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BRIEF COMMUNICATION

TWO-PHASE HEAT TRANSFER IN TWO COMPONENT VERTICAL FLOWS

G. ELAMVALUTHI and N. S. SRINIVAS
Department of Chemical Engineering, Indian Institute of Technology, Madras-600036, India

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INTRODUCTION

Two-phase two component heat transport in non-boiling situation is encountered in many chemical and thermal engineering processes. Simultaneous preheating of a liquid and an inert gas is however often required in catalytic and other processes. The vertical pipe flow of gas–liquid and liquid–liquid mixtures is widely encountered in petrolium industry.

In non-boiling systems, the enhancement of convective heat transfer by injecting a gas phase in confined liquid flows has been observed. Estimation of two phase heat transfer coefficients in non-boiling is very useful, yet this topic received comparatively little attention from researchers. Collier (1972) presents comprehensive literature survey. However table 1 presents the experimental details of previous investigators in two-phase two-component vertical pipe flows in round tubes. Shah (1981) presented a correlation to predict two-phase two component heat transfer coefficients covering bubbly, slug and annular regimes.

EXPERIMENTAL SET-UP AND PROCEDURE

The experimental set-up consisted of a brass tube test section of 10 mm i.d. with 2 mm wall thickness and 860 mm length. Two tappings are provided to measure the two phase pressure drop over this length. Four copper–constantan thermocouples (30 gauge) are fixed to the wall at equidistant to record the wall temperature. Test section was wound with nichrome wire (24 gauge) and was heated by passing electricity with the help of a variable transformer. Entire test section including the nichrome wire was insulated with asbestos powder to minimise the heat loss. Liquid–air mixture temperatures both at the entrance and exit of the test section were measured with the thermocouples (copper–constantan-24 gauge). All the thermocouples were previously calibrated.

Table 1. Experimental details of previous investigators in two-phase component vertical up flows in round tubes

Author(s)	Test Section	Tube I.D. (cm)	L/D	Fluids	Liquid flow kg/m^2s	Flow[+] regimes	U_G/U_L
Verschoor & Stemerding (1951)	Steam heated tube	1.4	28	air–water	140–446	B,S,A	0.1 - 200
Novasad (1972)	Water cooled tube	3.78	27	air–water	8–17	B,S	0.03 - 5.4
				H_2–water	17	B,S	0.34 - 3.12
				air–n butanol	14	B,S	0.12 - 5.2
				H_2–n butanol	14	B,S	0.05 - 9.6
				air–40% glycerine (aq)	15	B,S	0.04 - 0.86
Groothuis & Hendal (1959)	Steam heated tube	1.4	14	air–water	200–800	B,S,A	1 - 200
				air–oil	220–420	B,S,A	1 - 40
Kudirka *et al* (1965)	Elect.heated tube	1.6	14	air–water	156–224	B,S,A	0.16 - 75
				air–glycerol	56	B,S,A	0.25 - 75
Dorresteijn (1970)	Elect. heated tube	7.0	16	air–oil	20–4640	B,S,A	0.004 - 4500
Chu & Jones (1980)	Elect. heated tube	2.67	34	air–water	416–3211	B,S,A	0.12 - 2.14
Present	Elect. heated tube	1.0	86	air–water	300–1600	B,S	0.3 - 2.5
				air–glycerine (aq)	200–1500	B,S	0.6 - 4.6

[+]B = Bubbly, S = Slug, A = Annular

Table 2. Range of variables studied

Variable	Range studied
System	air–water, air–glycerine (aq)
Liquid flow	200–1600 kg/m^{2}s
U_G/U_L	0.3–4.6
Liquid viscosity	0.7–13 Ns/m^2
Wall temperature	36–86°C

Where U_G and U_L are gas and liquid superficial velocities m/s.

Experimental data was collected for two phase pressure drop, single phase and two phase heat transfer. At steady state the liquid flow, air flow and all the thermocouple readings are noted. An average of the four thermocouples readings fixed on the wall of the test section was considered as the wall temperature for calculation purposes. The range of variables studied is given in table 2.

RESULTS AND DISCUSSION

The experimental data collected are categorised as follows: (a) two-phase pressure drop; (b) single phase heat transfer; and (c) two phase heat transfer. The first two viz (a) and (b) confirm the reliability of the two phase heat transfer data collected in (c).

