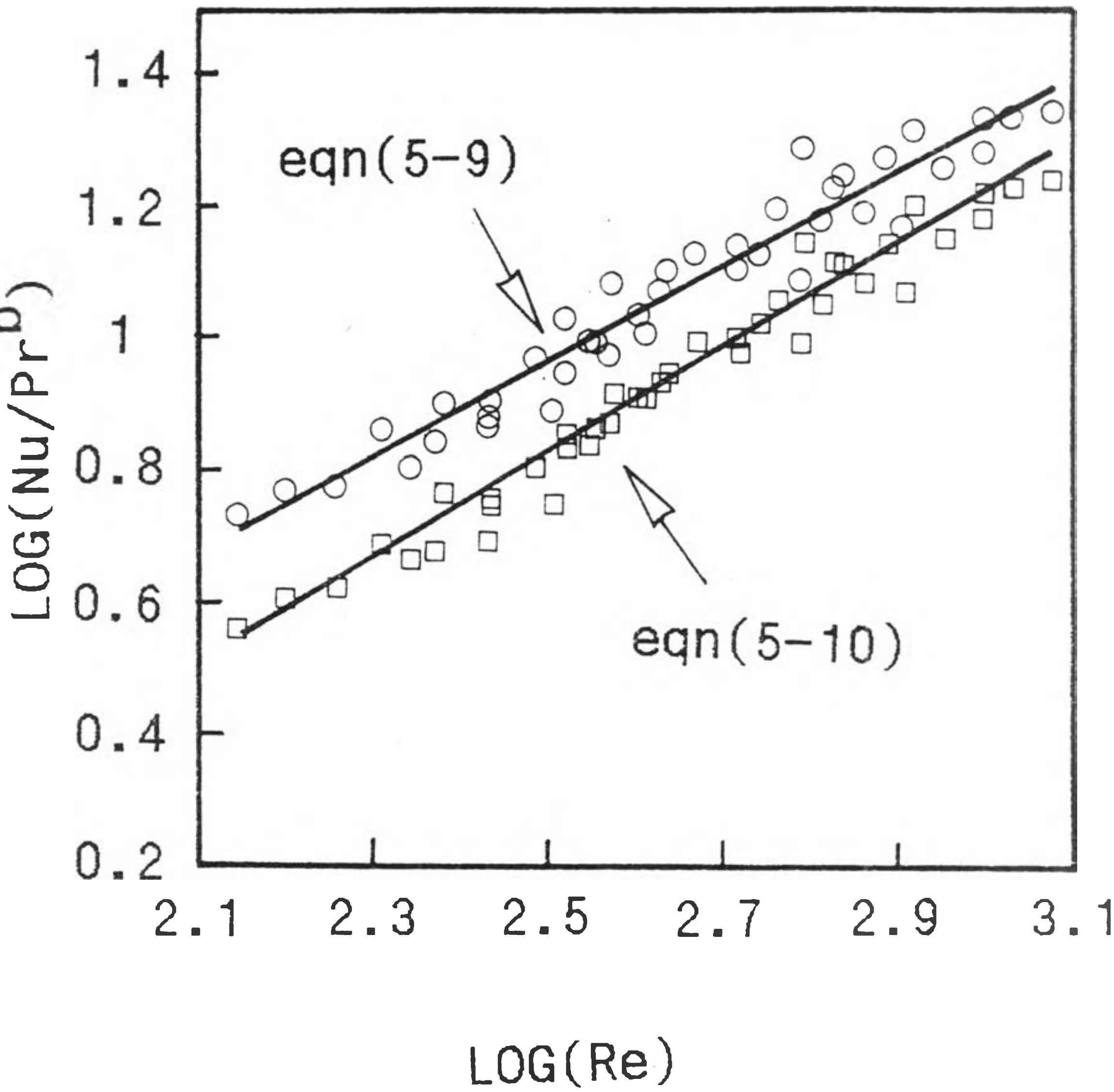

Figure 5.16 Experimental results for the case of equal syrup/syrup flow rates; (at hot water temperature ,T10 = 98, 85, and 75 °C , ○ : b = 0.4, □ : b = 0.54).

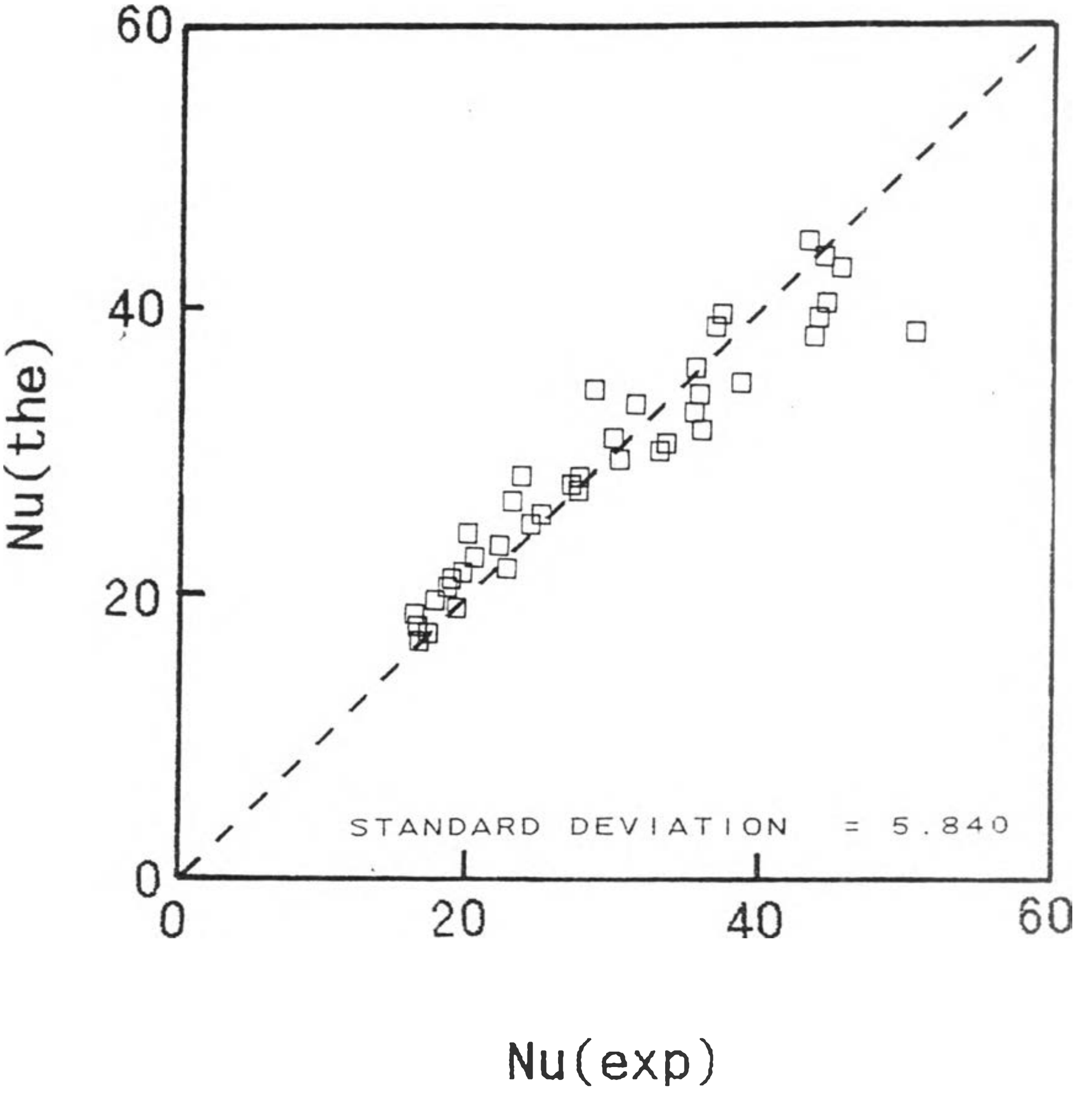

Figure 5.17 Comparison between Nu_{exp}, the experimental value of the Nusselt number and Nu_{the}, the theoretical value based on eqn(5-6) for the case of equal syrup/syrup flow rates.

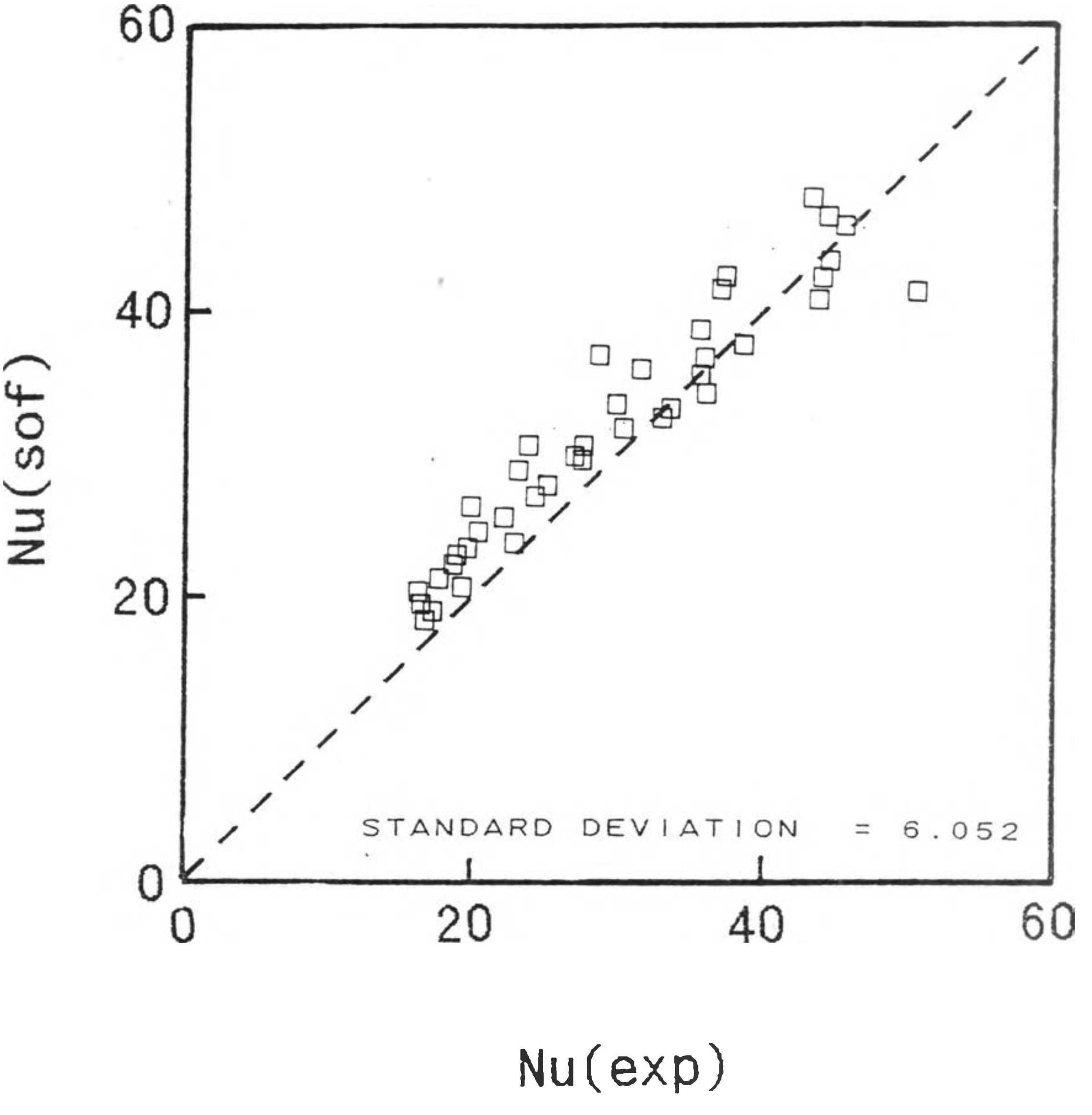

Figure 5.18 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-9) for the case of equal syrup/syrup flow rates.

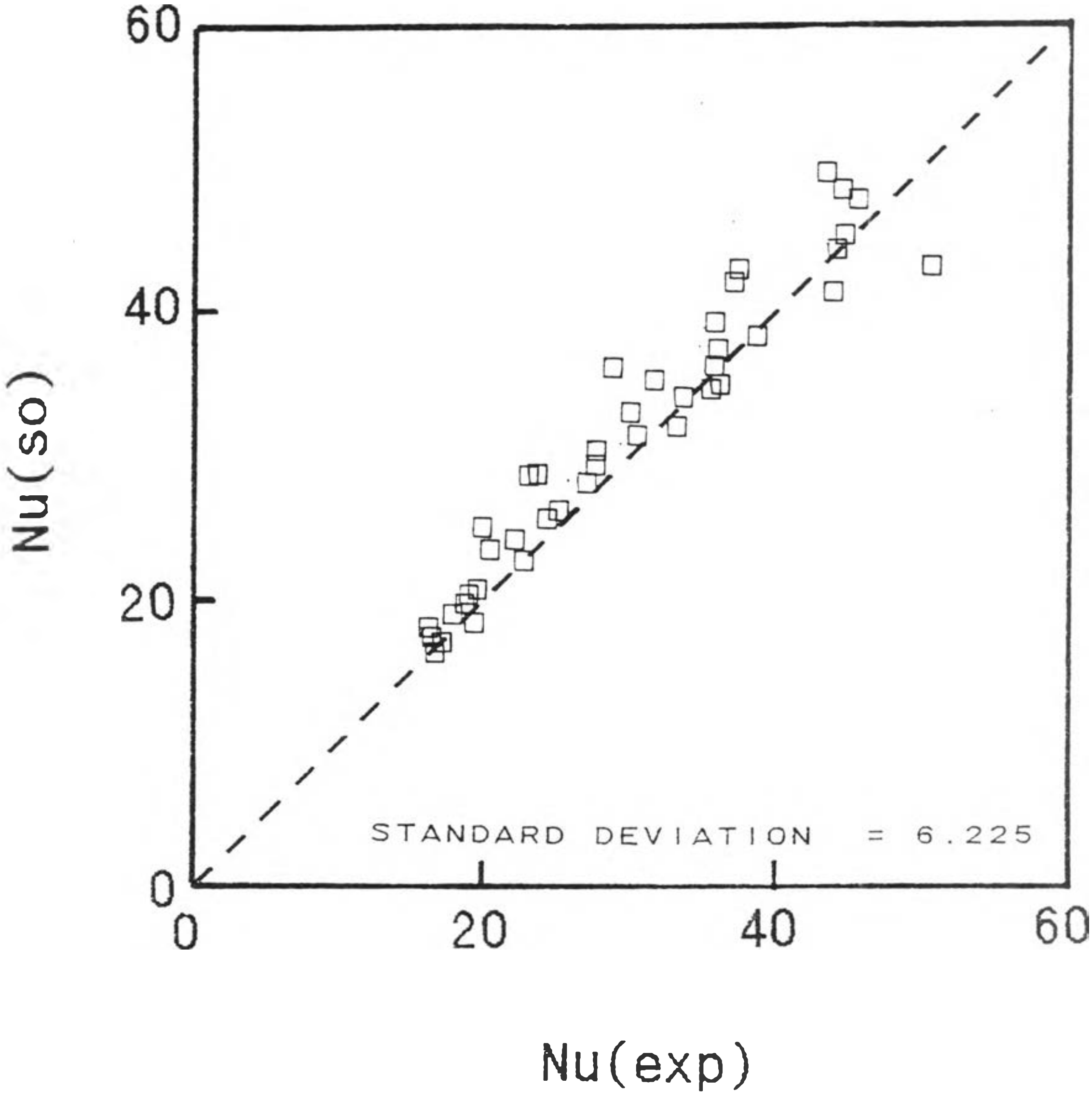

Figure 5.19 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-10) for the case of equal syrup/syrup flow rates.

Fig. 5-16 shows the experimental results obtained with equal flow rates of syrup and syrup streams. The symbol ○ is for the case in which the exponent b = 0.4, and □ for b = 0.54, respectively, are used to present the experimental results. It is obvious that the correlation obtained by unconstrained regression analysis, i.e. eqn (5-10), fits the experimental data better than that obtained by constrained regression analysis, i.e. eqn (5-9). The same conclusion is reached when one looks at Table 5.4.

Figs. 5.17-5.19 graphically compare Nu_{exp}, the experimental value of Nu, respectively with Nu_{the}, the theoretical value of Nu given by eqn (5-6), Nu_{sof}, the value of Nu predicted by constrained correlation (5-9), and Nu_{so} the value of Nu predicted by unconstrained correlation (5-10). The correlation (5-10) obviously fits the data reasonably well, since the relationship between Nu predicted and Nu_{exp} lies close to the dotted diagonol line.

In summary, it may be concluded that, for the case of equal flow rates of syrup and syrup streams, the correlation (5-10) gives the best predictions of the syrup film heat transfer coefficient expressed in terms of Nu.

Table 5.5 lists the experimental values of the overall heat transfer coefficient, U_{exp}, the values of U, i.e. U_{sof} or U(sof), predicted by correlation (5-9), the values of U, i.e. U_{so} or U(so) predicted by correlation (5-10), and the theoretical values of U, i.e. U_{the} or U(the), given by correlation (5-6). It is obvious that correlation (5-10) predictions the overall heat transfer coefficient reasonably well. Figs 5.20-5.22 graphically compare respectively the pairs of U_{exp} and U_{the}, U_{exp} and U_{sof}, and

Table 5.5 Experimental and estimated values of the overall heat transfer coefficient.

System: syrub/syrub (concentration 20 wt%)

T10(°C)	Flow(LPM)	U(exp)	U(the)	U(so)	U(sof)	U(to)	U(tof)
98	2	882.749	972.423	936.198	984.737	610.459	945.925
	3	1061.921	1261.704	1277.701	1302.382	860.465	1171.958
	4	1271.683	1508.138	1582.600	1576.398	1093.615	1358.954
	5	1633.067	1726.922	1861.710	1821.805	1314.253	1521.538
	6	1868.194	1933.830	2129.609	2056.179	1527.061	1671.342
85	2	844.293	945.234	911.712	952.962	604.548	929.346
	3	1194.661	1222.183	1240.522	1255.369	851.101	1148.876
	4	1380.934	1461.115	1536.627	1519.818	1081.760	1332.241
	5	1604.266	1675.663	1810.364	1759.619	1300.702	1492.997
	6	1900.279	1875.459	2070.023	1984.889	1511.045	1639.382
75	2	828.964	911.221	881.047	913.431	597.001	908.305
	3	2563.870	1184.391	1204.722	1210.637	841.967	1126.517
	4	1536.911	1426.238	1502.482	1478.036	1072.814	1312.202
	5	1860.631	1637.066	1771.653	1713.001	1290.320	1471.245
	6	1935.056	1835.272	2028.961	1936.020	1499.839	1617.107

System: syrub/syrub (concentration 30 wt%)

T10(°C)	Flow(LPM)	U(exp)	U(the)	U(so)	U(sof)	U(to)	U(tof)
98	2	749.996	832.634	808.695	826.595	568.640	849.504
	3	1055.024	1077.635	1101.594	1090.184	800.913	1050.778
	4	1244.448	1287.097	1363.675	1318.481	1017.798	1217.747
	5	1466.829	1479.579	1610.560	1530.802	1224.977	1366.616
	6	1806.779	1656.033	1842.095	1726.975	1423.312	1500.524
85	2	811.220	802.574	781.303	792.077	561.545	830.483
	3	1007.648	1040.681	1066.221	1046.963	791.426	1028.402
	4	1359.537	1244.185	1321.190	1267.708	1006.072	1192.473
	5	1573.121	1430.492	1560.737	1472.187	1210.940	1338.339
	6	1776.307	1601.204	1785.359	1661.029	1407.059	1469.490
75	2	678.568	781.542	762.112	768.048	556.485	817.003
	3	829.077	1006.226	1033.209	1006.902	782.390	1007.201
	4	1243.616	1208.504	1285.833	1225.709	996.137	1171.156
	5	1458.857	1385.874	1515.419	1419.208	1197.928	1312.224
	6	2000.719	1552.958	1735.383	1603.332	1392.459	1441.736

Table 5.5 (continued)

System: syrub/syrub (concentration 40 wt%)

T10(°C)	Flow(LPM)	U(exp)	U(the)	U(so)	U(sof)	U(to)	U(tof)
98	2	655.792	711.220	697.304	692.152	529.219	761.062
	3	874.685	926.394	955.809	919.709	747.125	945.047
	4	1077.910	1106.000	1183.052	1111.819	949.473	1094.931
	5	1380.266	1270.192	1396.385	1289.527	1142.570	1228.011
85	2	678.730	683.553	671.791	660.936	522.129	742.887
	3	802.903	886.404	917.060	873.711	736.008	919.965
	4	1071.955	1060.324	1137.254	1058.650	935.966	1067.082
	5	1381.082	1217.808	1342.513	1227.981	1126.358	1196.771
75	2	650.121	658.582	648.726	632.942	515.572	726.212
	3	879.338	849.892	881.628	832.043	725.563	896.578
	4	893.296	1021.493	1098.288	1013.765	924.202	1042.941
	5	1280.828	1173.351	1296.746	1176.116	1112.253	1169.733

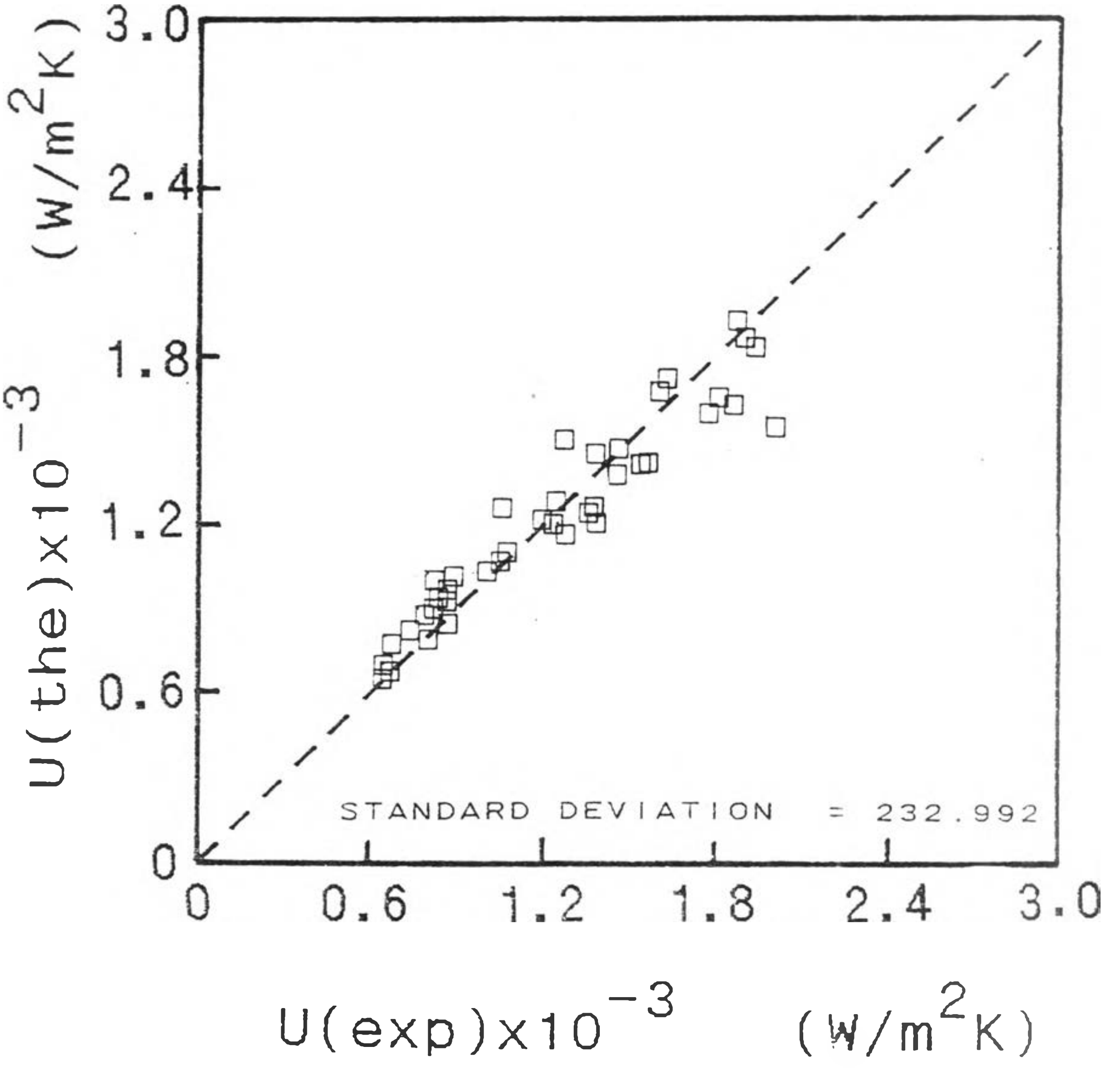

Figure 5.20 Comparison between the experimental value of the overall heat transfer coefficient and the theoretical value given by eqn(5-6) for the case of equal syrup/syrup flow rates.

