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Research on Heat Transfer Coefficient Measurement Based on Heat Exchanger Experiment

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Abstract

Heat transfer occurs all the time through substances in any phases by means of conduction, convection and radiation. Therefore, it becomes the fundamental concept in thermodynamics and in mechanical and chemical engineering, which requires designers to be familiar with. A large quantity of correlation formulas dealing with distinct situations have already obtained by plenty of previous testing experience.

Keywords

Heat Exchange; Heat Transfer; Coefficient Measurement.

1. Introduction

From Reference Data CIBSE Guide C, apparently, empirical correlations are differs in various fluids, tube cross sections and characteristic length, etc. This experiment, using water as medium flowing in pipe with circle cross section, is mainly focus on the measurement of heat transfer coefficient to gain the numerical relationship among Nusselt number, Prandtl number and Reynolds number, and the evaluation on the feasibility of the Dittus and Boelter correlation by comparing it with the experimental equation.

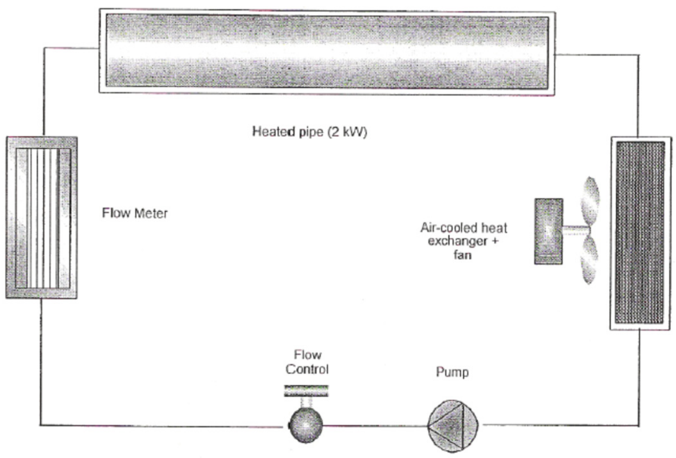

Figure 1. Schematic apparatus of the whole system

2. Description of Theory

A schematic apparatus is shown in Figure 1. It can be seen that the circulatory system consists of two major processes: heating and cooling.

Firstly, the pump starts to activate water to move. Simultaneously, the volume flow rate, adjusted desirably by the control valve nearby, is read from flow meter. The working pipe setting after the flow instrument is made of copper, which acts as an effective thermal conductive material, and is entirely wrapped by insulation, which can minimize heat loss during the operating. In the tube, 'the heat transfer from a solid surface to a fluid takes place partly by

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conduction and partly by convection' (1). In other words, both conduction and convection occurs when water absorbs the thermal energy, into which initial electric energy is converted.

After the heating section, water enters to a quite long tube, with compact structure, adjacent to an electric fan. Before it returns to the pump, normally, the fan turns frequently to provide sufficient ventilation and cool down the liquid inside.

3. Description of Apparatus

Heated pipe: a heating installation with tubular shape to increase the temperature of fluid flowing through (main part of the system).

Air-cooled heat exchanger fan: an electrical device to create air current aiming at decreasing the temperature of fluid flowing in the long tube.

Re-circulation pump: a common appliance to force the fluid to move from lower place to higher place

Flow control: a manual controller to regulate flow.

Flow meter: a measurement of volume flow rate in the unit of liters per minute.

4. Description of Experimental Method

1) Start to turn on the system. Rotate the power switch on the control panel to change the electric current while the voltage remains the same. Thus the heating power can be varied. At the beginning, amps as required should be a bit large in Unit 1.

2) Regulate fluid flow. After a while, check T_5 and T_6 to make sure whether their temperature difference is stable at 4 degree. If not, do this again to attain the purpose. Then, read T_1 to T_6, flow rate, electric current and voltage as one group of data.

3) Turn the current to be a little lower than before and repeat Step 2 to take down the data.

4) Apply the same method indicated in Step 3 to collect other 5 groups of testing statistics.

5) Determine the average of T_5 and T_6, and the mass flow rate based on the assumption that the water density is 1000 kg/m^3. Using the table (Table 1) from *Thermodynamic and Transport Properties of Fluids*, by linear method, calculate C_p, μ and λ with corresponding average temperature of T_5 and T_6 previously obtained. For example, λ at 35 ℃ and 40 ℃ are 718*10^{-6}kg/m s and 651*10^{-6}kg/m s respectively, so λ at 37 ℃ theoretically should be $(718-\frac{3*(718-651)}{5})*10^{-6} = 677.8*10^{-6}$kg/m s.

