Journal for Research | Volume 03 | Issue 11 | January 2018
ISSN: 2395-7549

Heat Transfer Correlation for Non-Boiling Stratified Flow Pattern

S. D Chougule
Lecturer
Department of Chemical Engineering(Polytechnic Wing)
Padmabhushan Vasantraodada Patil Institute of Technology
Budhgaon, Sangli, Maharashtra, India

U. S Patil
Head and Associate Professor
Department of Chemical Engineering(Polytechnic Wing)
Padmabhushan Vasantraodada Patil Institute of Technology
Budhgaon, Sangli, Maharashtra, India

V. B Pawar
S.G Lecturer and head
Department of Chemical Engineering(Polytechnic Wing)
Padmabhushan Vasantraodada Patil Institute of Technology
Budhgaon, Sangli, Maharashtra, India

M. M Joshi
Lecturer
Department of Chemical Engineering(Polytechnic Wing)
Padmabhushan Vasantraodada Patil Institute of Technology
Budhgaon, Sangli, Maharashtra, India

S. S Potdar
Lecturer
Department of Chemical Engineering(Polytechnic Wing)
Padmabhushan Vasantraodada Patil Institute of Technology, India

Abstract

In chemical industries two phase flow is a process necessity. A better understanding of the rates of momentum and heat transfer in multi-phase flow conditions is important for the optimal design of the heat exchanger. To simplify the complexities in design, heat transfer coefficient correlations are useful. In this work a heat transfer correlation for non- boiling air-water flow with stratified flow pattern in horizontal circular pipe is proposed. To verify the correlation, heat transfer coefficients and flow parameters were measured at different combinations of air and water flow rates. The superficial Reynolds numbers ranged from about 2720 to 5740 for water and from about 563 to 1120 for air. These experimental data were successfully correlated by the proposed two-phase heat transfer correlation. It is observed that superficial.

Keywords: Dryness Fraction, Stratified Flow, Superficial Reynolds Number, Two Phase Flow, Void Fraction

---

I. INTRODUCTION

The expression of ‘two-phase flow’ is used to describe the simultaneous flow of a gas- liquid or gas-solid or liquid- solid or two immiscible liquids. Among these types of two phase flow, gas-liquid flow has the most complexity due to the deformability and the compressibility of the phases[1]. Two-phase gas liquid flow occurs extensively throughout industries, such as solar heat collectors, tubular boilers, two-phase flow lubrication, pneumatic conveying, oil and geothermal wells, gas and oil transport pipelines, process pipelines, pneumatic conveying, sewage treatments, refrigerators, heat exchangers, and condensers [2,3]. The knowledge of heat transfer in two-phase gas-liquid flow is important in these industrial applications for economical design and optimized operation[2]. There are plenty of practical examples in industries which show how the knowledge of heat transfer in two phase flow is important. For example slug flow, which is one of the common flow patterns in two-phase gas-liquid flow, is accompanied by oscillations in pipe temperature. The high pipe wall temperature results in ‘dry out’, which causes damages in the chemical process equipment’s, nuclear power generating systems, refrigeration plants and other industrial devices[4]. Another example of two phase flow is in the field of petroleum industry. The petroleum products, such as natural gas and crude oil, are often collected and transported through pipelines located under sea or on the ground. During transportation, the pipelines carry a mixture of oil and gas. In this process of transportation, the knowledge of heat transfer is vital to prevent gas hydrate and wax deposition blockages, which results in repair, replacement, abandonment, or extra horsepower requirements[4]. In gas liquid flow the two phases can be distributed in the conduit in many configurations called flow regimes or flow patterns, differing from each other in the spatial distribution of the interface. The flow pattern depends on the operational variables, physical properties of fluids and geometrical variables of the system[5]. Without knowing the local flow patterns, one cannot correctly calculate the thermal, hydraulic design parameters[6]. In fact, the physical mechanisms controlling two-phase pressure drops and heat transfer coefficients are intrinsically related to the local flow patterns and thus flow pattern prediction is an important aspect of two-phase heat transfer and pressure drops [5, 6].