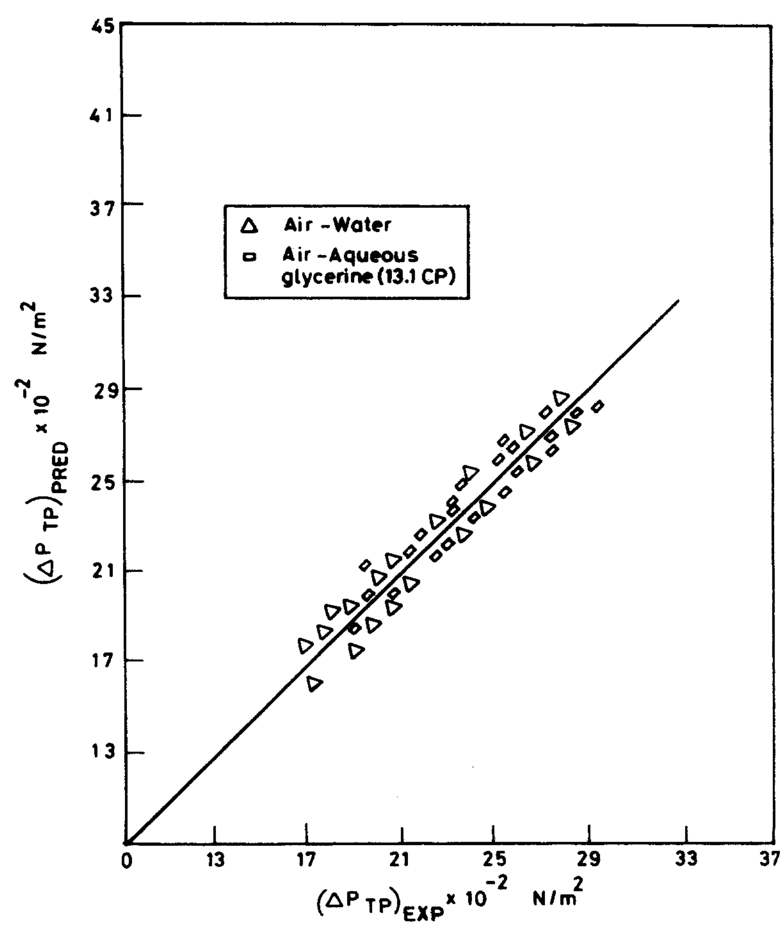

Figure 1. Comparison of experimental two phase pressure drop with Lockhart-Martinelli (1949) correlation.

(a) *Two-phase pressure drop*

Two phase pressure drop data has been collected for systems; air–water and air–glycerine (aq). Reynolds numbers range from laminar to turbulent for both the streams. Figure 1 shows a plot of $(\Delta T_{TP})_{EXP}$ vs $(\Delta T_{TP})_{PRED}$ over the length of 860 mm. $(\Delta P_{TP})_{PRED}$ was calculated with Lockhart & Martinelli (1949) correlation.

Where $(\Delta T_{TP})_{EXP}$ and $(\Delta T_{TP})_{PRED}$ are the two phase pressure drop experimentally obtained and the calculated with Lockhart & Martinelli (1949) correlation.

Density and viscosity of water and glycerine (aq) were experimentally measured over the temperature range investigated presently.

(b) *Single phase heat transfer*

Single phase heat transfer coefficients for water and glycerine (aq) were obtained. Heat transfer coefficient was calculated as per the following energy balance equation

$$h_{SP} = \frac{Q_L \rho_L C_L (T_2 - T_1)}{A \Delta T_{1m}}. \quad [1]$$

Where h_{SP} is single phase heat transfer coefficient, W/m^{2}K; Q_L is liquid volumetric flow rate, m^3/s; ρ_L is liquid density, kg/m^3; C_L is liquid specific heat, J/kg K; T_1 is inlet temperature, K; T_2 is outlet temperature, K; ΔT_{1m} is log mean temperature difference, K and A is heat transfer area, m^2. ($A = \pi DL$, D is test section inside diameter, m; and L is test section length,