Note: even though for the C_{pf} and k_f (i. e. λ) columns the numbers are not usually enhanced with the increasing of temperature, to simplify it, the assumption is made that the linear method is applied by the two nearest numbers for estimation.

6) Within the known conditions,

a). For Nusselt Number: ΔT(fluid, out-in), L and D are always 4℃, 1.5m and 0.0127m correspondingly. Hence, the pipe internal surface area A' is decided by formula

$$A' = \pi*D*L. \quad (1)$$

Then ΔT (wall – fluid) is depended on the equation

$$\frac{T_1+T_2+T_3+T_4}{4} - \frac{T_5+T_6}{2} \quad (2)$$

and

$$Q = \dot{m}*C_p*\Delta T\ (\text{fluid, out-in}) \quad (3)$$

Calculate heat transfer coefficient

$$\alpha = \frac{Q}{A'*\Delta T\ (\text{wall}-\text{fluid})} \quad (4)$$

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followed by

$$Nu = \alpha * D/\lambda \tag{5}$$

b). For Reynolds Number: using the information,

$$Re = \frac{\dot{m}}{\pi * D * \mu} \tag{6}$$

c). For Prandtl Number: using the information,

$$Pr = \frac{Cp * \mu}{\lambda} \tag{7}$$

7) With the help of Excel, automatically compute Nu, Pr and Re by equations above.

Table 1. Properties of water and Steam

t [°C]	p_s [bar]	v_f 10^{-2}[m³/kg]	c_{pf} [kJ/kg K]	c_{pg} [kJ/kg K]	μ_f 10^{-6}[kg/m s]	μ_g 10^{-6}[kg/m s]	k_f 10^{-6}[kW/m K]	k_g 10^{-6}[kW/m K]	$(Pr)_f$	$(Pr)_g$
0.01	0.006112	0.10002	4.210	1.86	1752	8.49	569	16.3	12.96	0.97
5	0.008719	0.10001	4.204	1.86	1501	8.66	578	16.7	10.92	0.96
10	0.01227	0.10003	4.193	1.86	1300	8.83	587	17.1	9.29	0.96
15	0.01704	0.10010	4.186	1.87	1136	9.00	595	17.5	7.99	0.96
20	0.02337	0.10018	4.183	1.87	1002	9.18	603	17.9	6.95	0.96
25	0.03166	0.10030	4.181	1.88	890	9.35	611	18.3	6.09	0.96
30	0.04242	0.10044	4.179	1.88	797	9.52	618	18.7	5.39	0.96
35	0.05622	0.10060	4.178	1.88	718	9.70	625	19.1	4.80	0.96
40	0.07375	0.10079	4.179	1.89	651	9.87	632	19.5	4.30	0.96
45	0.09582	0.10099	4.181	1.89	594	10.0	638	19.9	3.89	0.95
50	0.1233	0.1012	4.182	1.90	544	10.2	643	20.4	3.54	0.95
55	0.1574	0.1015	4.183	1.90	501	10.4	648	20.8	3.23	0.95
60	0.1992	0.1017	4.185	1.91	463	10.6	653	21.2	2.97	0.95
65	0.2501	0.1020	4.188	1.92	430	10.7	658	21.6	2.74	0.95
70	0.3116	0.1023	4.191	1.93	400	10.9	662	22.0	2.53	0.96
75	0.3855	0.1026	4.194	1.94	374	11.1	666	22.5	2.36	0.96
80	0.4736	0.1029	4.198	1.95	351	11.3	670	22.9	2.20	0.96
85	0.5780	0.1032	4.203	1.96	330	11.4	673	23.3	2.06	0.96
90	0.7011	0.1036	4.208	1.97	311	11.6	676	23.8	1.94	0.96
95	0.8453	0.1040	4.213	1.99	294	11.8	678	24.3	1.83	0.97
100	1.01325	0.1044	4.219	2.01	279	12.0	681	24.8	1.73	0.97
105	1.208	0.1048	4.226	2.03	265	12.2	683	25.3	1.64	0.98
110	1.433	0.1052	4.233	2.05	252	12.4	684	25.8	1.56	0.99
115	1.691	0.1056	4.240	2.07	241	12.6	686	26.3	1.49	0.99
120	1.985	0.1060	4.248	2.09	230	12.8	687	26.8	1.42	1.00
125	2.321	0.1065	4.26	2.12	220	13.0	687	27.3	1.36	1.01
130	2.701	0.1070	4.27	2.15	211	13.2	688	27.8	1.31	1.02
135	3.131	0.1075	4.28	2.18	203	13.4	688	28.3	1.26	1.03
140	3.614	0.1080	4.29	2.21	195	13.5	688	28.8	1.22	1.04
145	4.155	0.1085	4.30	2.25	188	13.7	687	29.4	1.18	1.05
150	4.760	0.1091	4.32	2.29	181	13.9	687	30.0	1.14	1.07
160	6.181	0.1102	4.35	2.38	169	14.2	684	31.3	1.07	1.09
170	7.920	0.1114	4.38	2.49	159	14.6	681	32.6	1.02	1.12
180	10.03	0.1128	4.42	2.62	149	15.0	676	34.1	0.97	1.15
190	12.55	0.1142	4.46	2.76	141	15.3	671	35.7	0.94	1.18
200	15.55	0.1157	4.51	2.91	134	15.7	665	37.5	0.91	1.22
210	19.08	0.1173	4.56	3.07	127	16.0	657	39.4	0.88	1.25
220	23.20	0.1190	4.63	3.25	121	16.3	648	41.5	0.86	1.28
230	27.98	0.1209	4.70	3.45	116	16.7	639	43.9	0.85	1.31
240	33.48	0.1229	4.78	3.68	111	17.1	628	46.5	0.84	1.35
250	39.78	0.1251	4.87	3.94	107	17.5	616	49.5	0.85	1.39
260	46.94	0.1276	4.98	4.22	103	17.9	603	52.8	0.85	1.43
270	55.05	0.1302	5.10	4.55	99	18.3	589	56.6	0.86	1.47
280	64.19	0.1332	5.24	4.98	96	18.8	574	61.0	0.88	1.53
290	74.45	0.1366	5.42	5.46	93	19.3	558	66.0	0.90	1.60
300	85.92	0.1404	5.65	6.18	90	19.8	541	72.0	0.94	1.70
320	112.9	0.1499								
340	146.1	0.1639								
360	186.7	0.1894								
370	210.5	0.2225								
374.15	221.2	0.317								