In two phase flow, the gas-liquid interfacial distribution can take an infinite number of possible forms. However, these forms can be classified into types of interfacial distribution, commonly called flow regimes or flow patterns[5]. Commonly observed flow regimes in horizontal flow are stratified flow, plug flow, bubble flow, slug flow, wavy flow etc. In these regimes, as gravity acts normal to flow direction, separation of the flow occurs[7]. The stratified flow pattern is commonly observed in chemical industry. In this flow pattern low liquid velocities $(V_L < 0.15\ m/s)$ and gas velocities $(0.6 m/s < V_G < 3\ m/s)$ cause complete separation of two phases[7]. The gas and liquid separated by an undisturbed horizontal interface. In this region the gas-liquid interface is smooth[5, 8].

However the field which has received relatively less attention is the study of heat transfer involving two phases (air-water) for a stratified flow regime. In the present work, experiments were carried out in a double pipe heat exchanger with hot water as the service fluid (annulus side) and two-phase mixtures of cold water and air in different ratios as the process fluid (tube side). Experimental runs with single-phase fluid (water) and two phase mixtures on the process side were carried out. The heat transfer coefficients on the cold side were correlated with superficial Reynolds numbers.

The objective of this study is to systematically gather gas–liquid non-boiling flow heat transfer data for stratified flow regime in a horizontal circular pipe. The data is used to better understand the non-boiling two-phase flow heat transfer behavior. Finally, develop a correlation for predicting non-boiling two-phase flow heat transfer coefficient in horizontal pipes. This correlation will be useful to find the relation between single phase (water) individual heat transfer coefficient(h_w), two phase (air-water) heat transfer coefficient(h_{TP}) , flow quality(X), void fraction(α) and Prandtl number.

II. EXPERIMENTATION

A. *Experimental Set Up*

A schematic diagram of the overall experimental setup for heat transfer measurements and flow visualizations in two-phase air-water pipe flow in horizontal positions is shown in Fig 2 and 3.

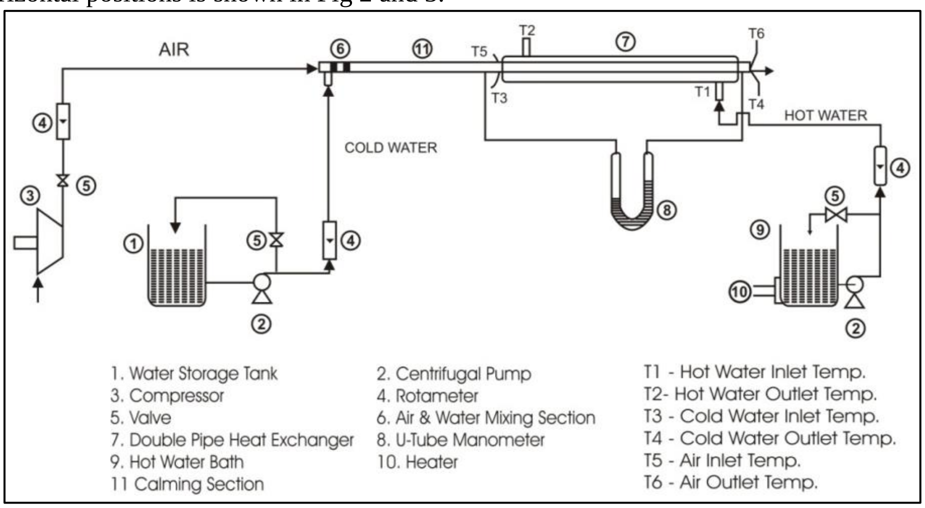

Fig. 1: Schematic Diagram of Experimental Setup

The setup consists of a double pipe heat exchanger. The test section is an 18.86 mm internal diameter straight brass tube, with a length to diameter ratio of 85. The heat exchanger dimensions are given in the table 1.