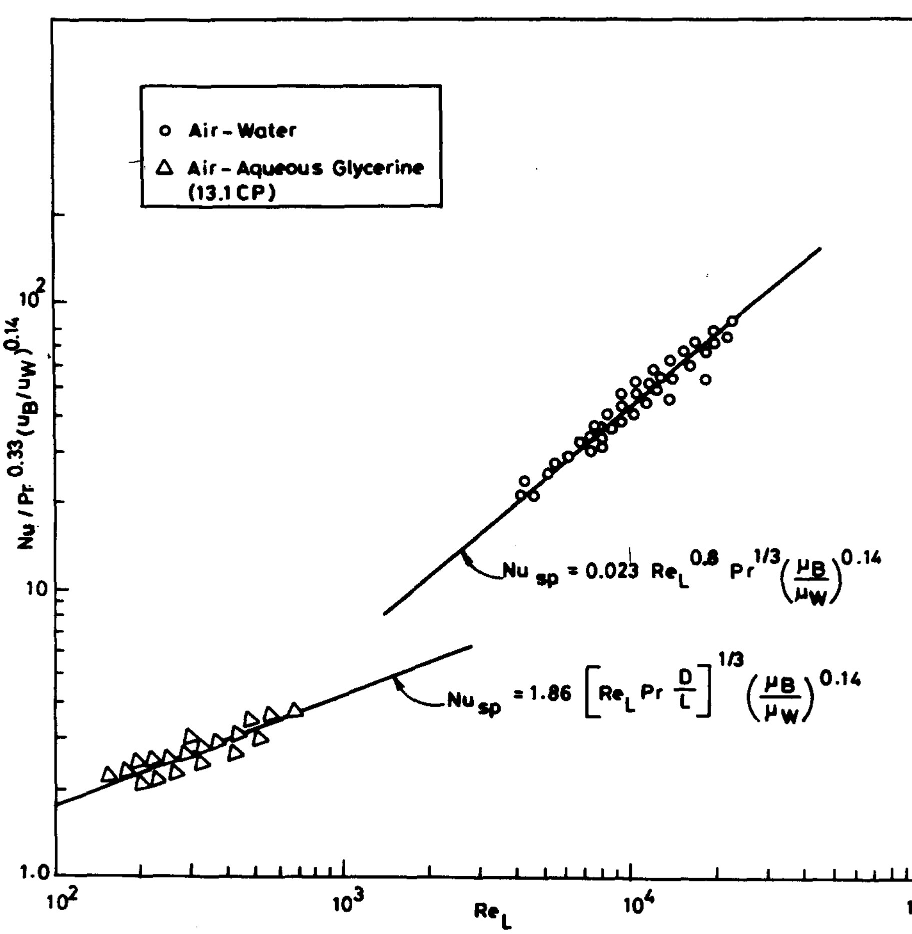

Figure 2. Comparison of the $(Nu_{SP}/Pr^{0.33}(\mu_B/\mu_W)^{0.14})$ obtained experimentally with standard correlations for laminar and turbulent flows.

m) and

$$\Delta T_{1m} = \frac{(T_W - T_1) - (T_W - T_2)}{\ln \dfrac{(T_W - T_1)}{(T_W - T_2)}}$$

where T_W is wall temperature, K.

Figure 2 shows a plot of log $(\mathrm{Nu}_{SP}/\mathrm{Pr}^{1/3}(\mu_B/\mu_W)^{0.14})$ vs log Re_L.

Where

$$\mathrm{Nu}_{SP} = \left(\frac{h_{SP}D}{k}\right)$$

is single phase Nusselt number. k is liquid thermal conductivity, W/mK;

$$\mathrm{Pr} = \left(\frac{C_L \mu_L}{k}\right)$$

is Prandtl number, μ_L is liquid viscosity, Ns/m^2; μ_W is liquid viscosity at the average of inlet and outlet temperatures, Ns/m^2; μ_W is liquid viscosity at wall temperature, Ns/m^2.

From figures 1 and 2 it is evident that the experimental measurements are reasonably accurate within experimental error.

(c) *Two-phase heat transfer coefficient*

The two-phase heat transfer coefficient is calculated using the equation

$$h_{TP} = \frac{(Q_G \rho_G C_G + Q_L \rho_L C_L (T_2 - T_1))}{A \Delta T_{1m}}. \qquad [2]$$