8) Draw a scatter diagram. Add the linear trend line to attain its own function in the style of y = mx + n (equivalent to Log (Nu/Pr^b) = Log A +a Log Re). Specify A and a in numbers while b is 0.4 for heating in this situation and change the function form into $Nu = A Re^a Pr^{0.4}$.

9) Compare the result with Dittus and Boelter correlation, $Nu = 0.023Re_D^{0.8} Pr^{0.4}$ for heating process.

5. Results

The calculated results by Excel is listed in Table 2, the columns of the three numbers are highlighted.

Table 2. Calculated results

Unit	T_6-T_5 (℃)	Average of T_1 to T_4 (℃)	Average of T_5 and T_6 (℃)	△T(wall-fluid) (℃)	C_p (kJ/kgK)	Q (kW)	α	$\lambda=k_f\ 10^{-6}$ (kW/m K)	Nu	$\mu\ 10^{-6}$ (kg/ms)	Re	Pr
1	4	47.25	37	10.25	4.1784	1.922064	3.1331	627.8	63.38	677.8	17009.94	4.5112
2	4	47.25	36	11.25	4.1782	1.587716	2.3581	626.4	47.81	704.6	13517.22	4.6998
3	4	44.25	35	9.25	4.1780	1.476227	2.6665	625.0	54.18	718.0	12334.07	4.7997
4	4	40.75	33	7.75	4.1784	0.974960	2.1019	622.2	42.90	749.6	7801.78	5.0340
5	4	40.75	31	9.75	4.1788	0.807901	1.3845	619.4	28.39	781.2	6202.84	5.2704
6	4	39.75	30	9.75	4.1790	0.668640	1.1458	618.0	23.55	797.0	5031.62	5.3894
7	4	41.75	29	12.75	4.1794	0.417940	0.5477	616.6	11.28	815.6	3073.05	5.5282

The diagram of the relationship, including the tendency, is illustrated in Figure 2.

From the displayed function in the diagram, a = 0.999 and Log A = -2.6482, i.e. A = 0.0022. The discrepancy for a is (0.999-0.8)/0.8=24.9% and for A is (0.023-0.0022)/0.023=90.4%.