The entire length of the test section is insulated with glass wool. The air from compressor is introduced into cold water supply through a mixer. The air-water two-phase mixture is passed through the central tube and hot water is passed through annulus. The hot fluid is heated in a mild steel vessel by using two electric heaters. A temperature controller is used to maintain the inlet temperature of hot water at constant level. Two centrifugal pumps are used to pump hot and cold water through the heat exchanger. A reciprocating compressor is used for continuous supply of air to the tube side of the heat exchanger.

Table - 1
Details of the double pipe Heat Exchanger

Exchanger details	*Values*
Material of construction of inner pipe	*Brass*
Inside diameter of inner pipe (d_i)	*18.86 mm*
outside diameter of inner pipe (d_o)	*25.5 mm*
Inside diameter of outer pipe (D_i)	*54.5 mm*
outside diameter of outer pipe (D_o)	*60.5 mm*
Pipe length (L)	*1.5 m*

By controlling the flow rates of air and water, two-phase stratified flow pattern was developed. The mixer is used for mixing air and water. The mixer consists of a perforated copper tube (6.35 mm I.D.) inserted into the liquid stream by means of a tee fitting as shown in the figure 2 and 3.

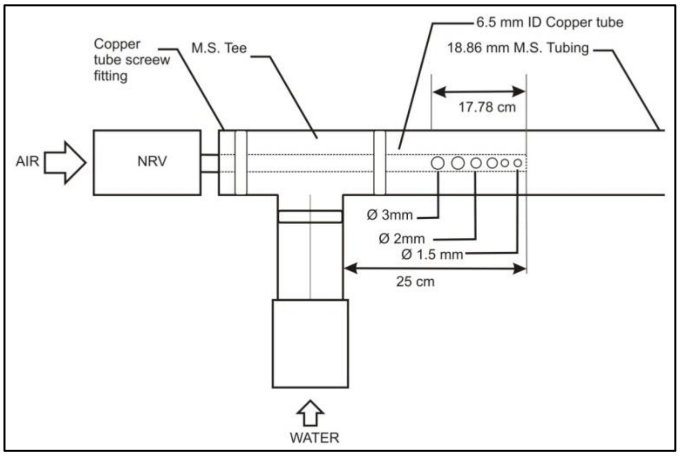

Fig. 2: Air –Water Mixer.


Fig. 3: Photograph of Air Water Mixer.

One end of the copper tube is soldered and fifteen holes (5 holes of 1.5 mm, 5holes of 2 mm and 5 holes of 3 mm) are drilled at 900 intervals and equally spaced along the length of the copper tube. The same type of geometry of mixer is used by Ghajar A J4. The two-phase flow leaving the mixer entered the transparent calming section as shown in the figure 1.

The calming section (clear acrylic pipe with 18.86 mm I.D. and 1m length) served as a flow developing and flow pattern observation section. One end of the calming section is connected to the gas-liquid mixer and the other end is connected to the test section with flange as shown in the figure 1. For the horizontal flow measurements, the test section and the observation section are carefully leveled to eliminate the effect of inclination. In the test section 6 RTD (pt100 type) probes are used for the measurement of inlet and outlet temperatures of hot water, cold water and air. All the RTD probes are calibrated with standard thermometer before conducting the experiments.

B. Experimental Procedure

The heat transfer measurements were carried out by measuring the inlet and outlet temperatures of hot and cold fluid in addition to other measurements such as the flow rates of gas and liquid. First the experimental runs with only water were carried out. Hot water at 50 0C was passed through annulus side and cold water was then passed through tube side. The flow rates of hot and cold water were maintained constant and steady state was allowed to reach. After attainment of steady state all the temperature sensor readings were noted. For the next run the flow rate of cold water was changed. The hot water flow rate and temperature was kept constant for all the experimental runs. The two phase air – water experimental runs were carried out in similar fashion. The air was bubbled through the water phase by using air-water mixer. As the air–water mixture move towards the test section, phase separation occurred and stratified flow pattern was obtained. This was observed in transparent acrylic tube. The air and water flow rates were controlled by needle valves. After the steady state condition was obtained, the temperature readings T1 to T6 were noted. The air and water flow rates were changed for next run in such a way that stratified flow was maintained. The flow rate of air was varied between 500 to 1000 LPH and water flow rate from 50 to 130 LPH to generate experimental data.