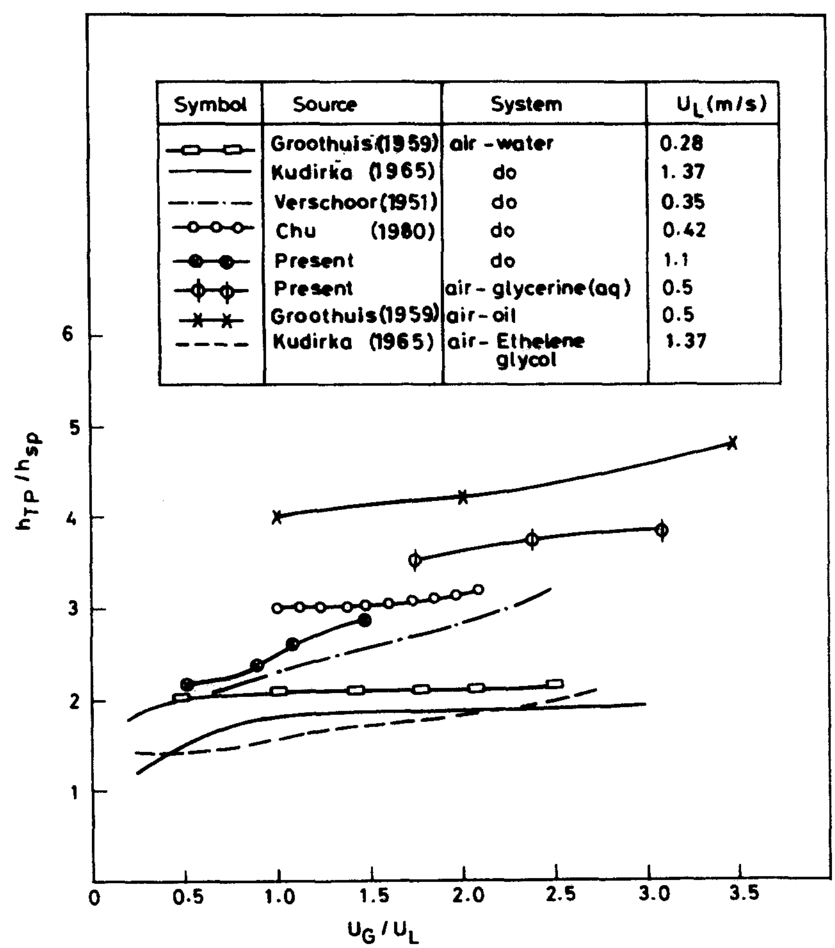

Figure 3. Plot of U_G/U_L vs h_{TP}/h_{SP} for various liquid velocities.

Where h_{TP} is two phase heat transfer coefficient, W/m^{2}K; Q_G is air volumetric flowrate, m^3/s; ρ_G is air density, kg/m^3; C_G is gas specific heat, J/kg K.

Figure 3 shows a plot of h_{TP}/h_{SP} vs U_G/U_L for different liquid velocities. This figure 3 presents the present experimental data as well as the data available in literature. It is evident from figure 3 that addition of air caused a sharp increase in two-phase heat transfer coefficient in the initial values of U_G/U_L. But there is definitely an effect of gas addition beyond U_G/U_L of 1.0 but only marginal. A correlation has been developed assuming seperated flow model concept. So far there exists no single simple correlation which predicts the two-phase heat transfer coefficient irrespective of the system combination. Present correlation is limited to Re_L range of 300–16,500 and U_G/U_L values of 0.3–4.6. The correlation is given by
where

$$\mathrm{Re}_L = \frac{DU_L\rho_L}{\mu_L}$$

is Reynolds number

$$\mathrm{Nu}_{TP} = 0.5\left(\frac{\mu_G}{\mu_L}\right)^{0.25}(\mathrm{Re}_M)^{0.7}(\mathrm{Pr})^{1/3}(\mu_B/\mu_W)^{0.14} \qquad [3]$$

where $\mathrm{Nu}_{TP} = (h_{TP}D/k)$ is two phase Nusselt number, Re_M is Reynolds number of mixed flow and $\mathrm{Re}_M = (DU_L\rho_L/\mu_L) + (DU_G\rho_G/\mu_G)$.