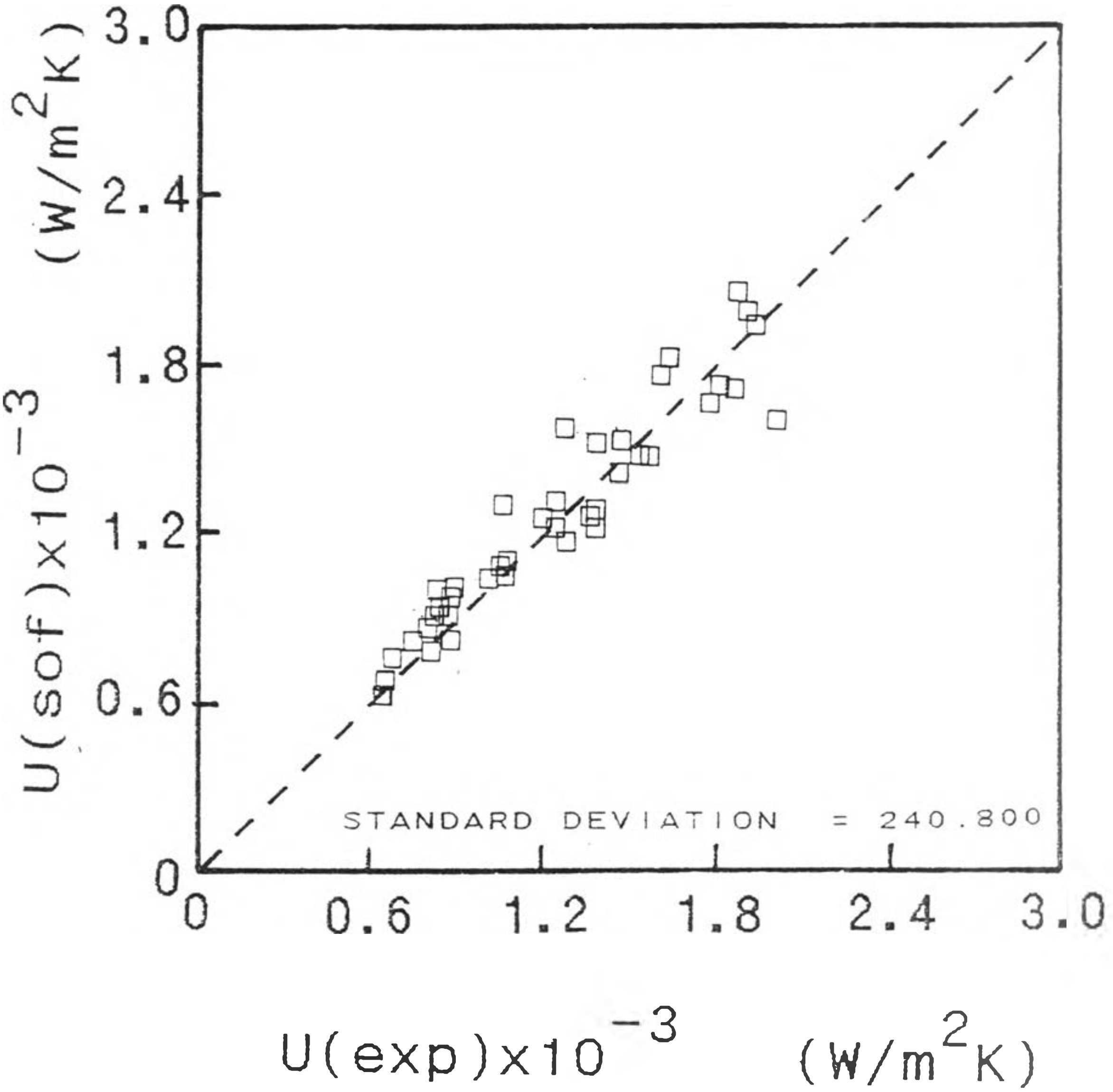

Figure 5.21 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-9) for the case of equal syrup/syrup flow rates.

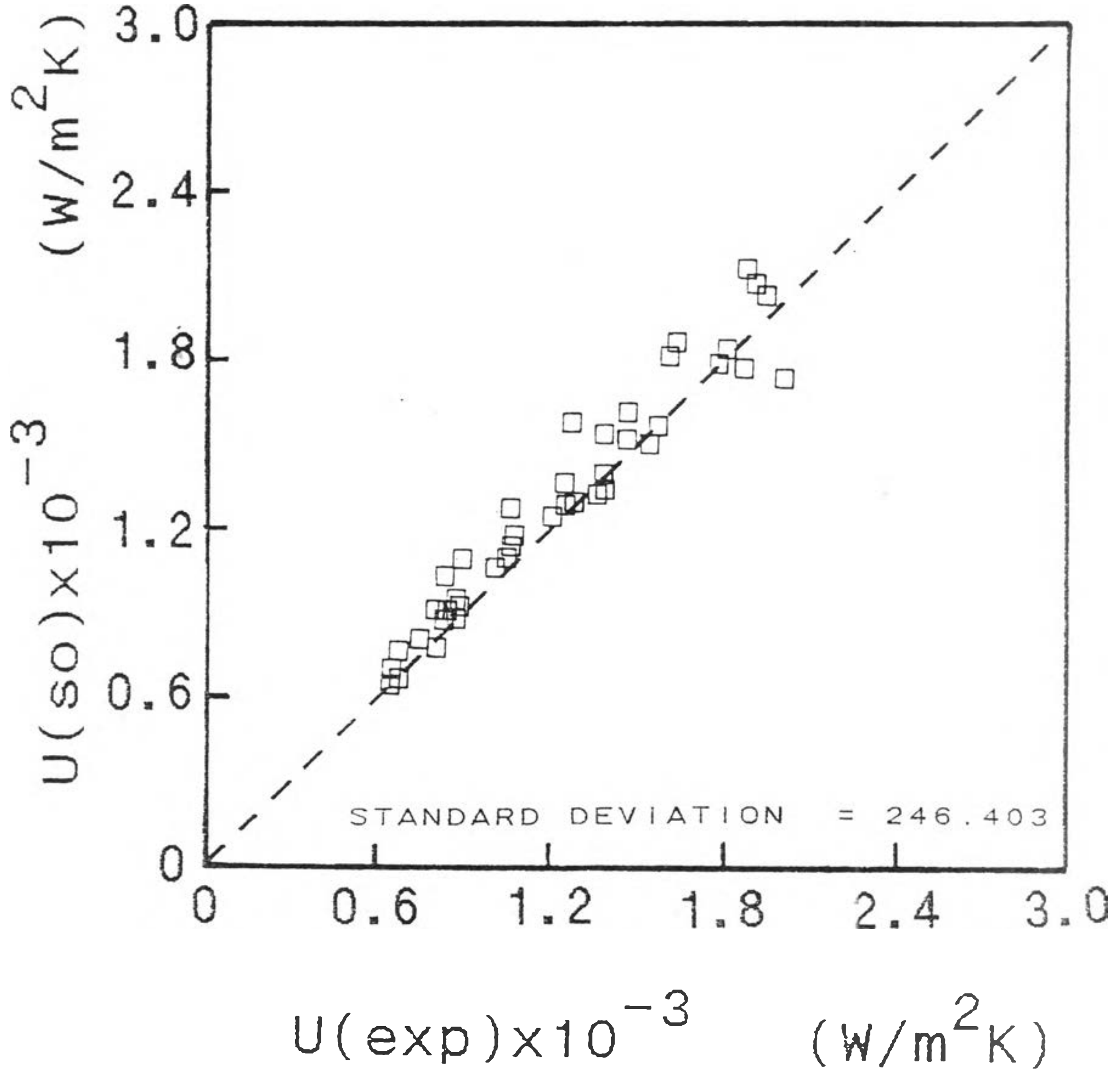

Figure 5.22 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn.(5-10) for the case of equal syrup/syrup flow rates.

U_{exp} and U_{eo}. As mentioned above, correlation (5-10) as represented by Fig. 5.16 gives the best predictions for the overall heat transfer coefficient U.

5.4. Equal glycerine/glycerine flow rates

In this set of experiments glycerine is used to increase further the values of the Prandtl number beyond those obtained in the case of syrup. Program 5 is handy to use in this set of experiments(see appendix A5). The program calculates the viscosity of glycerine (presented in appendix B) based on the inlet and outlet temperatures, the flow rates,densities and concentrations of glycerine. Table 5.6 lists, as function of Re and Pr, the experimental values of Nu(Nu_{exp}), the theoretical values of Nu given by correlation (5-6) (Nu_{the} or Nu(the)), the values of Nu predicted by correlation (5-11) (Nu_{gof} or Nu(gof)), and the values of Nu predicted by correlation (5-12) (Nu_{go} or Nu(go)). The meanings of Nu(to) and Nu(tof) in Table 5.6 will be explained later. Program 2 is again used to estimate the constants for the heat transfer correlations. For this set of experiments contains 42 data points with the Reynolds number ranging between 86 and 700 and the Prandlt number ranging between 11 and 40. The correlations obtained may be summarized as follows.

Constrained linear regression analysis (b set at 0.4):

$$Nu_{gof} = 0.23\ Re^{0.66}\ Pr^{0.4} \quad \text{with } \sigma = 0.039 \qquad (5\text{-}11)$$

Unconstrained linear regression analysis:

Table 5.6 Experimental and estimated values of the Nusselt number.

System: glycerine/glycerine (concentration 40 vol%)

T10(°C)	Flow(LPM)	Re	Pr	Nu(exp)	Nu(the)	Nu(go)	Nu(gof)	Nu(to)	Nu(tof)
98	2	248.40	10.83	18.13	20.83	19.46	22.72	15.55	21.54
	3	366.08	11.02	27.23	27.20	26.29	29.55	22.10	26.85
	4	481.04	11.19	34.55	32.85	32.55	35.60	28.35	31.39
	5	587.21	11.46	42.18	37.90	38.32	41.00	34.35	35.36
	6	698.75	11.57	44.36	42.72	43.90	46.17	40.27	39.06
85	2	217.75	12.34	17.76	20.10	18.99	21.94	15.25	21.11
	3	323.71	12.45	25.39	26.31	25.71	28.61	21.84	26.35
	4	421.11	12.76	36.65	31.70	31.74	34.36	27.97	30.74
	5	520.12	12.92	39.69	36.69	37.46	39.70	33.95	34.71
	6	614.72	13.12	46.05	41.28	42.84	44.61	39.74	38.29
75	2	195.40	13.72	23.71	19.53	18.60	21.32	15.18	20.75
	3	284.14	14.16	30.26	25.41	25.08	27.64	21.55	25.82
	4	369.62	14.54	30.38	30.60	31.01	33.22	27.65	30.15
	5	448.98	14.95	40.39	35.26	36.46	38.20	33.48	33.94
	6	530.49	15.20	40.88	39.67	41.72	42.93	39.21	37.45

System: glycerine/glycerine (concentration 50 vol%)

T10(°C)	Flow(LPM)	Re	Pr	Nu(exp)	Nu(the)	Nu(go)	Nu(gof)	Nu(to)	Nu(tof)
98	2	190.26	15.30	20.63	19.99	19.41	21.88	16.15	21.36
	3	275.01	15.91	26.71	25.97	26.15	28.34	22.94	26.57
	4	363.18	16.09	31.10	31.40	32.43	34.20	29.48	31.10
	5	441.83	16.56	36.09	36.19	38.19	39.38	35.75	35.04
	6	526.25	16.66	46.43	40.82	43.69	44.30	41.32	38.67
85	2	163.19	17.81	20.16	19.19	18.86	21.01	15.91	20.36
	3	238.04	18.34	26.71	24.98	25.45	27.27	22.60	25.97
	4	309.52	18.79	37.18	30.09	31.43	32.75	28.95	30.31
	5	377.56	19.29	38.83	34.71	37.02	37.73	35.12	34.16
	6	449.64	19.42	52.04	39.14	42.36	42.45	41.10	37.71
75	2	140.81	20.62	20.54	18.44	18.35	20.21	15.69	20.40
	3	207.43	21.01	28.01	24.07	24.80	26.29	22.29	25.43
	4	272.65	21.33	31.73	29.08	30.71	31.68	28.62	29.73
	5	337.02	21.56	41.40	33.67	36.23	36.60	34.70	33.55
	6	397.28	21.98	41.11	37.85	41.44	41.11	40.65	37.02

Table 5.6 (continued)

System: glycerine/glycerine (concentration 60 vol%)

T10(°C)	Flow(LPM)	Re	Pr	Nu(exp)	Nu(the)	Nu(go)	Nu(gof)	Nu(to)	Nu(tof)
98	2	116.06	27.60	19.34	18.16	18.75	19.99	16.64	20.61
	3	169.42	28.44	24.89	23.65	25.33	25.97	23.68	25.68
	4	221.86	28.94	33.37	28.53	31.31	31.24	30.35	29.99
	5	267.76	30.03	36.85	32.82	36.82	35.89	36.78	33.75
85	2	92.09	34.77	17.81	17.06	17.98	18.82	16.29	19.90
	3	139.70	34.40	24.65	22.45	24.42	24.67	23.22	24.92
	4	183.54	34.91	31.80	27.12	30.23	29.72	29.79	29.13
	5	223.61	35.85	36.48	31.27	35.58	34.21	36.11	32.81
75	2	86.01	37.11	17.96	16.75	17.73	18.46	16.15	19.67
	3	128.50	37.24	28.72	21.96	24.00	24.10	22.97	24.57
	4	165.73	38.56	30.93	26.39	29.63	28.91	29.45	28.65
	5	200.26	39.92	37.32	30.36	34.83	33.21	35.67	32.24

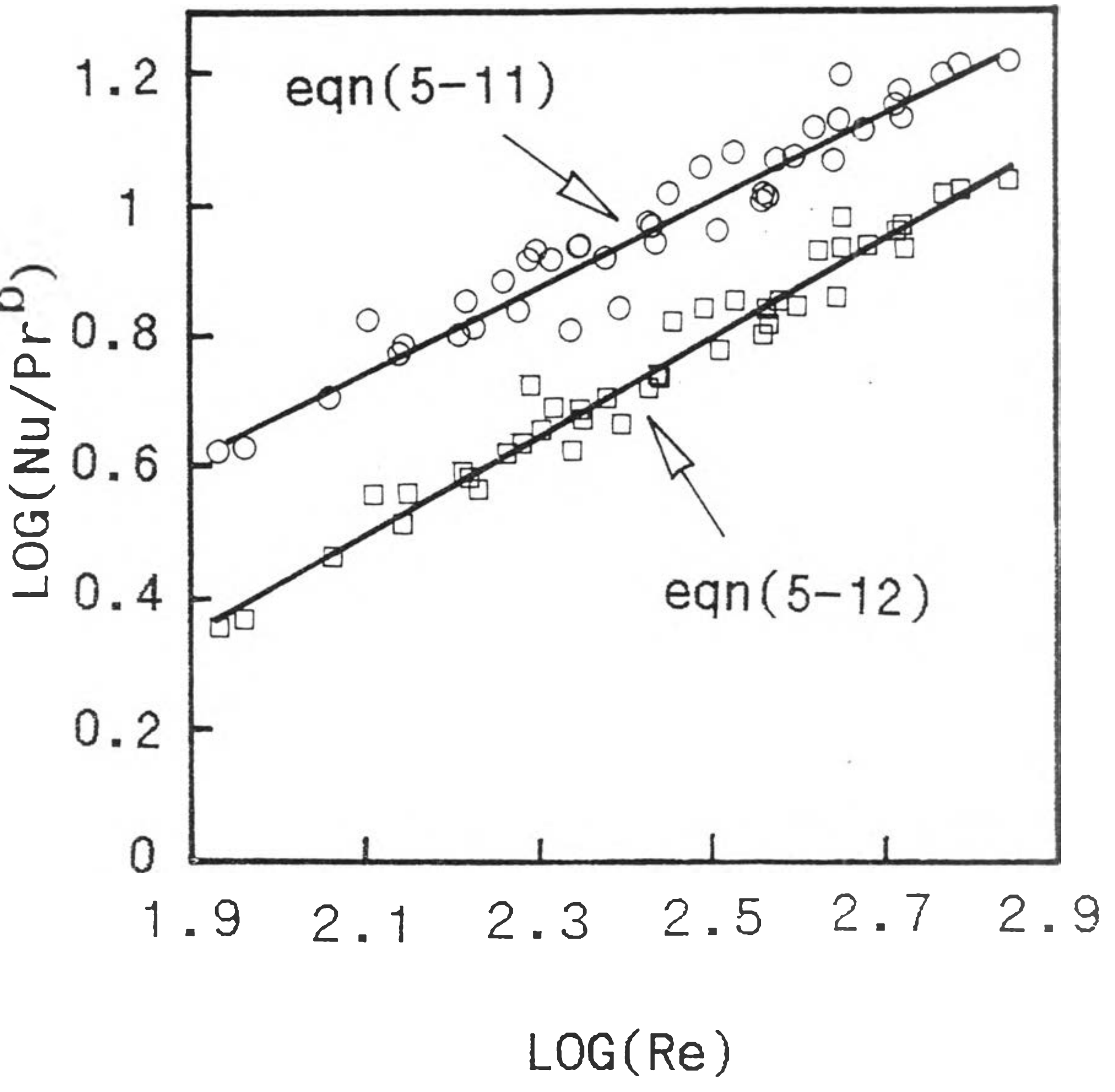

Figure 5.23 Experimental results for the case of equal glycerine/glycerine flow rates; (at hot water temperature ,T10 = 98, 85, and 75 °C , ○ : b = 0.4, □ : b = 0.57).