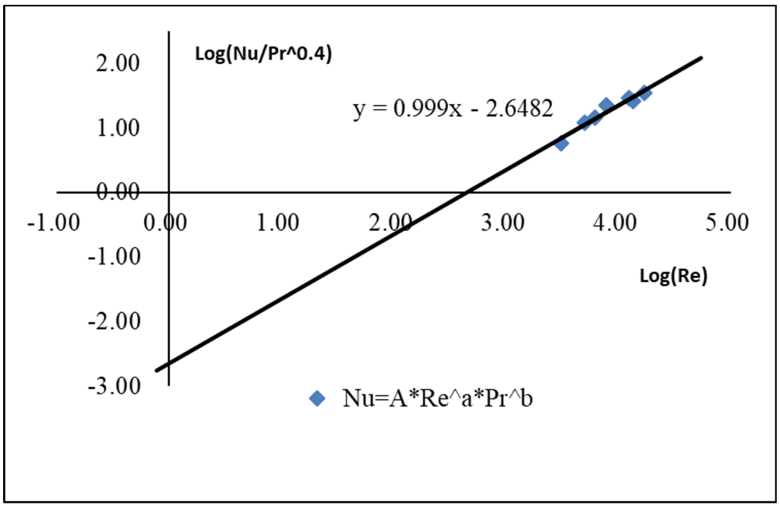

Figure 2. Scatter figure with the tendency line

6. Discussion

From the result table, the evidence reveals some characteristics of the fluid flow and the heat transfer. For Reynolds numbers, except the last one, are most more than 4000, namely that these flows should belong to turbulent flow. And as the heating power falls down, Re declines which means the degree of turbulence also drops.

For Nusselt number, as it is defined as the ratio of convective to conductive across the boundary (2), the all numerical magnitudes of Nu are over 10, which means the convection plays a much more significant roles than conduction in heat exchange section. From the change of Nu, though the convection remains as the majority, it becomes weaker and weaker while the conduction is growing stronger.

Last for Prandtl number, they are around 5, located in the range of Pr for water 1.7 -13.7 in common cases (3). Therefore, heat diffuses more slowly than momentum and the thermal boundary layer is relatively thinner than velocity boundary layer for this fluid flow.

Now make an intensive study of the connection among the three numbers. Obviously, the experimental consequence differs from the Dittus and Boelter correlation equation. There should be several key points and mistakes during the operation, which need to be explained and analyzed (4).

First of all, some theoretical assumptions may have impact on it. It is often assumed that the circulatory system runs in a steady condition. However, there are no ideal unchangeable conditions. For instance, when reading the temperatures, the trainers can observe that the numbers shown on the screen fluctuating sometimes actually. It is hard to be fixed in a perfectly stable condition. Another similar assumption is also made that the heating part is insulated excellently without any heat loss. As a matter of fact, there should be some heat loss even though the experimenters felt not warm when touching the outer insulation surface (only prove that it is insulated well). As a result, the temperatures would differ with the ones if the pipe is insulated perfectly, leading to the different heat transfer coefficient. In addition, the liner method utilized in the calculation for properties of water at different temperatures has no rigorous foundation in fact. It is merely a simply and common way to know the water properties.

Then the accuracy of thermometer is a little low, only to units' digit. Since that the temperature difference is 4 degree between T_5 and T_6, the readings should be accurate to one decimal place at least.

Selection of useful information is a vital factor in experiment analysis. Generally speaking, not all recordings are helpful, some maybe wrong owing to the inevitable errors of reading, the depreciation of instruments or the improper operation. Sometimes, by logical thinking, analyzers can easily eliminate the completely false information. In this case, the last group of data is very irregular. Because T_2, T_3 and T_4 remain too high after the reduction of heating power. Furthermore, they did not decrease despite provided enough time. Consequently, the diagram is improved, which only use 6 groups of data, shown in Figure 3. A = 0.0120, a = 0.8192, and final correlation should be $Nu = 0.012Re^{0.8192}Pr^{0.4}$, which is closer to the truth (5).