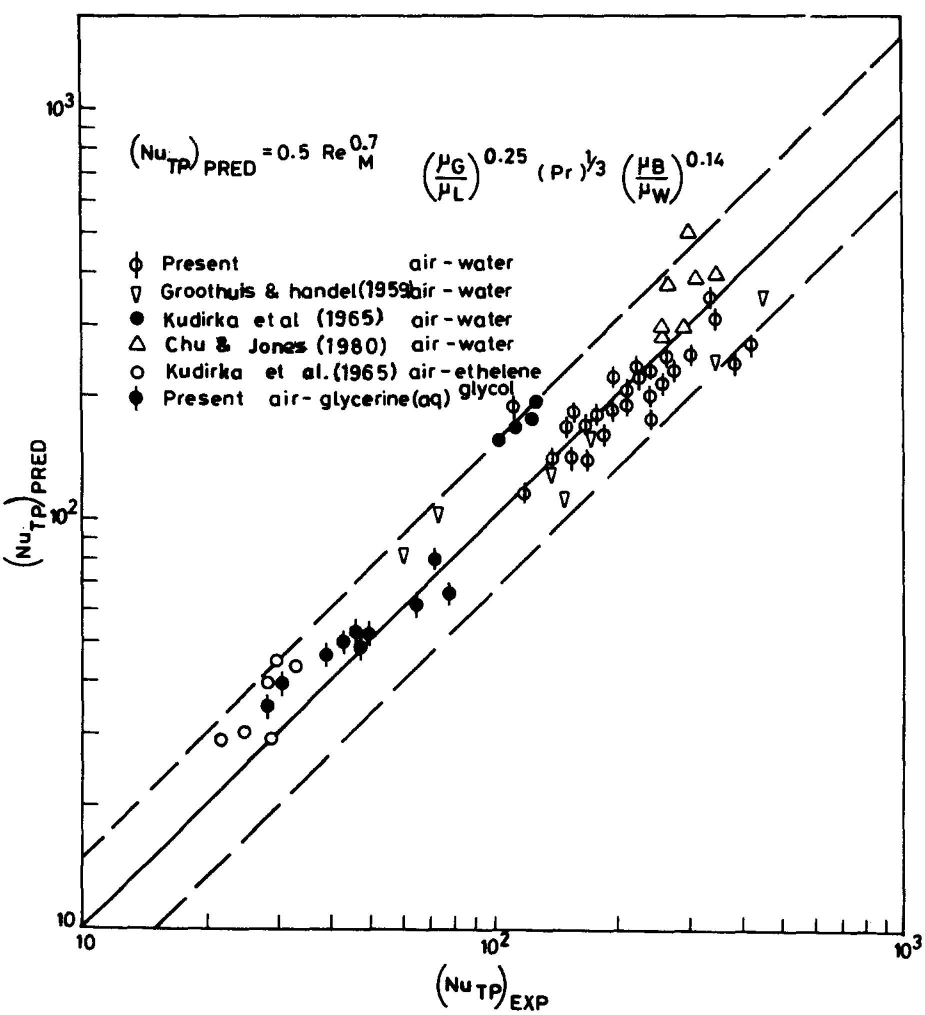

Figure 4. Comparison of $(\mathrm{Nu}_{TP})_{PRED}$ and $(\mathrm{Nu}_{TP})_{EXP}$.

Figure 4 shows a plot of $(Nu_{TP})_{EXP}$ vs $(Nu_{TP})_{PRED}$, where present experimental as well as the literature values are presented. About 90% of the total data points fall within ±25%.

CONCLUSION

It has been observed that the addition of small amount of air increased the two phase heat transfer coefficients by 200%. This increase is not very predominent at higher Reynolds number of liquid. The increase in two phase heat transfer coefficient will definitely reduce the size of the equipment for a given heat duty. Though there is increase in h_{TP} at high values of Re_L and U_G/U_L ratios, the pressure drop considerations must be viewed for economic design of the heat transfer equipment.

REFERENCES

CHU, Y. C. & JONES, B. G. 1980 Convective heat transfer coefficient studies in upward and downward, vertical, two phase, non-boiling flows. *AIChE Symp. Series* **76**, 79–91.

COLLIER, J. G. 1972 *Convective Boiling and Condensation.* McGraw-Hill, New York.

DORRESTEIJN, W. R. 1970 Experimental study of heat transfer in upward and downward two-phase flow of air and oil through 70 mm Tubes. *Proc. 4th Int. Heat Transfer Conf.*, Vol. V, B5.9. Elsevier, Amsterdam.

GROOTHUIS, H. & HANDEL, W. P. 1959 Heat transfer in two-phase flow. *Chem. Engng Sci.* **11**, 212–220.

KUDIRKA, A. A., GROSH, R. J. & Mc. FADDEN, P. W. 1965 Heat transfer in two-phase flow of gas liquid mixtures. *Ind. Engng Chem. Fund* **4**, 339–344.

LOCKHART, R. W. & MARTINELLI, R. C. 1949 Proposed correlation of data for isothermal two-phase two-component flow in pipes. *Chem. Engng Prog.* **45**, 39–48.

NOVOSAD, Z. (Ref. COLLIER 1972).

SHAH, M. M. 1981 Generalized prediction of heat transfer during two component gas–liquid flow in tubes and other channels. *AIChE Symp. Series* **77**, 140–151.

VERSCHOOR, H. & STEMMERDING, S. 1951 Heat transfer in two phase flow. *Proc. of Gen. Discussion on Heat Transfer*, 27, Section 2. Inst. Mech. Engrs, London.