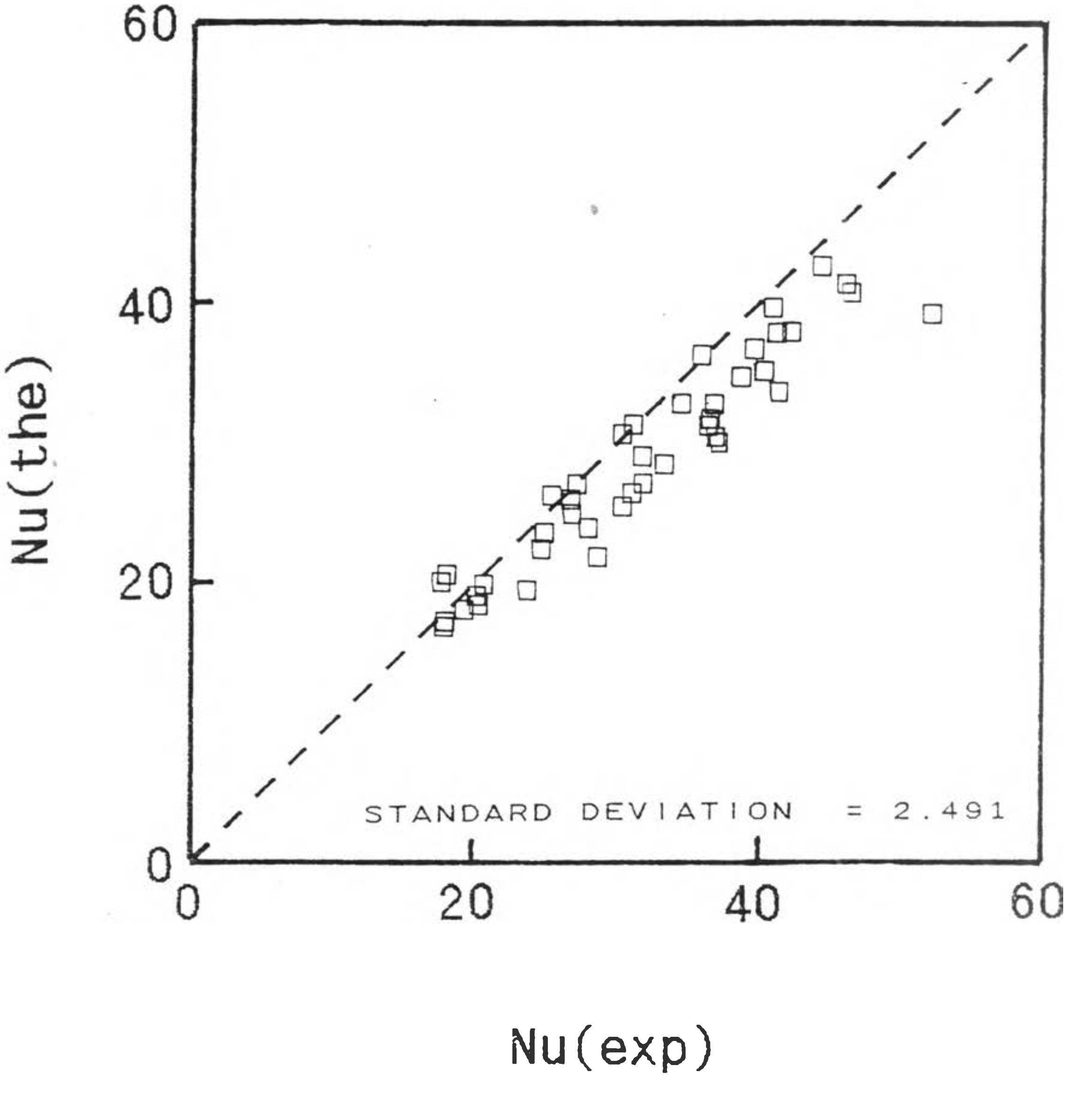

Figure 5.24 Comparison between Nu_{exp}, the experimental value of the Nusselt number and Nu_{the}, the theoretical value based on eqn(5-6) for the case of equal glycerine/glycerine flow rates.

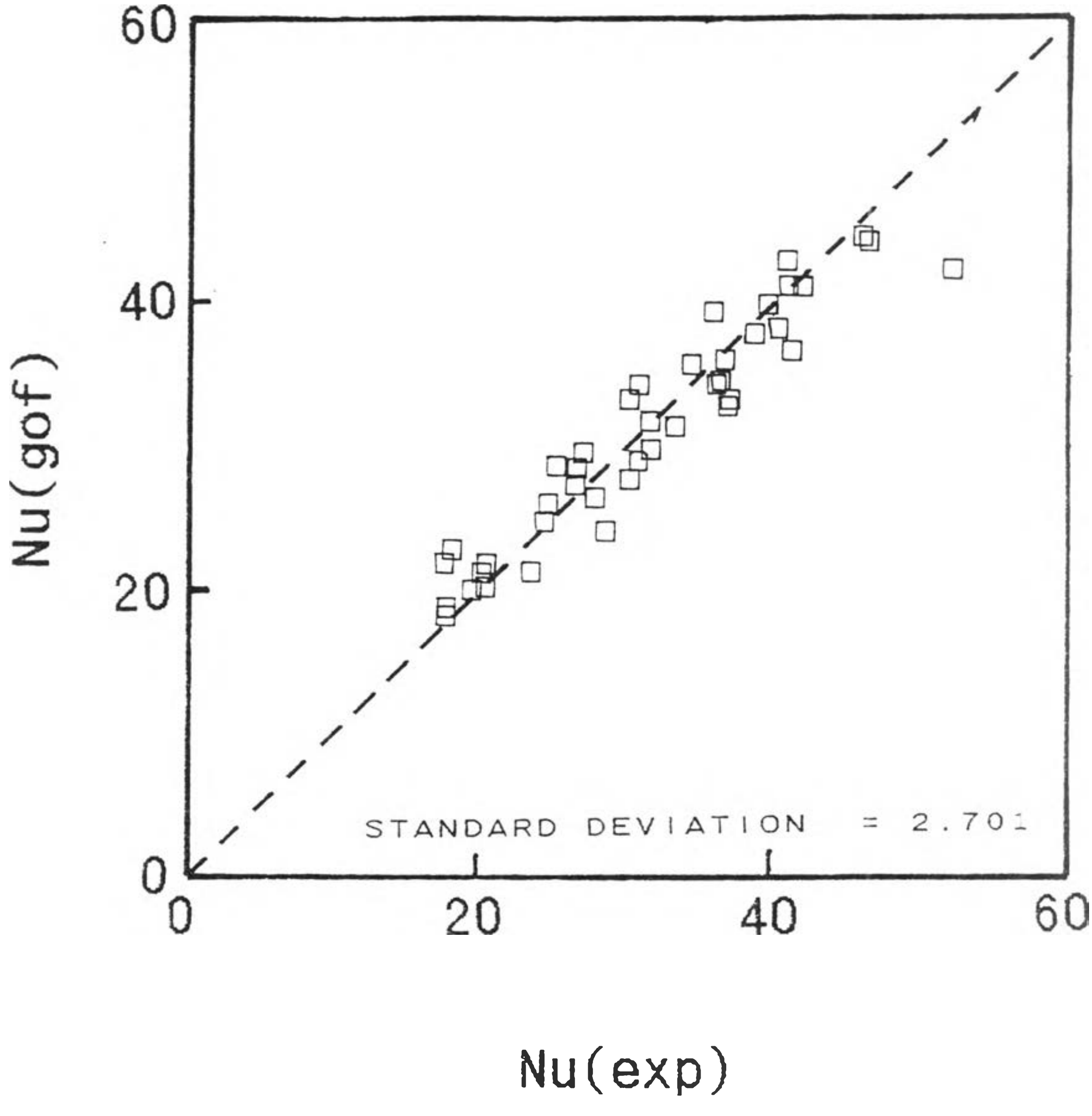

Figure 5.25 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-11) for the case of equal glycerine/glycerine flow rates.

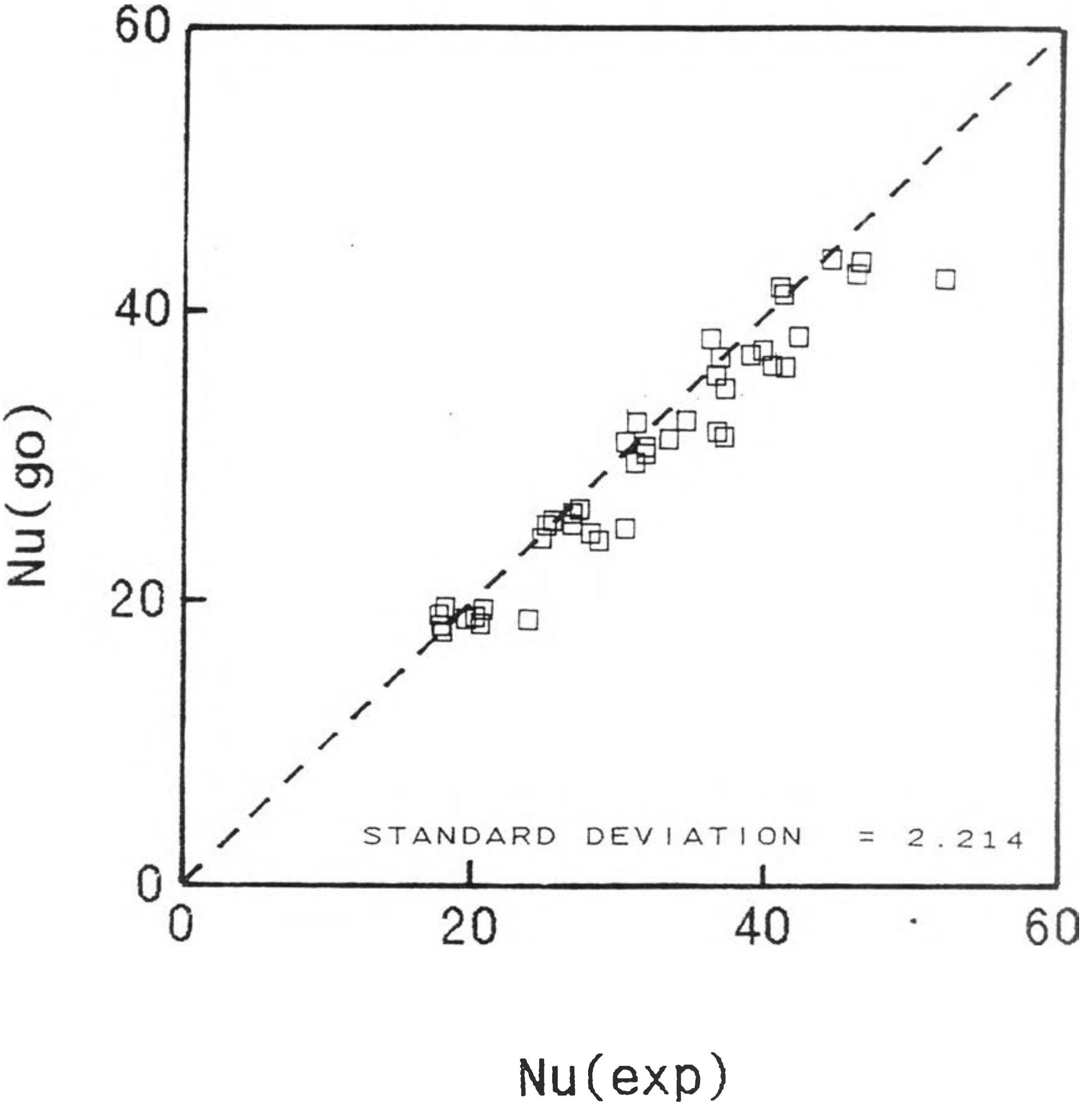

Figure 5.26 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-12) for the case of equal glycerine/glycerine flow rates.

$$Nu_{go} = 0.08\ Re^{0.75}\ Pr^{0.57} \quad \text{with } \sigma = 0.032 \qquad (5\text{-}12)$$

Fig. 5.23 show the two correlations obtained by constrained (b = 0.4) and unconstrained (b = 0.57 here) linear regression analysis versus the corresponding experimental results. It is obvious that the latter case, i.e. eqn (5-12), fits the experimental data better than the former, i.e. eqn (5-11). The same conclusion is reached when one looks at Table 5.7.

Figs. 5.24-5.26 graphically compare Nu_{exp}, the experimental value of Nu, respectively with Nu_{the}, the theoretical value of Nu given by eqn (5-6), Nu_{gof}, the value of Nu predicted by constrained correlation (5-11), and Nu_{go}, the value of Nu predicted by unconstrained correlation (5-12). Here again correlation (5-12) obviously fits the data best, since the relationship between Nu predicted and Nu_{exp} lies most close to the dotted diagonol line.

In summary, it may be concluded that, for the case of equal flow rates of glycerine and glycerine streams, the correlation (5-12) gives the best predictions of the glycerine film heat transfer coefficient expressed in terms of Nu.

Table 5.7 lists the experimental values of the overall heat transfer coefficient, U_{exp}, the values of U, i.e. U_{gof} or U(gof), predicted by correlation (5-11), the values of U, i.e. U_{go} or U(go) predicted by correlation (5-12), and the theoretical values of U, i.e. U_{the} or U(the), given by correlation (5-6). It is obvious that correlation(5-12) gives the best fit for the overall heat transfer coefficient.

Figs. 5.27-5.29 graphically compare respectively the pairs

Table 5.7 Experiment and estimated values of the overall heat transfer coefficient.

System: glycerine/glycerine (concentration 40 vol%)

T10(°C)	Flow(LPM	U(exp)	U(the)	U(go)	U(gof)	U(to)	U(tof)
98	2	634.382	725.876	677.638	788.133	543.881	748.634
	3	941.504	940.238	907.610	1016.371	766.250	926.892
	4	1183.733	1127.433	1114.318	1214.851	975.074	1077.167
	5	1431.416	1292.622	1302.239	1389.532	1172.557	1207.432
	6	1501.111	1448.151	1480.314	1553.486	1362.920	1326.813
85	2	621.663	701.320	662.237	762.501	537.632	734.463
	3	880.080	910.685	888.465	985.677	758.081	910.580
	4	1252.355	1089.602	1089.226	1175.697	963.970	1056.885
	5	1350.999	1253.159	1275.601	1348.805	1160.440	1186.738
	6	1555.028	1401.979	1448.702	1505.949	1348.215	1303.016
75	2	823.466	681.841	649.891	742.141	532.570	723.063
	3	1042.200	880.466	868.675	954.246	749.545	893.659
	4	1046.488	1053.327	1064.922	1138.104	953.107	1037.174
	5	1373.705	1206.701	1243.905	1300.791	1145.868	1162.031
	6	1389.599	1350.030	1412.765	1452.387	1331.328	1275.877

System: glycerine/glycerine (concentration 50 vol%)

T10(°C)	Flow(LPM)	U(exp)	U(the)	U(go)	U(gof)	U(to)	U(tof)
98	2	666.615	646.245	625.602	703.686	522.248	687.755
	3	856.776	833.349	835.488	903.639	734.705	849.461
	4	992.404	1001.132	1027.147	1082.113	935.578	988.247
	5	1144.940	1147.348	1200.165	1237.292	1124.998	1107.540
	6	1455.526	1287.153	1365.615	1385.159	1308.300	1217.947
85	2	651.801	620.779	609.039	677.017	515.259	672.580
	3	856.776	802.746	814.897	871.742	725.555	831.984
	4	1178.117	961.078	999.561	1040.510	922.872	966.040
	5	1227.975	1102.434	1168.666	1190.767	1110.078	1083.170
	6	1620.927	1236.928	1329.928	1333.257	1291.039	1191.208
75	2	663.808	597.179	593.495	652.266	508.617	658.277
	3	897.299	774.505	795.672	842.263	716.914	815.603
	4	1012.007	929.872	977.839	1008.053	912.761	948.492
	5	1305.368	1070.861	1146.284	1158.015	1099.366	1065.795
	6	1296.741	1198.006	1301.989	1292.981	1277.391	1170.210

Table 5.7 (continued)

T10(°C)	Flow(LPM)	U(exp)	U(the)	U(go)	U(goi)	U(to)	U(toi)
98	2	576.086	541.187	555.845	592.364	494.027	610.619
	3	736.885	700.370	744.188	763.372	695.870	755.727
	4	978.679	840.740	914.531	913.543	885.940	878.824
	5	1076.918	962.375	1067.870	1043.416	1064.978	984.260
85	2	531.407	509.077	533.649	558.543	484.041	590.272
	3	729.839	666.013	719.676	727.357	684.288	734.931
	4	934.194	800.294	885.034	871.295	871.517	855.105
	5	1066.538	918.663	1035.397	997.872	1048.652	959.173
75	2	535.787	500.210	527.427	549.187	481.200	584.540
	3	846.613	651.970	709.521	712.613	679.426	726.278
	4	909.610	779.513	869.677	849.551	863.911	942.705
	5	1089.893	893.016	1016.100	971.108	1038.829	944.205

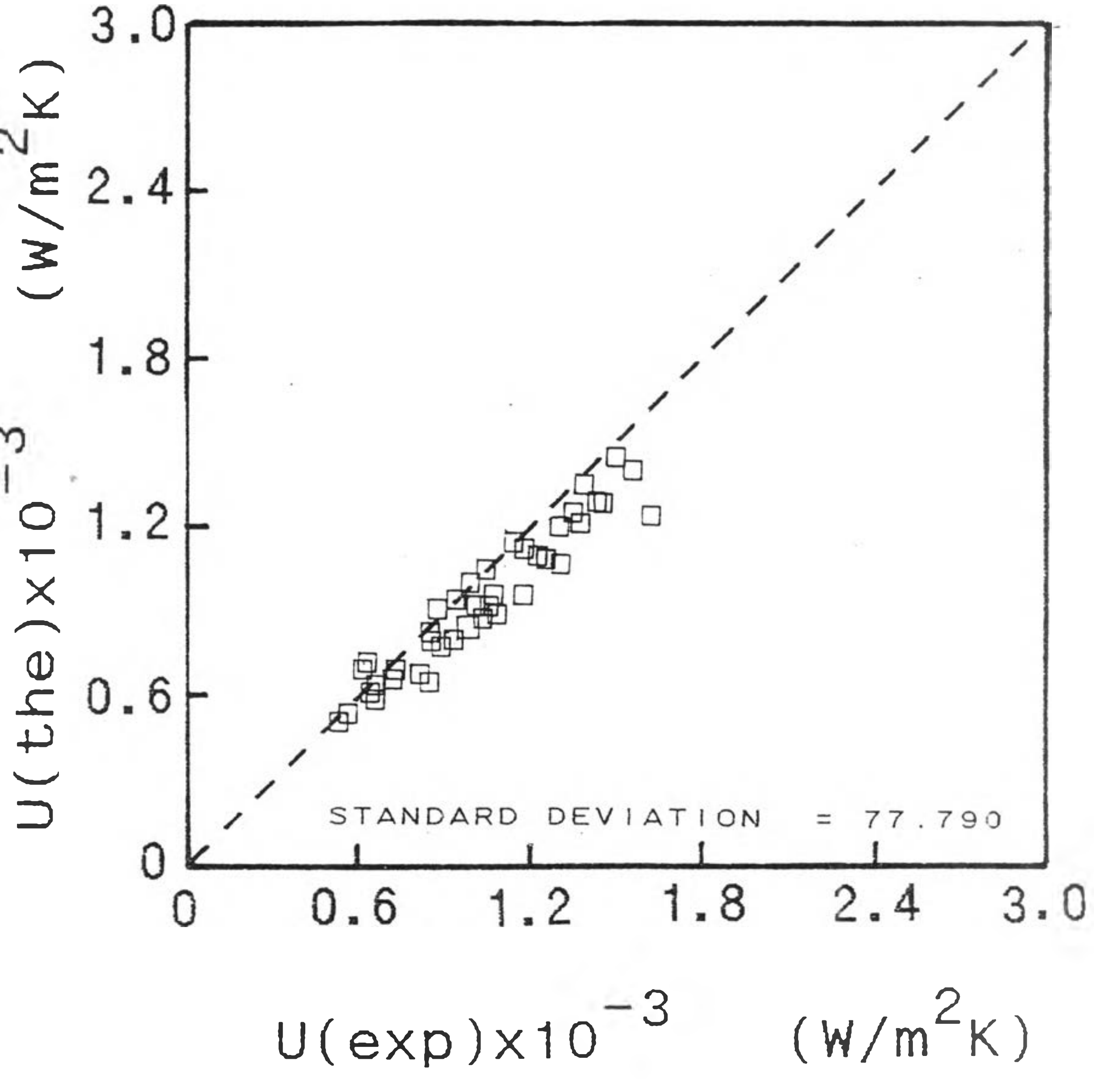

Figure 5.27 Comparison between the experimental value of the overall heat transfer coefficient and the theoretical value given by eqn(5-6) for the case of equal glycerine/glycerine flow rates.

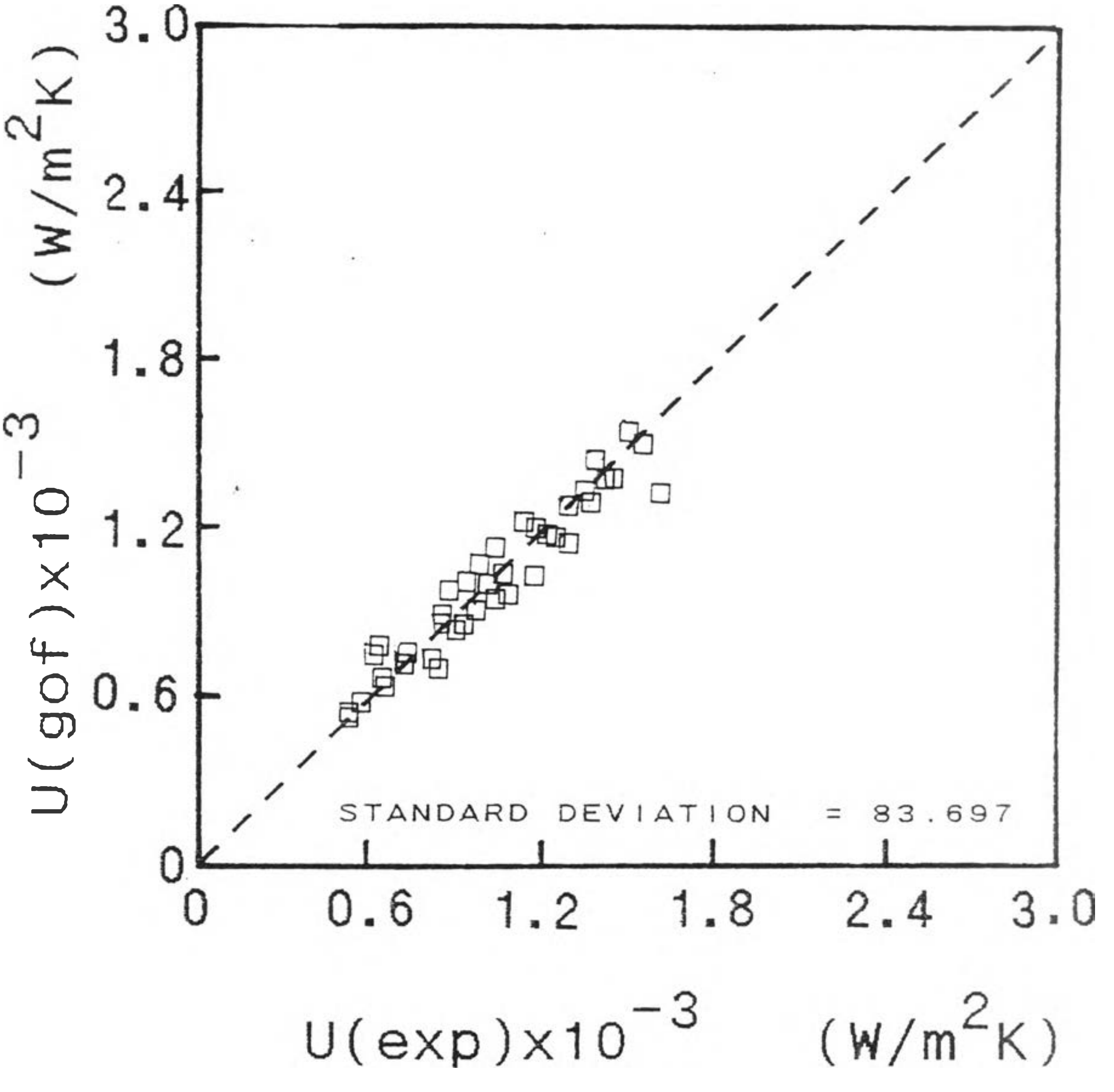

Figure 5.28 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-11) for the case of equal glycerine/glycerine flow rates.