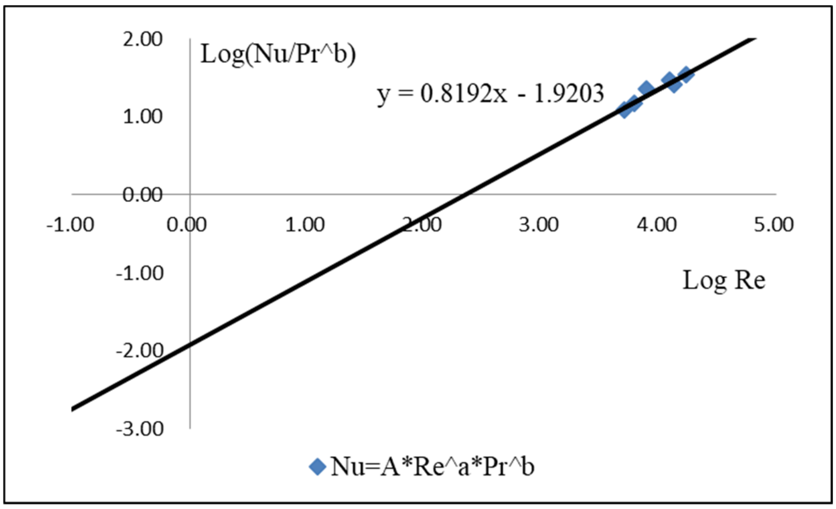

Figure 3. Mproved scatter figure with the tendency line
(the function is for the unique heat transfer in this fluid flow)

Another reason for the large difference is that there is a limitation for the Dittus and Boelter correlation. From *Reference Data CIBSE Guide C*, the valid range $0.7 \leq Pr \leq 160$ and $Re_D > 10000$ is the premise for this equation. Thus another developed equation which matches the condition using the first three groups of data is displayed in Figure 4. A = 0.03453, a = 0.7065 and the function is $Nu = 0.03453Re^{0.7065}Pr^{0.4}$. Calculate the discrepancy in percentage: for a, it is (0.8-0.7065)/0.8 = 11.7% and for A, it is (0.03453-0.023)/0.023 = 50.1%, both are lower than that in Results Section. Despite these, the Dittus and Boelter correlation still seems not very proper for this case. But if more testing is taken, the constant A and a maybe closer to 0.023 and 0.8 individually since that the Dittus and Boelter correlation itself is an empirical equation.

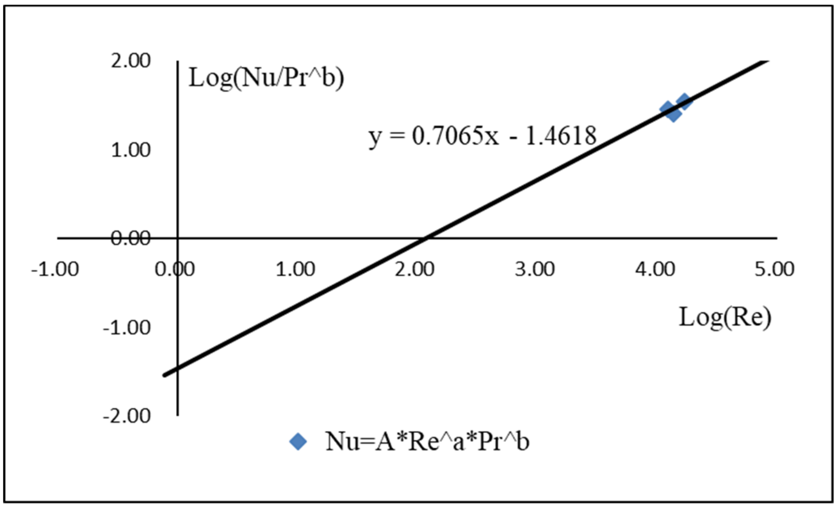

Figure 4. Improved scatter figure with the tendency line
(Used to compare with the Dittus and Boelter correlation)

7. Conclusion

There are two basic procedures, heating and cooling and the main feature of this experiment is the large quantity of data manipulation. The existence of difference between the experiment and experience is very normal since it is impossible for testing at first time perfectly matching expectation. It would probably have some mistakes and limitations during every experimental process, commonly such as the reading errors, inappropriate operation, decreasing of equipment function and the lack of information. The assumption of linear method for calculating detailed water properties is a case on the point for lacking information (6). If a diagram or some software which offer these, the function can be more precise. So far, however, selecting valuable statistics is a suitable approach to raise the accuracy to a certain degree. For example, the discrepancies between the obtained one and experiential one for A and a turn to be much lower after deleting useless data beyond the valid range. Furthermore, another function of this unique fluid flow is also promoted by abandon the last data. In Summary, $Nu = 0.03453Re^{0.7065}Pr^{0.4}$ is used for comparison with the Dittus and Boelter correlation and $Nu = 0.012Re^{0.8192}Pr^{0.4}$ is the most correct equation in this case.

8. Recommendations for Future Work

As mentioned above, for apparatus, the thermometer needs to be more accurate and detailed water properties require to obtain by creditable website, document or software. The more testing times are taken, the closer to truth for function. Additional future work such as apparatus checking and maintenance should be done frequently to ensure them running

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smoothly in the experiment. Further study on the heat transfer characteristics linking to internal fluid flow is also necessary for experimenters.

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