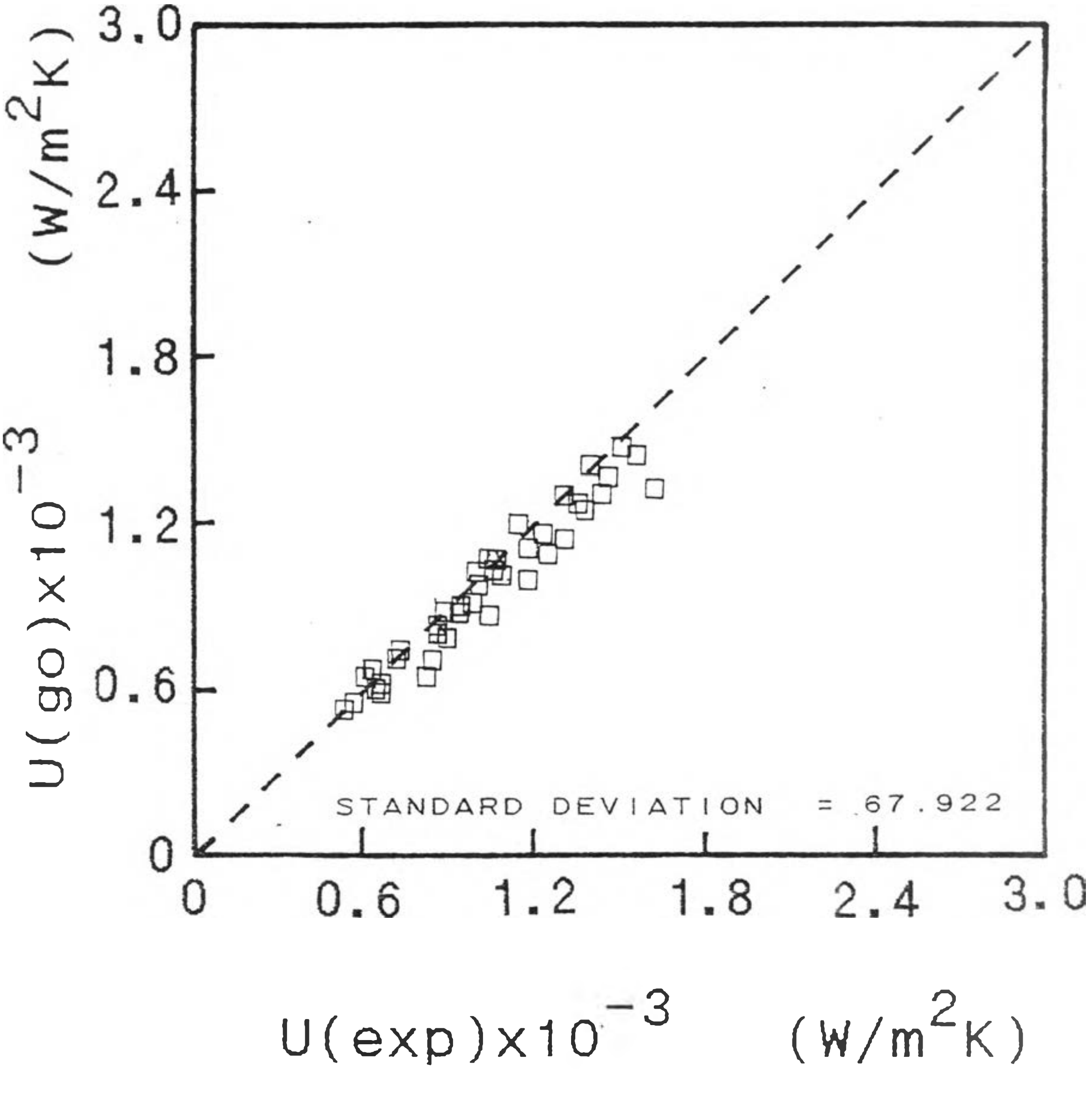

Figure 5.29 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-12) for the case of equal glycerine/glycerine flow rates.

of U_{exp} and U_{the}, U_{exp} and U_{gof}, and U_{exp} and U_{go}. As mentioned above, correlation (5-12) as represented by Fig. 5.23 gives the best fit for the overall heat transfer coefficient U.

5.5. Unequal water/syrup flow rates.

The set of experimental data used here is taken from those belonging to the heating and cooling sections, where heat transfer takes place between water and syrup streams of unequal flow rates. The viscosity of the syrup is much more sensitive to temperature than that of water. The data analysis is again carried out with the aid of program 4. The assumption that the film heat transfer coefficient of the cold side is equal to that of the hot side no longer holds in the case of water/syrup heat transfer. Nevertheless, the observed U_{exp} for the water/syrup case may be analyzed to find the film heat transfer coefficient on the syrup side. This is because the film heat transfer coefficient of the water side, h_w, can be calculated using either the theoretical correlation, i.e. eqn (5-6), or the constrainted linear regression (b set at 0.4), i.e. eqn (5-7) , or the unconstrainted linear regression analysis (b = 1.38), i.e. eqn (5-8). With U_{exp} obtained experimentally, h_w estimated, and x_p and k_p known, the film heat transfer coeffcient of the test liquid, i.e. the syrup solution, h_s, is readily estimated from:

$$U = \frac{1}{\frac{1}{h_w} + \frac{x_p}{k_p} + \frac{1}{h_s}} \qquad (5\text{-}13)$$

The obtained film heat transfer coefficient, h_s, is next used to calculate the Nusselt number of the syrup, Nu_s. Program 2 is again used to estimate the constants of the correlations. The present set of experimental data contains 84 points with the Reynolds number ranging between 89 and 1,848 and the Prandlt number ranging between 3 and 27. Depending on the specific correlation used to estimated h_w, the following correlations for the heat transfer coefficient of the syrup side have been obtained.

5.5.1 <u>Theoretical correlation is used to estimate h_w</u>

In this case the correlations for h_s are:

a. Constrained linear regression analysis (b set at 0.4):

$$Nu_{sof} = 0.64\ Re^{0.395}\ Pr^{0.4} \quad \text{with } \sigma = 0.181 \qquad (5\text{-}14)$$

b. Unconstrained linear regression analysis:

$$Nu_{so} = 0.014\ Re^{1.07}\ Pr^{1.3} \quad \text{with } \sigma = 0.123 \qquad (5\text{-}15)$$

5.5.2 <u>Constrained correlation (5-7) is used to estimate h_w</u>

In this case, the correlations for h_s are:

a. Constrained linear regression analysis (b set at 0.4):

$$Nu_{sof} = 0.73\ Re^{0.39}\ Pr^{0.4} \quad \text{with } \sigma = 0.204 \qquad (5\text{-}16)$$

b. Unconstrained linear regression analysis:

$$Nu_{wo} = 0.001\ Re^{1.14}\ Pr^{1.4} \quad \text{with } \sigma = 0.144 \qquad (5\text{-}17)$$

5.5.3 <u>Unconstrainted correlation (5-8) is used to estimate h</u>

In this case, the correlations for h_w become:

a. Constrained linear regression analysis (b set at 0.4):

$$Nu_{wof} = 0.36\ Re^{0.52}\ Pr^{0.4} \quad \text{with } \sigma = 0.127 \qquad (5\text{-}18)$$

b. Unconstrained linear regression analysis:

$$Nu_{wo} = 0.006\ Re^{0.96}\ Pr^{1.02} \quad \text{with } \sigma = 0.111 \qquad (5\text{-}19)$$

In all of the above cases, the resulting unconstrained correlations for h_w have a smaller standard deviation than their constrained counterparts. Thus Table 5.8 lists only the values of Nut or Nu_{wo} estimated from correlation (5-15) with b= 1.3, the values of Nucc or Nu_{wo} estimated from correlation (5-17) with b= 1.4 and the values of Nuc or Nu_{wo} estimated from correlation (5-19) with b = 1.02, using the experimental values of the Reynolds and Prandtl numbers.

Since case 5.5.3, in which correlation (5-19) is used to predict h_w, gives the least standard deviation, the other two cases may be disregarded. Fig. 5.30 show the two correlations of case 5.5.3, i.e. eqn(5-18) and eqn(5-19) versus the corresponding experimental values. It is obvious that the correlation (5-19),

Table 5.8 Predicted values of Nusselt number based on correlations (5-15), (5-17), and (5-19), respectively.

System: water/syrup (concentration 20 wt%)

T10(°C)	Flow(LPM)	Section	Re	Pr	Nut	Nucc	Nuc
98	2	3	234.89	9.41	14.14	16.11	15.48
		2	651.28	3.12	6.16	6.49	9.33
	3	3	358.51	9.23	20.92	24.37	21.30
		2	968.61	3.15	10.56	11.33	16.50
	4	3	478.01	9.23	27.45	32.54	26.31
		2	1264.07	3.22	13.85	14.97	20.64
	5	3	594.07	9.29	37.36	45.91	33.82
		2	1546.32	3.29	20.41	22.60	31.72
	6	3	712.88	9.29	41.90	51.53	36.68
		2	1847.56	3.31	22.48	24.86	32.50
85	2	3	236.26	9.35	12.47	13.98	13.54
		2	548.95	3.74	5.68	5.96	7.85
	3	3	350.29	9.47	23.82	28.41	24.16
		2	816.03	3.77	10.65	11.45	15.43
	4	3	467.06	9.47	30.45	36.84	28.86
		2	1063.65	3.87	13.80	14.94	19.01
	5	3	587.22	9.41	31.33	37.13	28.72
		2	1305.51	3.94	17.28	18.86	23.07
	6	3	700.59	9.47	36.36	43.41	32.10
		2	1552.32	3.98	26.39	29.82	37.03
75	2	3	228.14	9.73	14.21	16.20	15.57
		2	466.97	4.44	6.14	6.48	8.26
	3	3	348.26	9.54	19.97	23.10	20.21
		2	697.14	4.47	8.02	8.48	10.04
	4	3	467.06	9.47	22.31	25.56	21.45
		2	920.73	4.51	13.16	14.22	16.85
	5	3	583.82	9.47	26.92	31.10	24.91
		2	1129.13	4.60	16.78	18.30	20.90
	6	3	692.47	9.60	82.79	131.16	63.95
		2	1354.96	4.60	24.28	27.20	30.91

Table 5.8 (continued)

System: water/syrup (concentration 30 wt%)

T10(°C)	Flow(LPM)	Section	Re	Pr	Nut	Nucc	Nuc
98	2	3	148.86	9.41	14.70	16.69	16.29
		2	451.79	3.12	6.88	7.27	10.70
	3	3	223.30	9.23	16.29	18.17	16.50
		2	664.68	3.15	11.99	12.93	19.31
	4	3	297.73	9.23	23.25	26.55	22.53
		2	856.45	3.22	16.02	17.45	24.62
	5	3	372.16	9.29	35.22	42.14	32.41
		2	1054.89	3.29	22.43	24.93	35.28
	6	3	443.70	9.29	45.38	56.00	39.77
		2	1247.26	3.31	22.83	25.12	32.08
85	2	3	145.03	9.35	14.76	16.76	16.22
		2	370.33	3.74	6.08	6.39	8.37
	3	3	217.54	9.47	24.79	29.41	25.29
		2	549.83	3.77	10.62	11.37	14.92
	4	3	291.96	9.47	24.43	28.10	23.58
		2	707.13	3.87	12.50	13.37	16.22
	5	3	367.34	9.41	28.04	32.25	26.23
		2	870.26	3.94	16.15	17.43	20.58
	6	3	435.08	9.47	56.76	74.36	48.26
		2	1033.48	3.98	19.79	21.53	24.80
75	2	3	144.08	9.73	14.75	16.76	16.22
		2	319.99	4.44	9.87	10.72	16.18
	3	3	214.71	9.54	14.05	15.42	14.13
		2	462.33	4.47	11.14	11.99	15.03
	4	3	280.67	9.47	26.30	30.60	25.04
		2	613.13	4.51	13.80	14.90	17.55
	5	3	353.17	9.47	24.16	27.24	22.53
		2	737.89	4.60	14.67	15.74	17.45
	6	3	418.24	9.60	40.22	48.37	35.17
		2	880.66	4.60	18.32	19.83	21.48

Table 5.8 (continued)

System: water/syrup (concentration 40 wt%)

T10(°C)	Flow(LPM)	Section	Re	Pr	Nut	Nucc	Nuc
98	2	3	95.40	24.86	11.84	13.00	12.83
		2	309.69	7.10	5.81	6.07	8.07
	3	3	142.06	25.06	17.53	19.56	17.91
		2	469.61	7.02	10.97	11.70	16.34
	4	3	188.06	25.26	25.91	29.76	25.18
		2	599.42	7.35	16.83	18.30	25.65
	5	3	236.77	25.06	22.73	25.24	21.64
		2	732.97	7.52	18.99	20.62	26.75
85	2	3	92.00	25.87	12.05	13.25	13.05
		2	253.34	8.77	7.11	7.50	10.13
	3	3	138.01	25.87	15.25	16.76	15.45
		2	371.38	8.98	14.59	15.94	22.97
	4	3	186.70	25.46	13.12	14.04	12.90
		2	475.52	9.37	12.87	13.73	16.50
	5	3	230.01	25.87	23.75	26.49	22.52
		2	580.69	9.60	18.86	20.51	24.56
75	2	3	89.36	26.72	10.63	11.56	11.38
		2	211.29	10.62	7.83	8.32	11.00
	3	3	131.12	27.38	18.41	20.66	18.63
		2	303.86	11.10	9.92	10.54	12.61
	4	3	177.41	26.94	22.17	24.93	21.47
		2	395.43	11.39	13.60	14.59	16.86
	5	3	218.53	27.38	32.84	38.32	30.32
		2	482.37	11.69	17.65	19.11	21.39

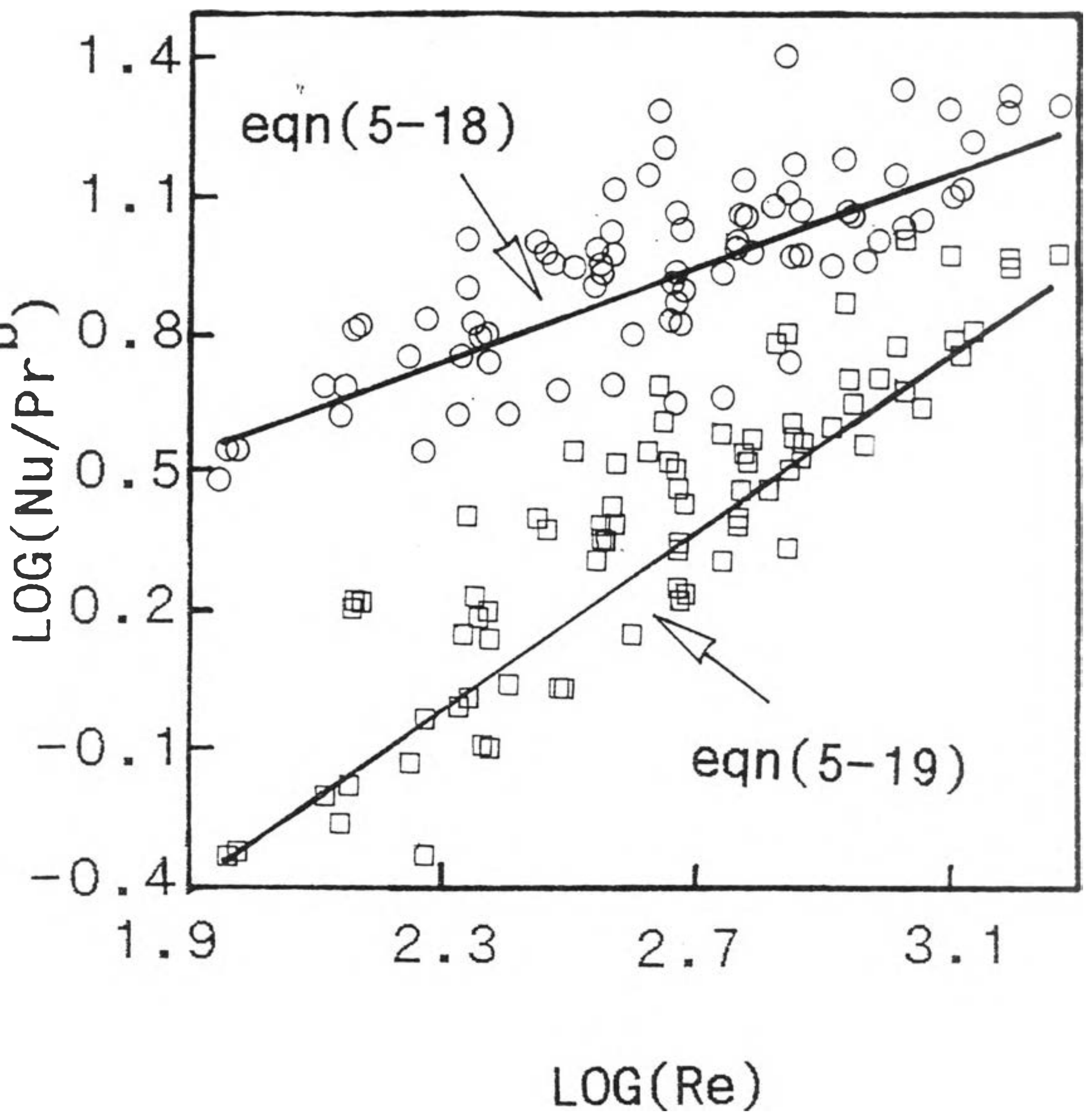

Figure 5.30 Experimental results for the case of water/syrup flow rates; (at hot water temperature ,T10 = 98, 85, and 75 °C , ○ : b = 0.4, □ : b = 1.02).

fits the experimental data better than correlation (5-18).

5.6. Unequal water/glycerine flow rates

The set of experimental data used here is taken from those belonging to the heating and cooling sections, where heat transfer takes place between water and glycerine streams of unequal flow rates. As in the case of unequal water/syrup flow rates, the film heat transfer coefficient on the water side, h_w, is calculated by using either the theoretical correlation (5-6), or the correlation (5-7), or the unconstrainted correlation (5-8). Likewise the film heat transfer coefficient of the glycerine side, h_g, is readily estimated from

$$U = \frac{1}{\frac{1}{h_w} + \frac{x_p}{k_p} + \frac{1}{h_g}} \qquad (5\text{-}20)$$

The obtained film heat transfer coefficient, h_g, is next used to calculate the Nusselt number of the glycerine, Nu_g. Program 2 is again used to estimate the constants of the correlations the set of experimental data used contains 84 points with the Reynolds number ranging between 50 and 1,137 and the Prandtl number ranging between 6 and 63. Depending on the specific correlation used to estimate h_w, the following correlations for the heat transfer coefficient of the glycerine side have been obtained.

5.6.1 Theoretical correlation is used to estimated h_w

In this case the correlations for h_g are:

a. Constrained linear regression analysis (b set at 0.4):

$$Nu_{gof} = 0.66\ Re^{0.4}\ Pr^{0.4} \quad \text{with } \sigma = 0.171 \qquad (5\text{-}21)$$

b. Unconstrained linear regression analysis:

$$Nu_{go} = 0.002\ Re^{1.03}\ Pr^{1.22} \quad \text{with } \sigma = 0.123 \qquad (5\text{-}22)$$

5.6.2 Constrained correlation (5-7) is used to estimate h_w

In this case the correlations for h_g are:

a. Constrained linear regression analysis (b set at 0.4):

$$Nu_{gof} = 0.75\ Re^{0.4}\ Pr^{0.4} \quad \text{with } \sigma = 0.198 \qquad (5\text{-}23)$$

b. Unconstrained linear regression anslysis

$$Nu_{go} = 0.001\ Re^{1.09}\ Pr^{1.3} \quad \text{with } \sigma = 0.149 \qquad (5\text{-}24)$$

5.6.3 Unconstrained correlation (5-8) is used to estimated h_w

In this case, the correlations for h_g are:

a. Constrained linear regression analysis (b set at 0.4):

$$Nu_{gof} = 0.41\ Re^{0.51}\ Pr^{0.4} \quad \text{with } \sigma = 0.121 \qquad (5\text{-}25)$$

b. Unconstrained linear regression analysis:

$$Nu_{go} = 0.072\ Re^{0.89}\ Pr^{0.89} \quad \text{with } \sigma = 0.098 \qquad (5\text{-}26)$$

In all of the above cases, the resulting unconstrained correlations for h_g have a smaller standard deviation than their constrained counterparts. Thus Table 5.9 lists only the values of Nut or Nu_{go} estimated from correlation (5-22) with b= 1.22, the values of Nucc or Nu_{go} estimated from correlation (5-24) with b= 1.3 and the values of Nuc or Nu_{go} estimated from correlation (5-26) with b = 0.89, using the experimental values of the Reynolds and Prandtl numbers.

Since case 5.6.3, in which correlation (5-26) is used to predict h_w, gives the least standard deviation, the other two cases may be disregarded. Fig. 5.31 show the two correlations of case 5.6.3, i.e. eqn(5-25) and eqn(5-26) versus the corresponding experimental values. It is obvious that the correlation (5-26), fits the experimental data better than correlation (5-25).

5.7 Generalized heat transfer correlation

Program 2 is finally used to estimate the constants of the generalized correlation which is on all the available experimental data of equal liquid/liquid flow rates. The set of data contains 147 points with the Reynolds number ranging between 86 and 3,000 and the Prandtl number ranging between 2 and 40. The resulting correlations

Table 5.9 Predicted values of Nusselt number based on correlations (5-22), (5-24), and (5-26), respectively.

System: water/glycerine (concentration 40 vol%)

T10(°C)	Flow(LPM)	Section	Re	Pr	Nut	Nucc	Nuc
98	2	3	134.73	19.87	16.92	19.14	19.28
		2	416.25	6.43	8.70	9.19	13.64
	3	3	200.72	20.01	22.76	25.94	23.76
		2	611.68	6.57	13.45	14.38	20.50
	4	3	267.63	20.01	32.93	38.68	32.63
		2	798.90	6.70	18.38	19.86	27.31
	5	3	327.74	20.43	51.08	64.05	47.28
		2	962.91	6.95	21.00	22.69	29.00
	6	3	395.99	20.29	47.42	57.03	42.92
		2	1137.47	7.06	22.95	24.76	30.08
85	2	3	131.10	20.43	11.19	12.13	12.06
		2	337.17	7.94	8.42	8.90	12.20
	3	3	195.30	20.57	22.26	25.31	23.04
		2	500.30	8.03	15.96	17.33	24.59
	4	3	258.62	20.71	29.26	33.75	28.67
		2	642.05	8.34	15.58	16.67	20.36
	5	3	327.74	20.43	31.49	35.99	29.94
		2	780.76	8.57	19.90	21.47	25.42
	6	3	382.61	20.99	128.11	234.89	100.43
		2	926.60	8.67	24.57	26.72	30.87
75	2	3	128.42	20.85	9.41	10.07	10.02
		2	285.57	9.38	8.20	8.67	11.20
	3	3	187.38	21.44	15.04	16.38	15.29
		2	414.00	9.70	12.28	13.11	16.05
	4	3	249.84	21.44	21.16	23.43	20.78
		2	533.33	10.04	15.92	17.10	19.98
	5	3	303.73	22.04	27.92	31.45	26.36
		2	647.67	10.34	17.99	19.30	21.44
	6	3	359.41	22.35	79.12	110.58	65.52
		2	763.76	10.52	25.65	28.09	30.78

Table 5.9 (continued)

System: water/glycerine (concentration 50 vol%)

T10(°C)	Flow(LPM)	Section	Re	Pr	Nut	Nucc	Nuc
98	2	3	91.44	31.66	14.19	15.60	15.50
		2	348.12	8.32	9.83	10.41	15.80
	3	3	136.07	31.91	23.22	26.28	23.95
		2	497.73	8.73	14.04	14.98	20.99
	4	3	182.88	31.66	26.36	29.65	25.91
		2	647.73	8.94	19.17	20.65	27.95
	5	3	228.61	31.66	37.31	43.23	35.31
		2	785.47	9.21	29.17	32.25	45.16
	6	3	272.15	31.91	33.90	38.17	31.53
		2	931.11	9.33	27.79	30.26	37.70
85	2	3	89.28	32.43	13.52	14.80	14.68
		2	270.69	10.70	7.95	8.34	10.91
	3	3	133.92	32.43	21.98	24.70	22.64
		2	390.87	11.11	14.07	15.04	19.68
	4	3	175.71	32.95	31.74	36.65	31.03
		2	504.77	11.47	18.54	19.97	24.94
	5	3	221.41	32.69	28.18	31.45	26.88
		2	607.03	11.92	18.80	20.08	23.20
	6	3	259.37	33.49	54.58	66.61	48.58
		2	723.73	12.00	23.46	25.26	28.58
75	2	3	86.46	33.49	11.18	12.04	11.95
		2	220.11	13.15	8.44	8.90	11.33
	3	3	127.61	34.03	17.56	19.27	17.85
		2	319.38	13.60	13.01	13.86	16.89
	4	3	171.52	33.76	26.51	29.86	25.90
		2	411.84	14.06	17.22	18.49	21.60
	5	3	214.40	33.76	27.93	31.15	26.57
		2	504.51	14.35	19.57	21.00	23.38
	6	3	255.21	34.03	40.82	47.21	37.21
		2	589.25	14.74	23.67	25.56	27.77

Table 5.9 (continued)

System: water/glycerine (concentration 60 vol%)

T10(°C)	Flow(LPM)	Section	Re	Pr	Nut	Nucc	Nuc
98	2	3	56.49	56.27	16.68	18.48	18.53
		2	212.97	14.93	11.29	12.00	18.68
	3	3	83.37	57.20	18.55	20.28	18.98
		2	309.71	15.40	14.88	15.84	21.98
	4	3	111.16	57.20	29.94	33.86	29.41
		2	397.78	15.98	20.72	22.31	30.02
	5	3	138.95	57.20	39.75	45.91	37.57
		2	466.82	17.02	21.49	22.98	28.19
85	2	3	50.33	63.16	12.02	12.94	12.72
		2	158.84	20.01	10.62	11.27	15.68
	3	3	77.40	61.60	17.78	19.37	17.99
		2	235.14	20.28	14.57	15.53	19.93
	4	3	104.07	61.09	22.42	24.58	21.93
		2	303.30	20.96	17.82	19.03	22.95
	5	3	130.08	61.09	28.01	30.97	26.62
		2	361.78	21.97	25.59	27.82	33.17
75	2	3	53.78	59.11	13.77	14.97	14.92
		2	130.69	24.32	12.02	12.88	17.76
	3	3	79.35	60.09	18.91	20.72	19.28
		2	194.69	24.49	12.10	12.78	15.06
	4	3	105.80	60.09	26.70	29.79	26.24
		2	247.32	25.71	18.86	20.27	23.53
	5	3	125.82	63.16	35.12	39.93	32.82
		2	300.65	26.43	24.14	26.18	29.41

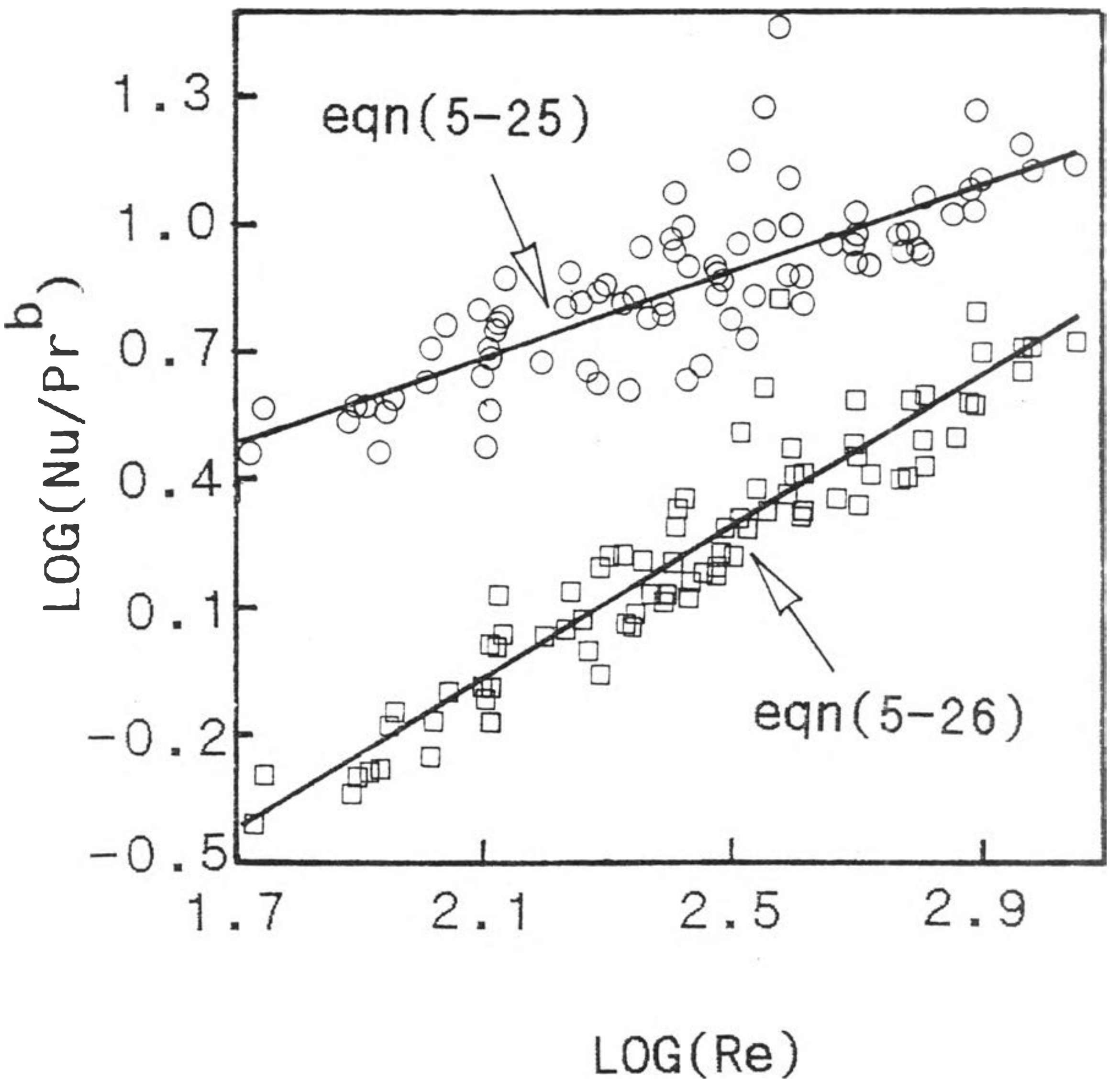

Figure 5.31 Experimental results for the case of water/gycerine flow rates; (at hot water temperature ,T10 = 98, 85, and 75 °C , ○ : b = 0.4, □ : b = C.89).

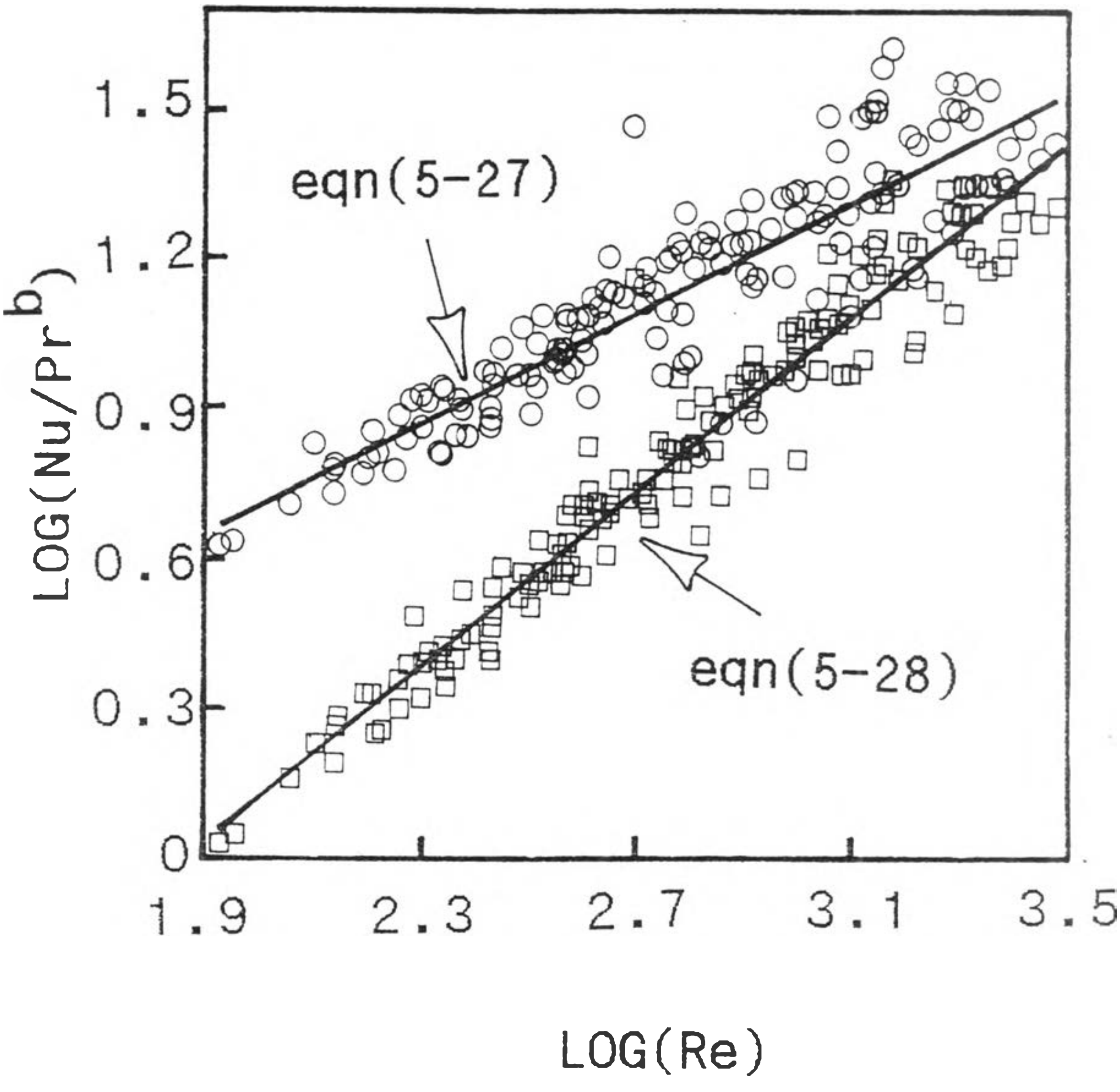

Figure 5.32 Experimental results for the case of overall data of equal flow rates;(at hot water temperature ,T10 = 98, 85, and 75 °C , ○ : b = 0.4, □ : b = 0.87).

are as follows:

Constrained linear regression analysis (b set at 0.4):

$$Nu_{tof} = 0.4\ Re^{0.55}\ Pr^{0.4} \quad \text{with } \sigma = 0.161 \qquad (5\text{-}27)$$

Unconstrained linear regression analysis:

$$Nu_{to} = 0.02\ Re^{0.87}\ Pr^{0.78} \quad \text{with } \sigma = 0.081 \qquad (5\text{-}28)$$

Fig. 5.32 shows the two correlations (5-27) and (5-28) against the corresponding experimental data. It is obvious that the unconstrained correlation, eqn(5-28), fits the whole experimental data better than the constrained one, eqn(5-27). Naturally the values of the constants in correlations (5-27) and (5-28), namely , a, b and k, are roughly the average values found in the constrained correlations (5-7), (5-9), (5-11) and (5-25) and the average values found in the unconstrained correlations (5-8), (5-10), (5-12), (5-19) and (5-26), respectively. In other words, both correlations (5-27) and (5-28) represent the generalized correlations for the constrained and unconstrained cases, respectively. Needless to say, the standard deviation of correlation (5-28) is smaller than that of the unconstrained correlation (5-27). So it may be concluded that the best generalized correlation for the present pilot-scale plate exchanger is correlation (5-28).

To substantiate this conclusion, the predicted values of Nu_{tof}, which are obtained from the constrained correlation (5-27),

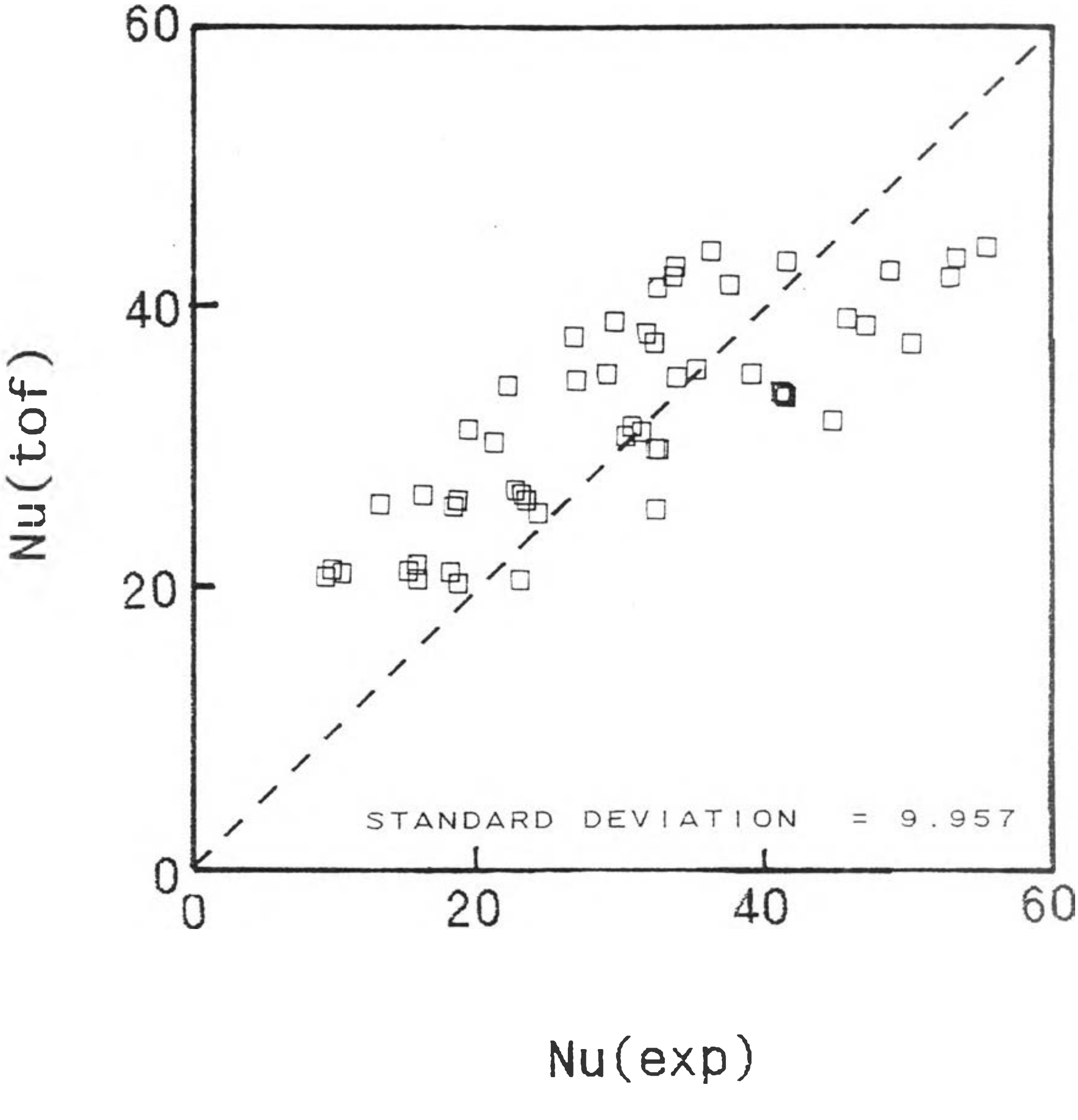

Figure 5.33 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-27) for the case of equal water/water flow rates.

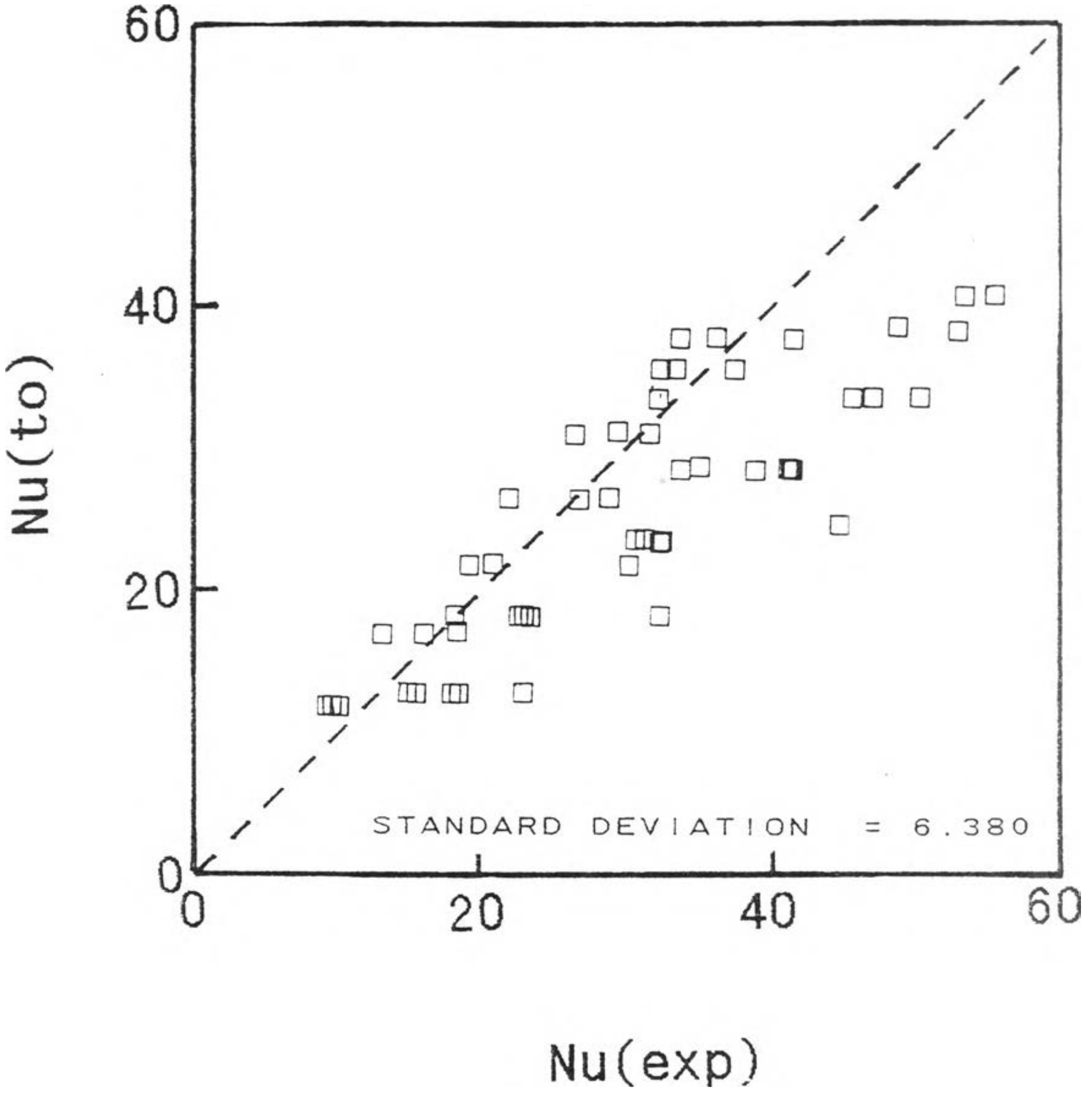

Figure 5.34 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-28) for the case of equal water/water flow rates.

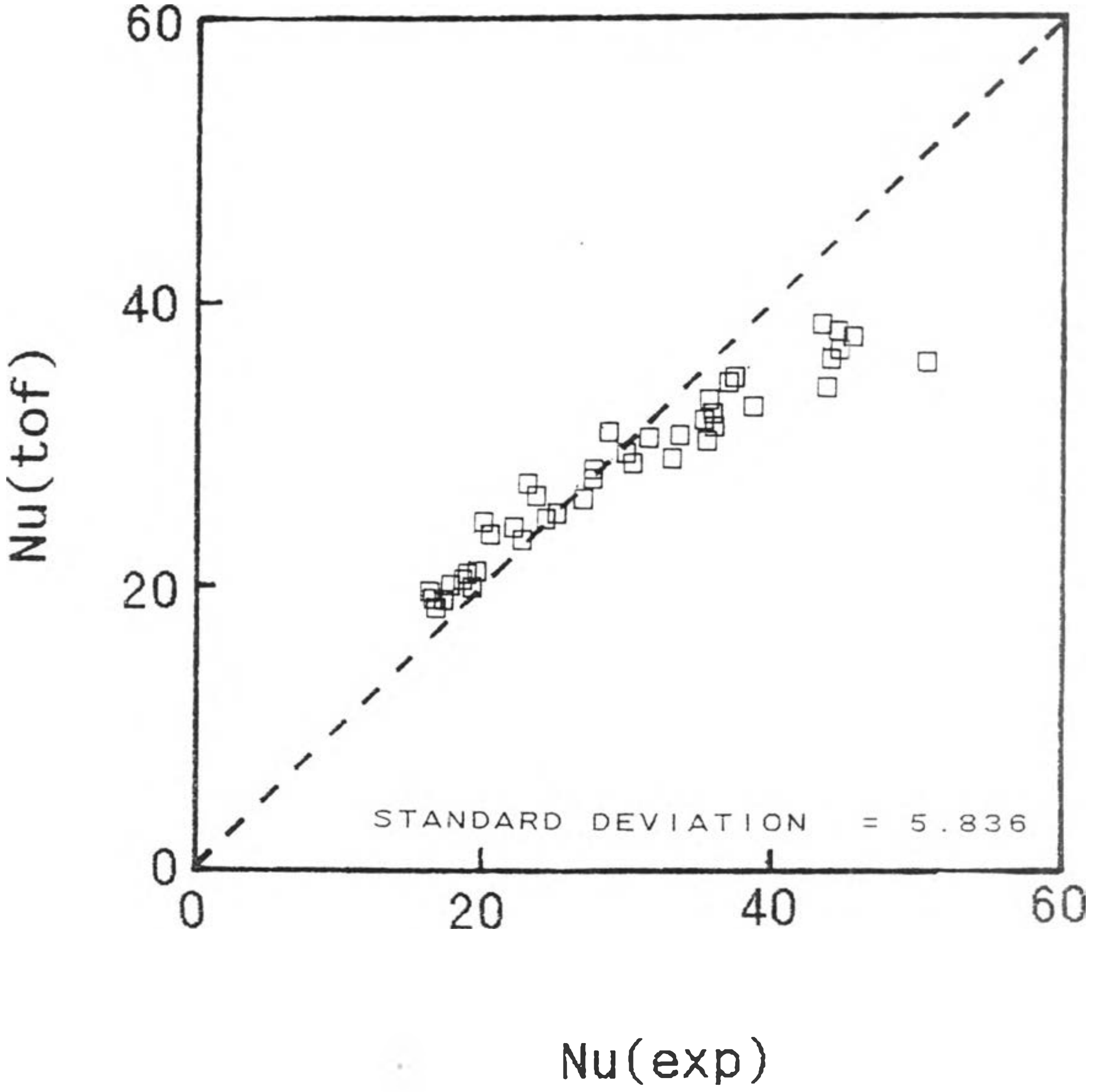

Figure 5.35 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-27) for the case of equal syrup/syrup flow rates.

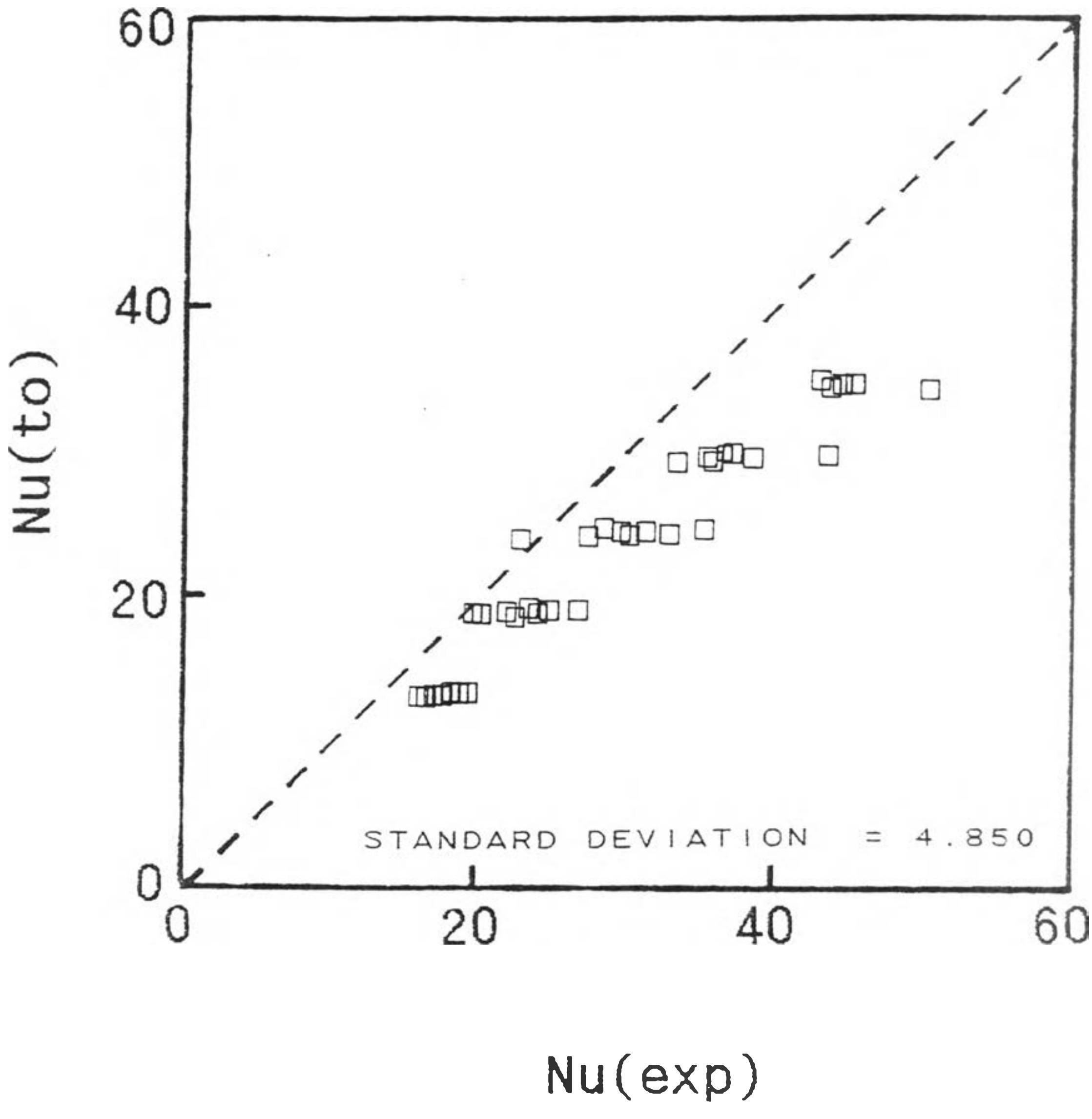

Figure 5.36 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-28) for the case of equal syrup/syrup flow rates.

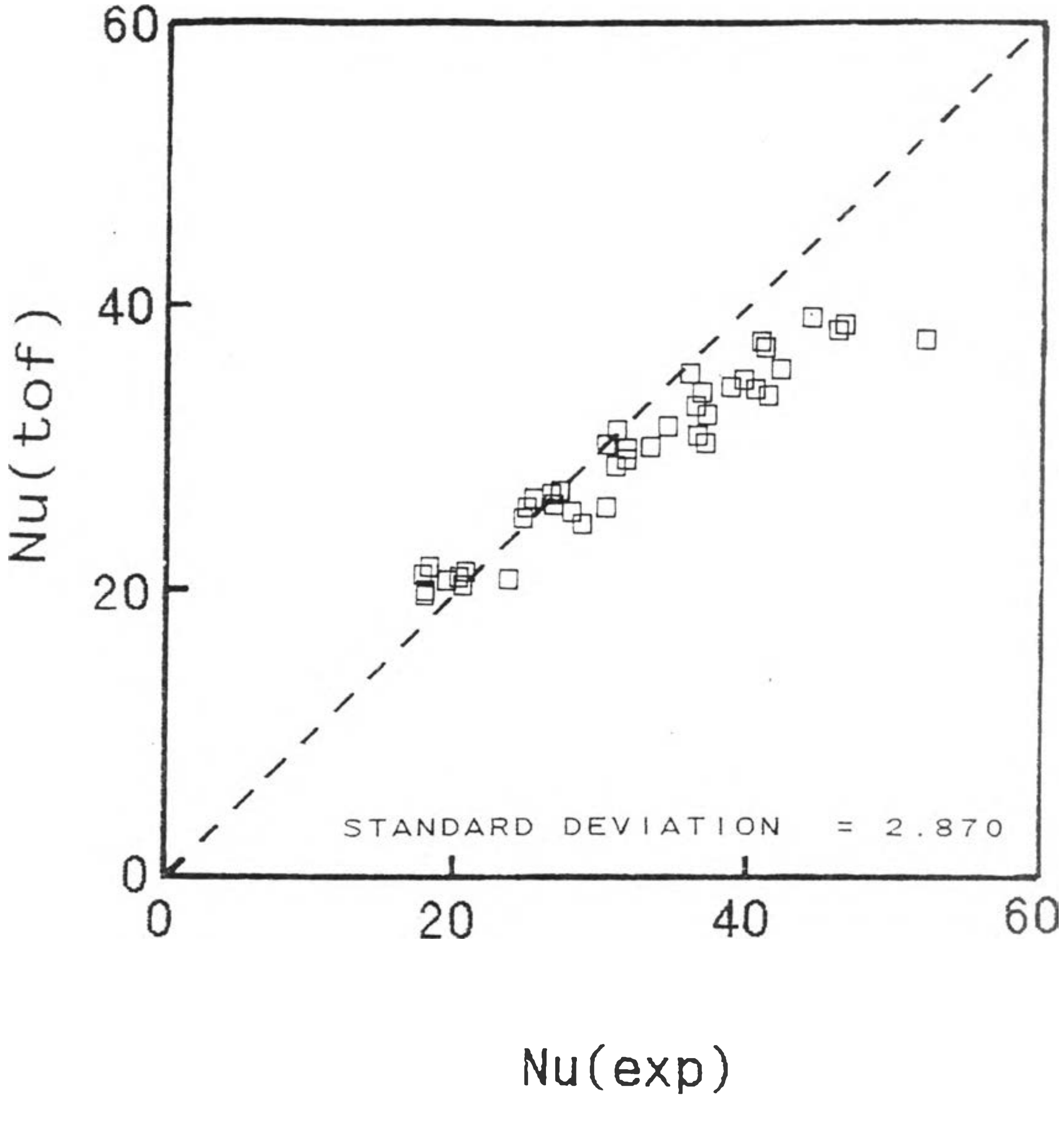

Figure 5.37 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-27) for the case of equal glycerine/glycerine flow rates.

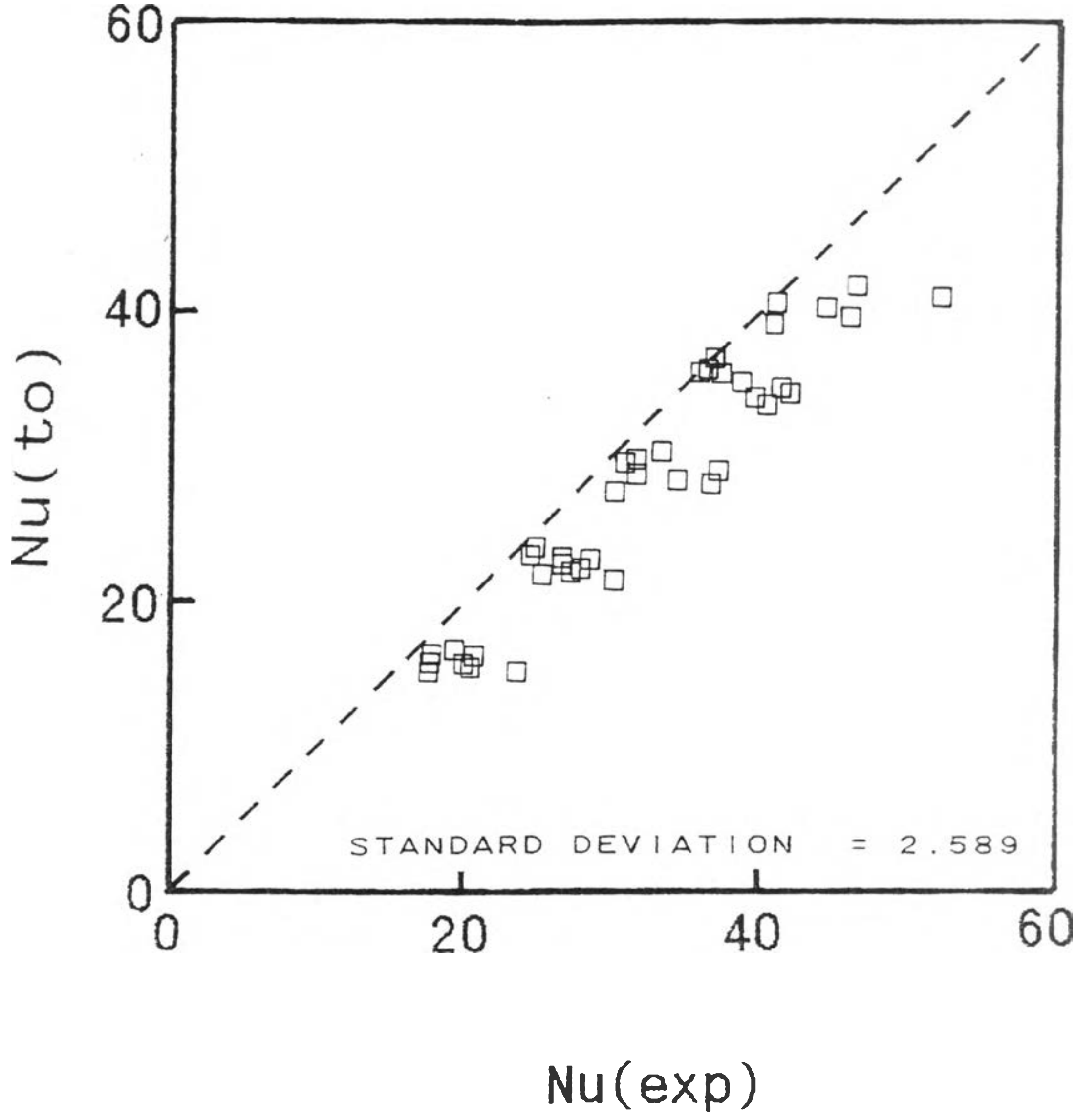

Figure 5.38 Comparison between the experimental value of the Nusselt number and value estimated with eqn(5-28) for the case of equal glycerine/glycerine flow rates.

and the predicted values of Nu_{to}, which are obtained from the unconstrained correlation(5-27), for the cases of equal water/water flow rates, equal syrup/syrup flow rates and equal glycerine /glycerine flow rates, respectively, are presented in Tables 5.1, 5.4 and 5.5. In addition, Figs. 5.33-5.38 graphically compare the pairs of Nu_{exp} and Nu_{tof} or Nu(tof), and Nu_{exp} and Nu_{to} or Nu(to) for the cases of equal water/water flow rates, equal syrup/syrup flow rates and equal glycerine/glycerine flow rates, respectively. Here again correlation (5-28) obviously fits the data best, since the relationship between Nu predicted and Nu_{exp} lies most close to the dotted diagonal line in each figure.

The predicted values of the overall heat transfer coefficient obtained using the constrained correlation (5-27), i.e. U_{tof} or Utof and the predicted values obtained using the unconstrained correlation i.e. U_{to} or Uto, for the cases of equal water/water flow rates, equal syrup/syrup flow rates, equal glycerine/glycerine flow rates, unequal water/syrup flow rates and unequal water/glycerine flow rates, respectively, are presented in Table 5.2, 5.5, 5.7, 5.10 and 5.11.

Next Figs. 5-39-5.43 graphically compare the pairs of U_{exp} and U_{tof} , and U_{exp} and U_{to} for all of the cases mentioned above.

Table 5.10 Experimental and estimated values of the overall heat transfer coefficient.

System : water/syrup (concentration 20 wt%)

T10(°C)	Flow(LPM)	Section	U(exp)	U(to)	U(tof)
98	2	3	757.233	597.499	905.993
		2	469.376	614.968	1047.541
	3	3	1059.808	843.797	1126.510
		2	751.396	866.312	1295.486
	4	3	1330.774	1073.746	1309.476
		2	958.004	1101.262	1501.802
	5	3	1664.284	1292.249	1469.547
		2	1301.632	1323.191	1680.197
	6	3	1858.664	1502.092	1615.332
		2	1437.007	1537.462	1844.717
85	2	3	701.216	597.789	907.038
		2	433.569	605.492	1020.033
	3	3	1135.701	842.100	1122.213
		2	743.261	852.824	1260.621
	4	3	1402.432	1071.968	1304.726
		2	938.752	1084.250	1461.273
	5	3	1515.165	1291.174	1466.884
		2	1141.783	1303.906	1636.933
	6	3	1721.166	1499.879	1609.823
		2	1561.588	1513.534	1793.979
75	2	3	756.031	596.450	902.877
		2	453.447	595.992	992.272
	3	3	1028.244	841.808	1121.448
		2	589.975	840.065	1228.681
	4	3	1178.362	1071.968	1304.726
		2	892.689	1069.120	1425.953
	5	3	1389.125	1290.534	1465.204
		2	1099.650	1236.110	1597.137
	6	3	2461.806	1499.098	1608.431
		2	1457.236	1495.014	1754.715

Table 5.10 (continued)

System : water/syrup (concentration 30 wt%)

T10(°C)	Flow(LPM)	Section	U(exp)	U(to)	U(tof)
98	2	3	750.100	575.607	854.108
		2	487.051	595.139	993.799
	3	3	875.597	810.688	1057.282
		2	785.694	837.822	1227.553
	4	3	1167.462	1032.476	1230.321
		2	1012.954	1064.232	1421.014
	5	3	1565.108	1243.566	1382.796
		2	1326.022	1280.196	1592.726
	6	3	1875.538	1444.721	1518.427
		2	1387.307	1486.503	1746.553
85	2	3	748.660	573.897	849.904
		2	434.559	584.941	964.219
	3	3	1122.990	809.411	1053.995
		2	706.604	824.344	1193.055
	4	3	1199.929	1030.781	1226.740
		2	831.625	1047.305	1380.964
	5	3	1375.567	1242.604	1380.676
		2	1037.656	1259.675	1547.409
	6	3	2081.051	1443.054	1514.946
		2	1235.289	1463.315	1698.264
75	2	3	748.290	573.608	849.235
		2	616.932	576.498	940.788
	3	3	790.108	808.164	1050.785
		2	720.229	811.551	1160.962
	4	3	1246.039	1027.758	1218.860
		2	881.331	1033.279	1348.760
	5	3	1248.631	1238.221	1370.442
		2	951.835	1242.117	1508.445
	6	3	1749.465	1438.329	1503.910
		2	1150.304	1443.778	1656.161

Table 5.10 (continued)

System : water/syrup (concentration 40 wt%)

TiO(°C)	Flow(LPM)	Section	U(exp)	U(to)	U(tof)
98	2	1	626.124	553.030	800.659
		2	401.910	574.523	937.593
	3	1	882.563	779.572	991.964
		2	699.691	810.831	1163.226
	4	1	1199.070	991.933	1152.546
		2	999.411	1029.301	1344.957
	5	1	1160.797	1195.097	1296.266
		2	1129.468	1238.251	1507.333
85	2	1	631.773	551.569	796.678
		2	465.357	564.753	909.372
	3	1	801.693	777.204	986.853
		2	844.615	795.256	1123.341
	4	1	758.127	990.601	1150.247
		2	806.624	1010.764	1301.750
	5	1	1191.096	1192.477	1291.037
		2	1102.328	1215.156	1457.293
75	2	1	578.192	550.350	793.399
		2	493.991	555.573	884.530
	3	1	902.948	774.067	979.618
		2	626.174	782.122	1091.247
	4	1	1083.013	986.971	1142.073
		2	827.302	995.130	1265.655
	5	1	1443.117	1187.964	1281.352
		2	1034.127	1197.271	1417.492

Table 5.11 Experimental and estimated values of the overall heat transfer coefficient.

System : water/glycerine (concentration 40 vol%)

T10(°C)	Flow(LPM)	Section	U(exp)	U(to)	U(tof)
98	2	3	750.912	716.668	838.475
		2	488.902	580.554	919.618
	3	3	990.475	960.787	1082.984
		2	722.866	817.768	1137.158
	4	3	1320.633	1182.082	1298.602
		2	951.170	1040.010	1319.500
	5	3	1764.316	1381.510	1485.803
		2	1084.344	1249.661	1476.397
	6	3	1789.559	1572.498	1664.817
		2	1190.044	1451.983	1620.756
85	2	3	568.748	712.884	832.219
		2	472.901	570.965	894.377
	3	3	975.279	956.642	1076.290
		2	810.687	804.606	1106.666
	4	3	1229.813	1174.978	1287.590
		2	834.401	1022.357	1282.764
	5	3	1356.271	1380.796	1484.840
		2	1033.070	1229.949	1436.728
	6	3	2681.240	1567.895	1657.186
		2	1236.286	1429.097	1577.222
75	2	3	501.569	711.363	829.522
		2	459.771	562.734	873.490
	3	3	752.353	950.475	1066.457
		2	663.510	792.242	1078.843
	4	3	1003.138	1169.501	1278.946
		2	840.712	1007.689	1251.191
	5	3	1253.922	1364.714	1460.507
		2	951.139	1212.376	1401.586
	6	3	2251.912	1551.074	1632.524
		2	1261.068	1408.675	1537.444

Table 5.11 (continued)

System: water/glycerine (concentration 50 vol%)

T10(°C)	Flow(LPM)	Section	U(exp)	U(to)	U(tof)
98	2	3	634.896	672.790	762.541
		2	505.981	570.819	882.097
	3	3	953.299	902.726	986.113
		2	703.929	803.115	1088.520
	4	3	1100.486	1111.607	1184.150
		2	926.140	1021.359	1263.033
	5	3	1431.487	1305.029	1363.427
		2	1290.063	1227.914	1414.526
	6	3	1406.307	1462.236	1523.171
		2	1289.115	1426.710	1552.948
85	2	3	614.113	670.718	759.052
		2	424.516	560.400	855.078
	3	3	921.169	901.184	983.522
		2	698.375	788.739	1055.512
	4	3	1231.236	1106.296	1175.689
		2	895.076	1003.103	1224.396
	5	3	1203.033	1298.598	1353.850
		2	934.966	1205.381	1370.690
	6	3	1842.338	1474.007	1510.458
		2	1130.702	1401.373	1505.285
75	2	3	536.919	668.393	755.006
		2	442.307	551.248	831.954
	3	3	792.894	894.617	973.264
		2	653.000	776.224	1027.949
	4	3	1102.142	1102.258	1169.562
		2	840.649	987.490	1192.538
	5	3	1194.735	1292.802	1345.096
		2	955.427	1188.707	1337.453
	6	3	1569.901	1469.887	1504.601
		2	1129.076	1380.953	1467.218

Table 5.11 (continued)

System: water/glycerine (concentration 60 vol%)

T10(°C)	Flow(LPM)	Section	U(exp)	U(to)	U(tof)
98	2	3	669.797	626.804	682.093
		2	526.995	554.450	821.380
	3	3	778.369	839.274	879.734
		2	689.667	781.091	1016.071
	4	3	1130.089	1033.212	1055.960
		2	920.970	992.535	1177.342
	5	3	1412.611	1213.033	1216.010
		2	977.736	1191.711	1315.179
85	2	3	530.470	615.402	664.271
		2	498.093	542.883	791.809
	3	3	753.136	829.781	865.411
		2	672.426	765.564	981.304
	4	3	932.380	1022.473	1040.328
		2	815.833	973.575	1138.300
	5	3	1130.089	1199.869	1197.417
		2	1098.162	1169.215	1272.443
75	2	3	586.886	622.525	675.147
		2	542.487	534.469	771.309
	3	3	787.825	833.828	871.196
		2	578.478	753.981	956.963
	4	3	1050.433	1027.027	1046.340
		2	843.869	958.685	1108.201
	5	3	1303.949	1194.629	1189.416
		2	1045.250	1153.746	1242.403

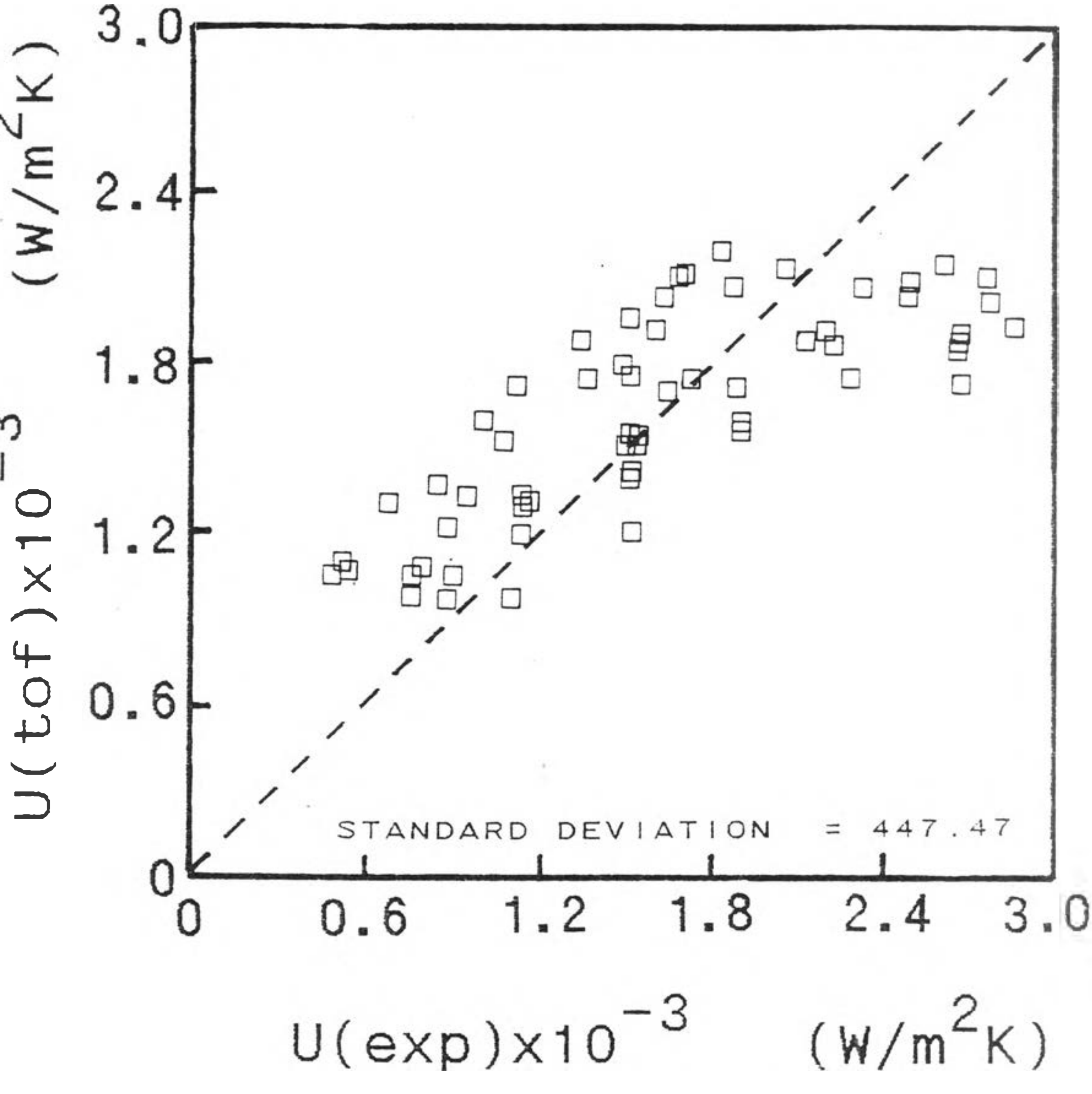

Figure 5.39 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-27) for the case of equal water/water flow rates.

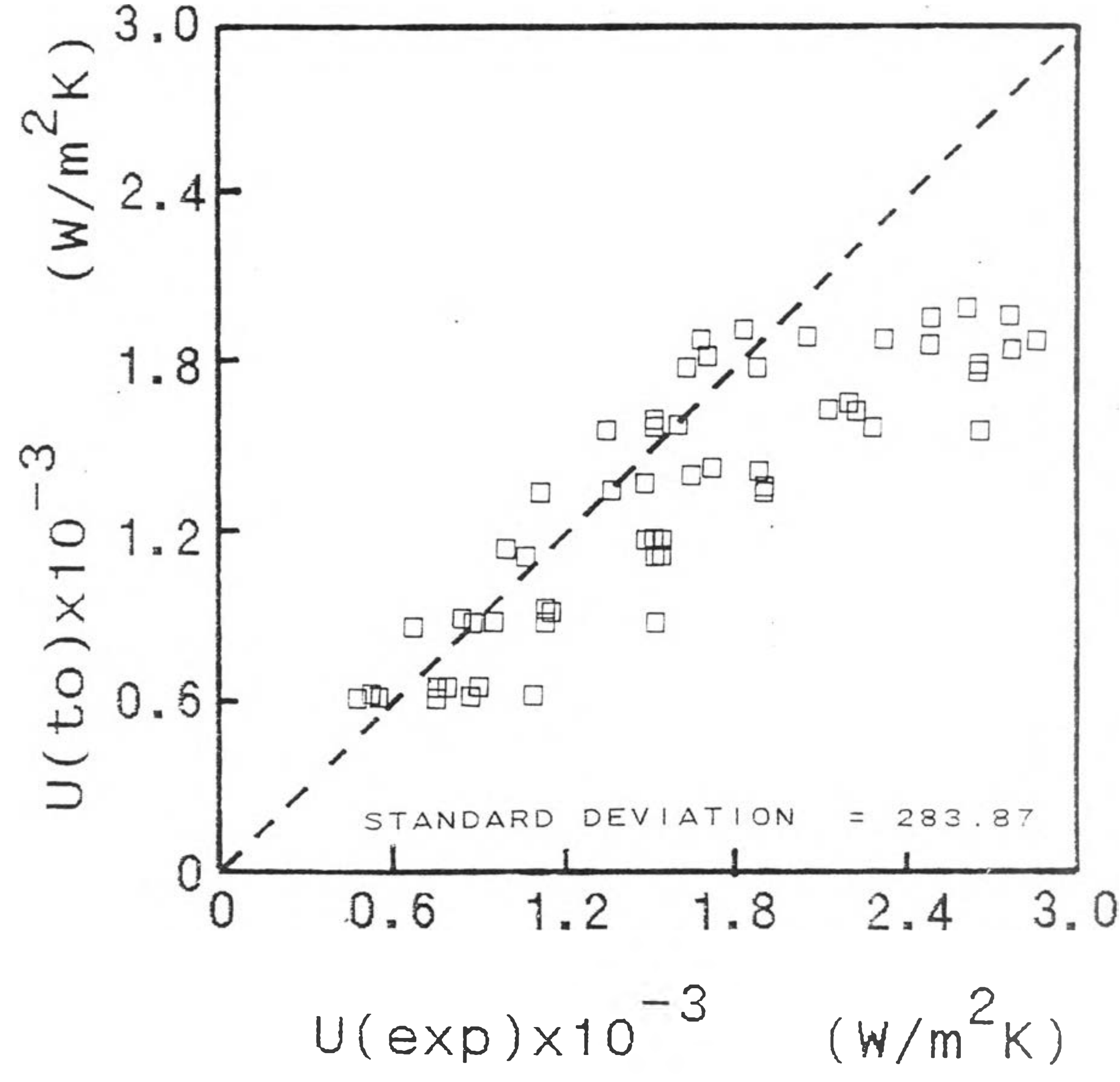

Figure 5.40 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-28) for the case of equal water/water flow rates.

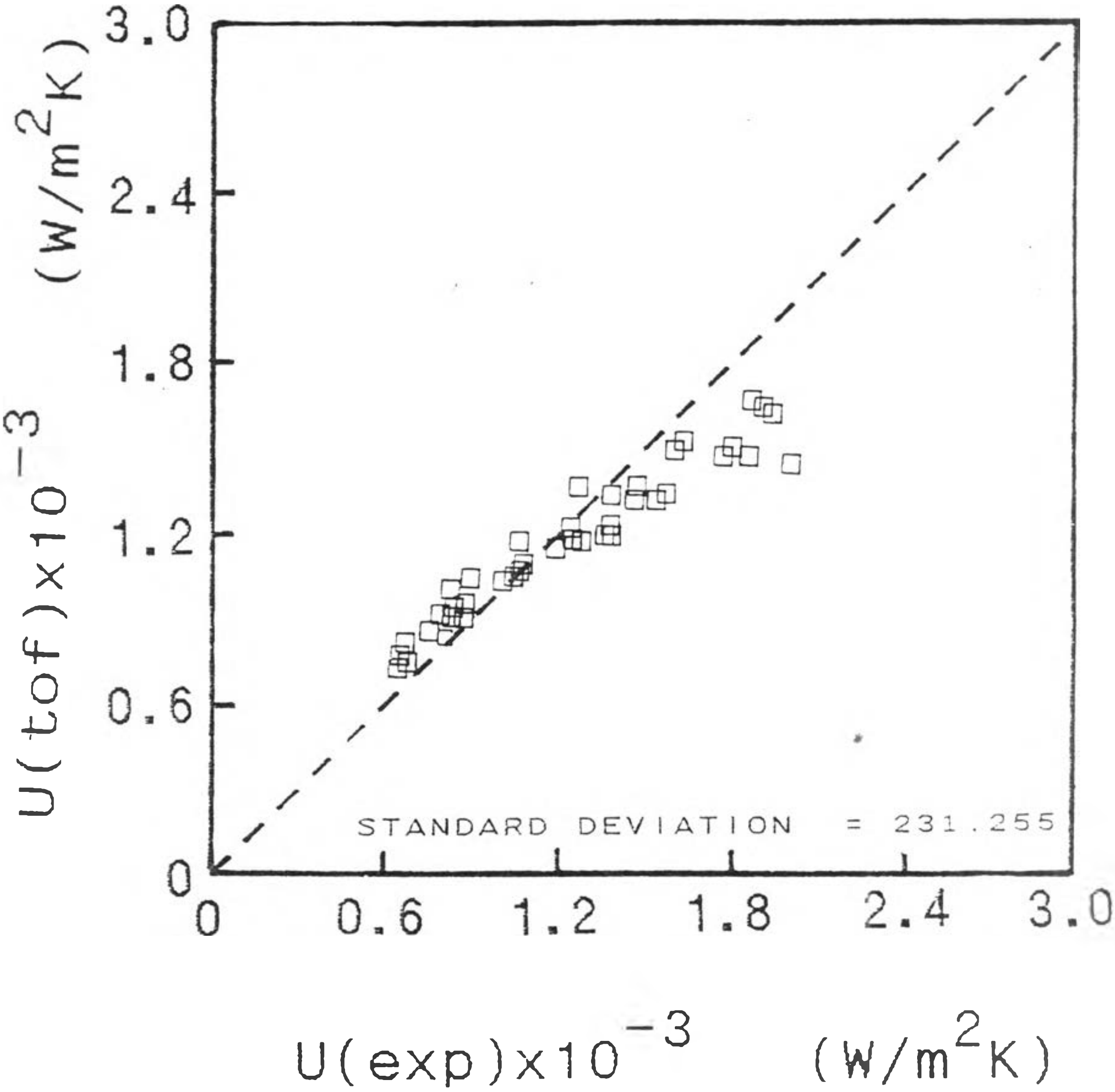

Figure 5.41 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-27) for the case of equal syrup/syrup flow rates.

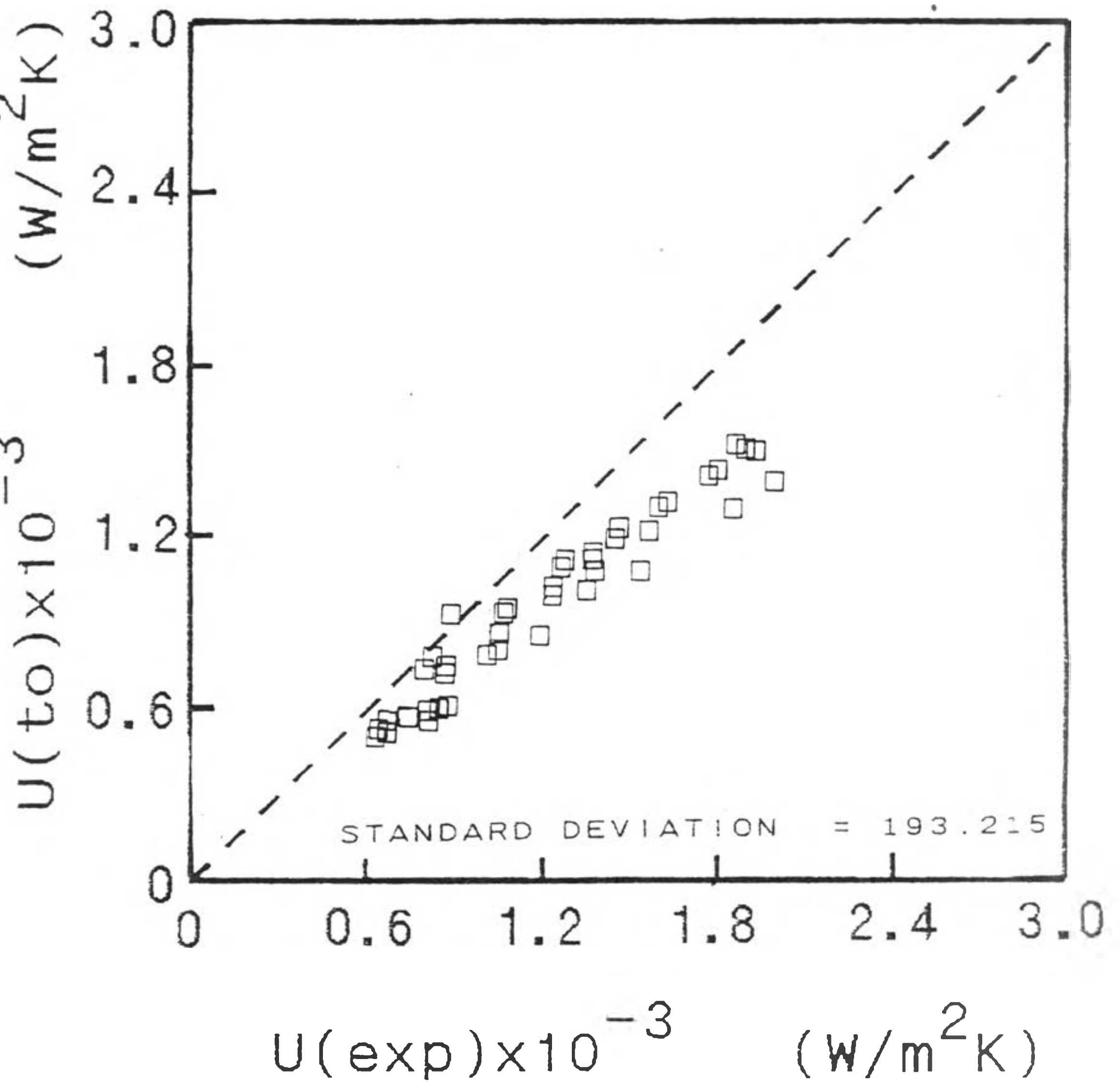

Figure 5.42 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-28) for the case of equal syrup/syrup flow rates.

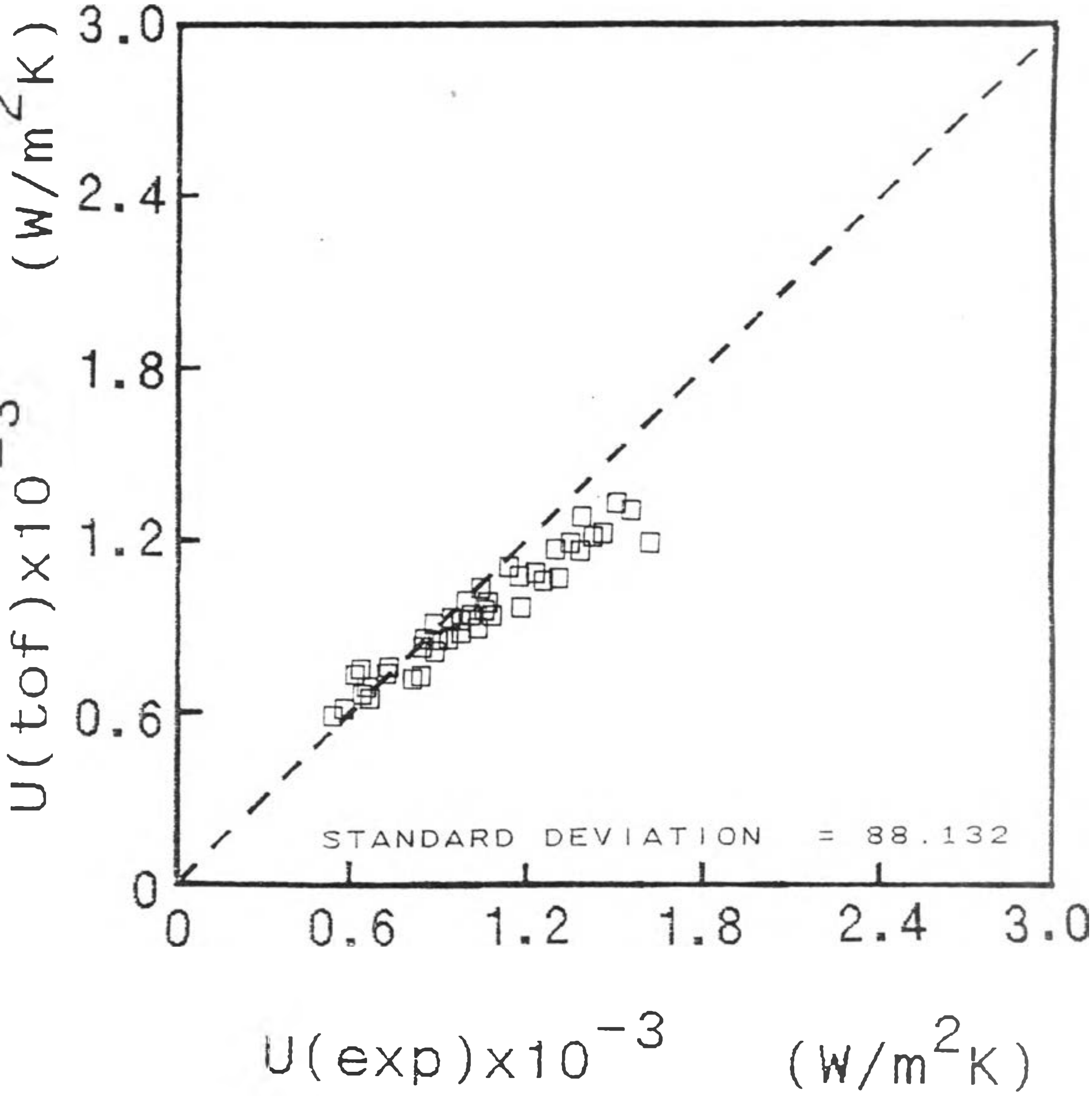

Figure 5.43 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-27) for the case of equal glycerine/glycerine flow rates.

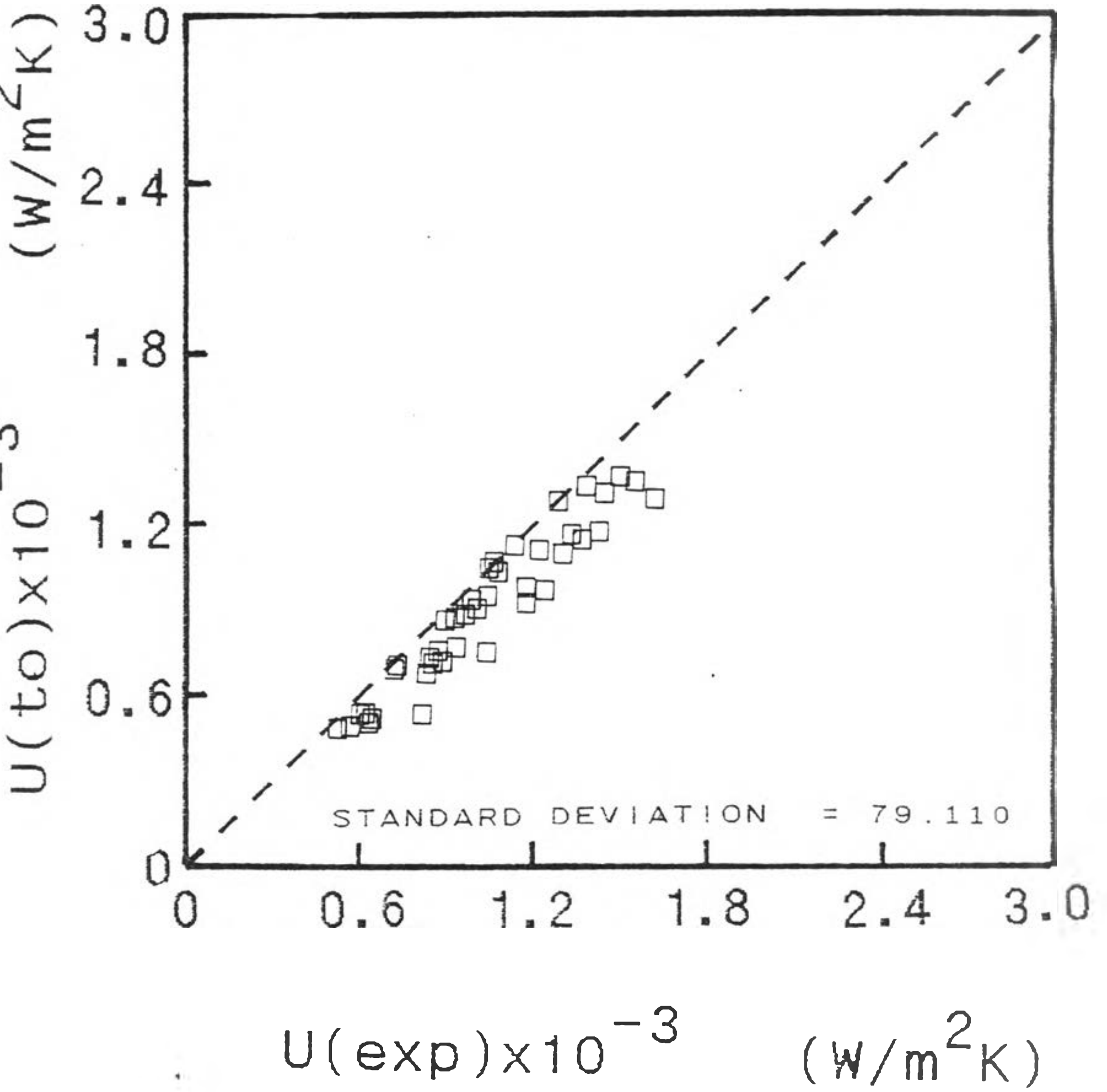

Figure 5.44 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-28) for the case of equal glycerine/glycerine flow rates.

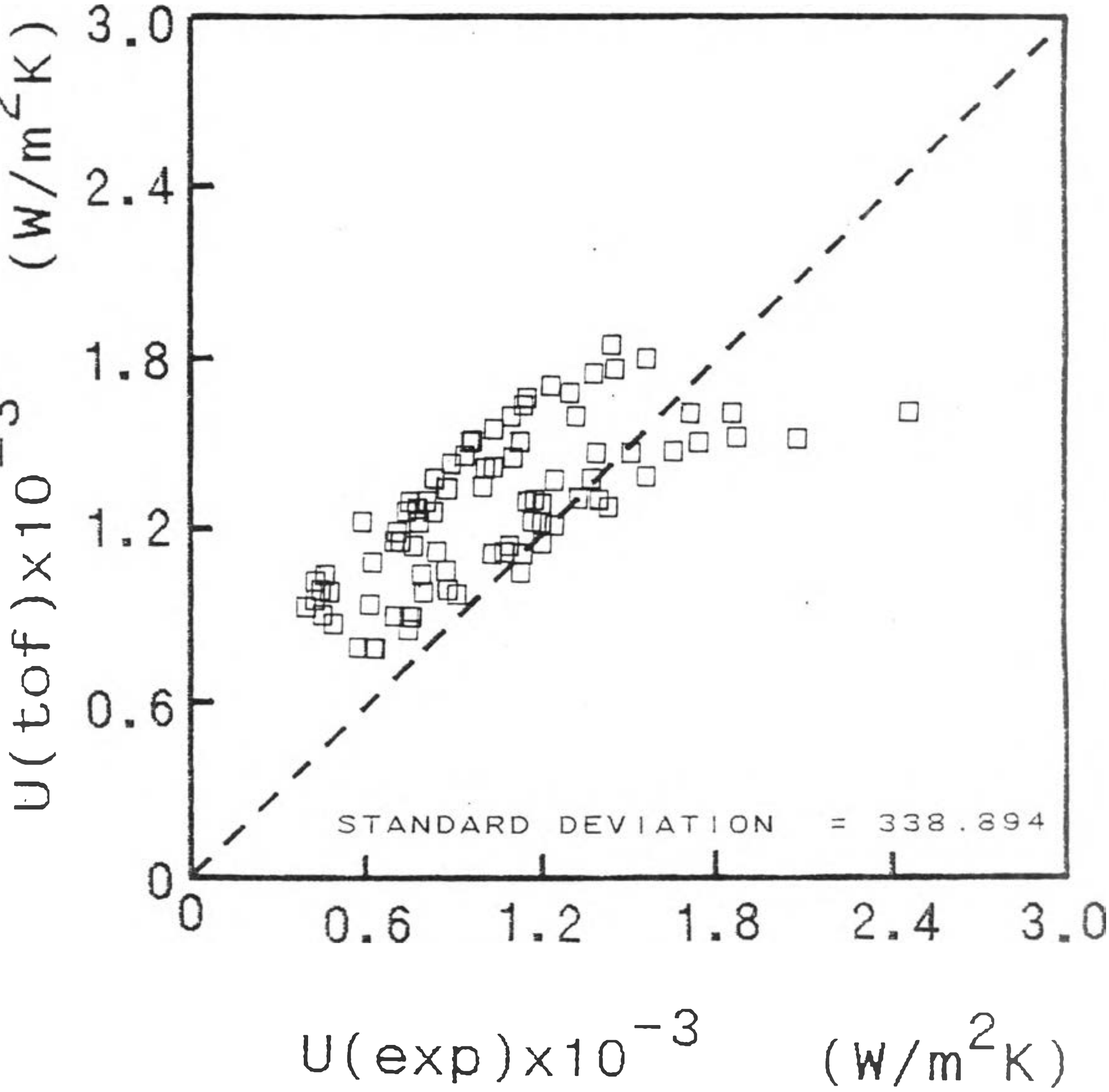

Figure 5.45 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-27) for the case of water/syrup flow rates.

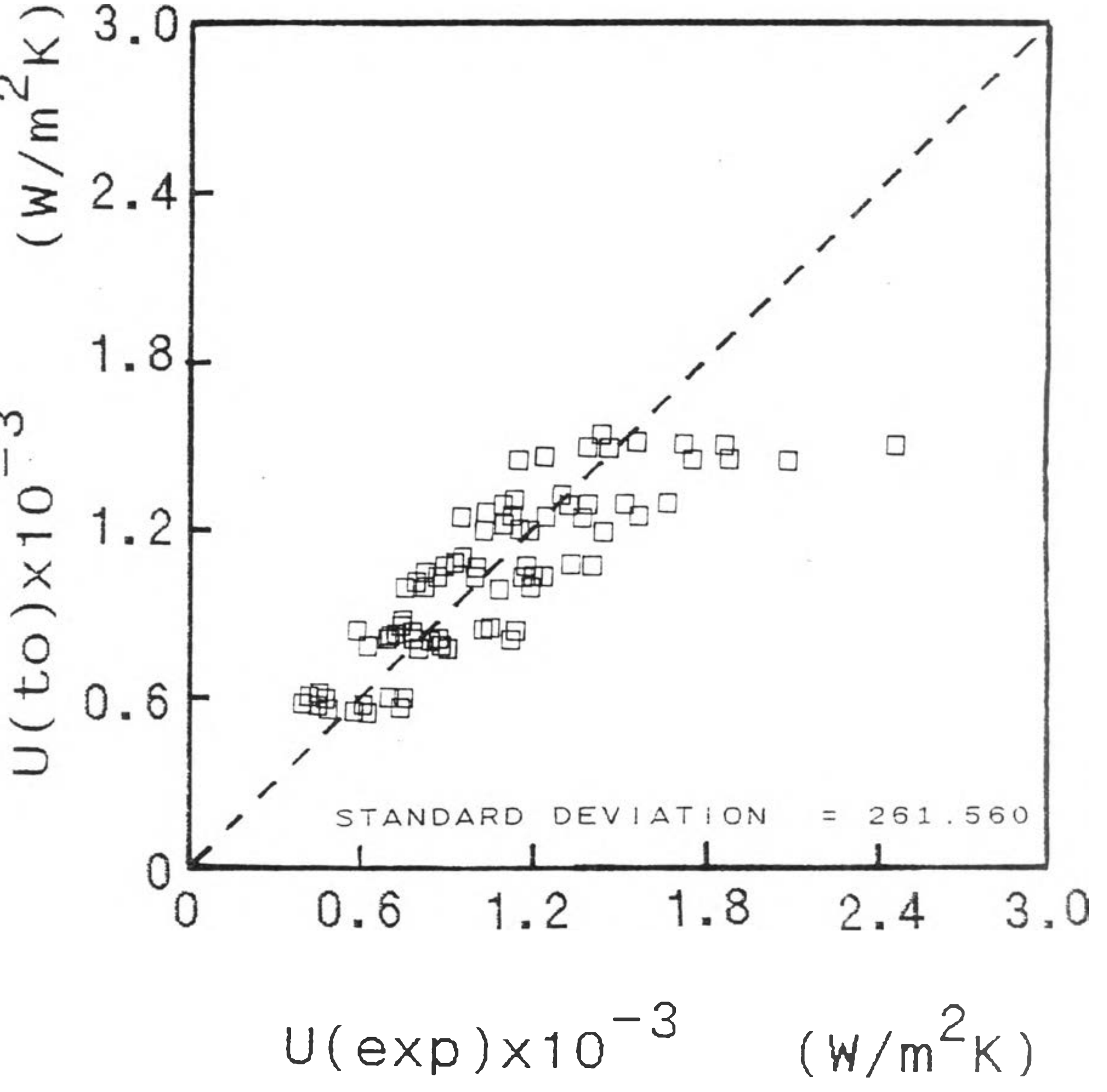

Figure 5.46 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-28) for the case of water/syrup flow rates.

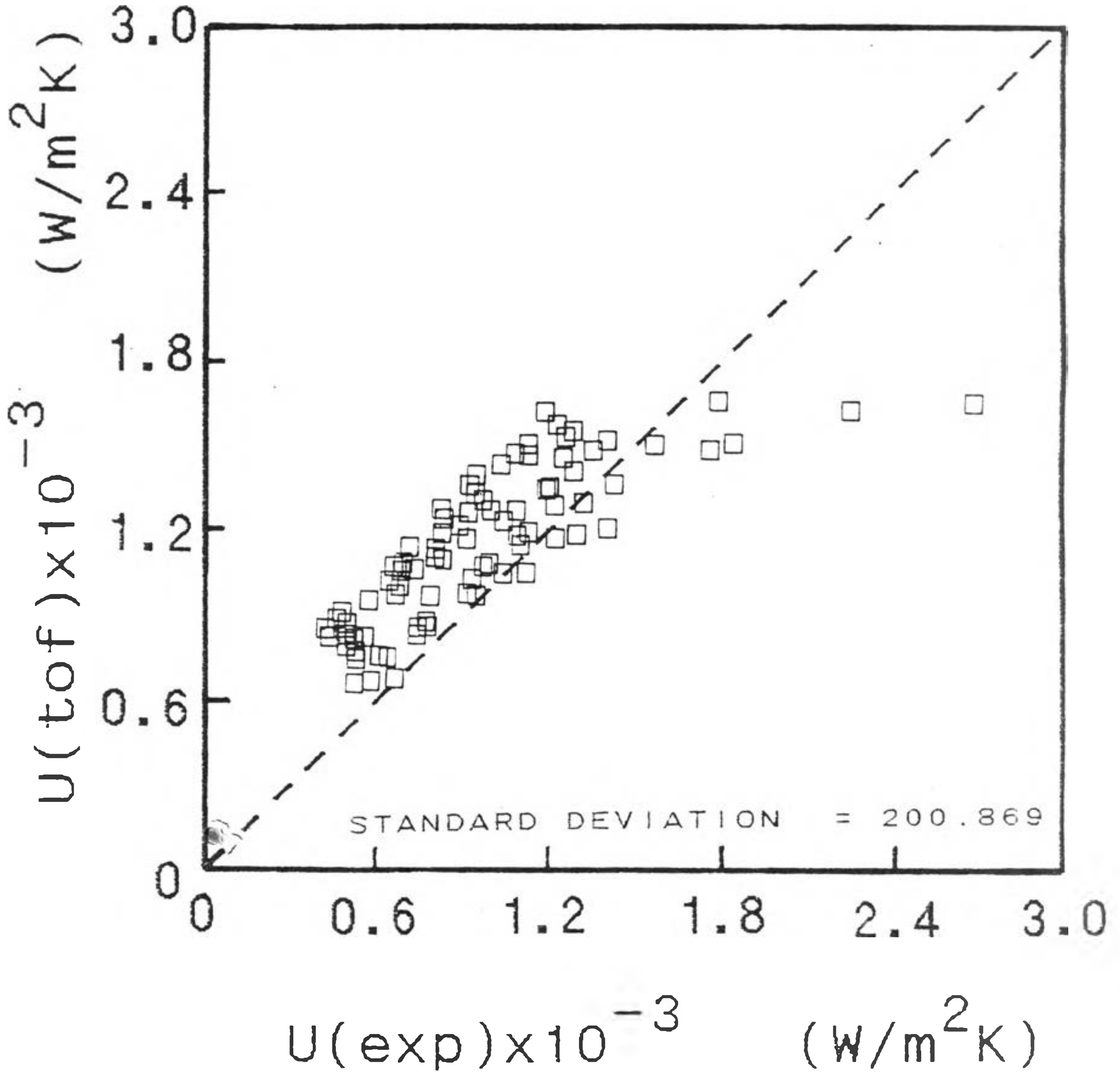

Figure 5.47 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-27) for the case of water/glycerine flow rates.

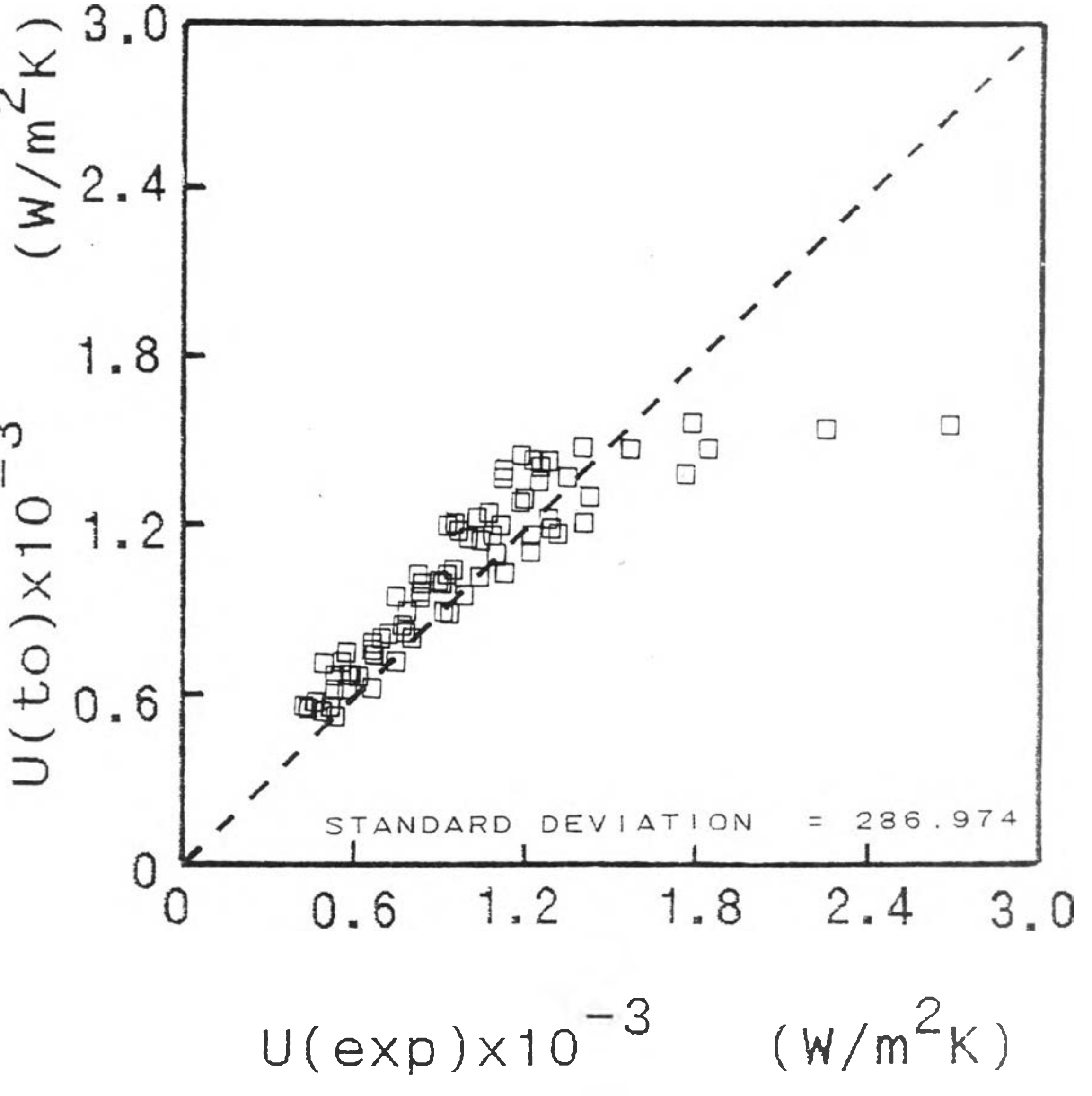

Figure 5.48 Comparison between the experimental value of the overall heat transfer coefficient and the estimated from eqn(5-28) for the case of water/glycerine flow rates.