C. Calculation Methodology

a) The following basic relations were used for calculating the overall heat transfer coefficients and individual inside heat transfer coefficients on the single phase (water).

The rate of heat transfer for cold water (tube side) was calculated by,

$$q_W = \dot{m}_W \ C_P \ (T4 - T3) \quad (1)$$

All the specific heat (C_P) data were calculated at average temperature of fluid.

Overall heat transfer coefficient based on inside area (U_i) was calculated by following equation,

$$U_i = \ q_W \ /(A_i \ \overline{\Delta T_L}) \quad (2)$$

Outside (annulus side) heat transfer coefficient (h_o) was calculated by Dittus-Boelter equation,

$$h_o\,D_e/k = 0.023\,(Re_o)^{0.8}\,(Pr_o)^{0.33} \quad (3)$$

Inside (tube side) heat transfer coefficient (h_W) was calculated by the equation

$$(1/U_i) = (1/h_W) + (d_i)/(d_o h_o) + (x_w d_i)/(k_w \overline{d_L}) \quad (4)$$

b) The following basic relations were used for calculating the overall heat transfer coefficients and individual heat transfer coefficients on the air water two phase mixtures.

Overall heat transfer coefficient based on inside area (U_i) was calculated by following equation,

$$U_i = q_{TP}\,/(A_i\,\overline{\Delta T_L}) \quad (5)$$

Where two phase rate of heat transfer (q_{TP}) is the sum of rate of heat transfer for water (q_W) and rate of heat transfer rate for air (q_A)

$$q_W = \dot{m}_W\,C_P\,(T4 - T3) \quad (6)$$

$$q_A = \dot{m}_A\,C_P\,(T6 - T5) \quad (7)$$

Outside (annulus side) heat transfer coefficient (h_o) was calculated by Dittus-Boelter equation,

$$h_o\,D_e/k = 0.023\,(Re_o)^{0.8}\,(Pr_o)^{0.33} \quad (8)$$

Two phase (tube side) heat transfer coefficient (h_{TP}) was calculated by the equation.

$$(1/U_i) = (1/h_{TP}) + (d_i)/(d_o h_o) + (x_w d_i)/(k_w \overline{d_L}) \quad (9)$$

The void fraction (α) is the ratio of the gas flow cross sectional area to the total cross sectional area. It is calculated by 9,

$$\alpha = [1 + K\,\{(1 - X)/X\}(\rho_A/\rho_W)]^{-1} \quad (10)$$

Where

$$K = (\rho_W/\rho_m)^{0.5} \quad (11)$$

and

$$1/\rho_m = (1 - X)/\rho_W + X/\rho_A \quad (12)$$

The mass flow ratio (also often referred to as the ratio of the gas mass flow rate to the total mass flow rate) is called the 'quality' or the 'dryness fraction' and is given by5,

$$X = \dot{m}_A/\dot{m} \quad (13)$$

c) To correlate the two phase heat transfer coefficient (h_{TP}), with single phase heat transfer coefficient (h_W), void fraction (α), quality(X), and Prandtl number, the modified form of general correlation was used, which was developed by Ghajar A. J.10,

$$h_{TP} = (1 - \alpha)\,h_W\left[1 + C\left\{\left(\frac{X}{1-X}\right)^m \left(\frac{\alpha}{1-\alpha}\right)^n \left(\frac{Pr_A}{Pr_W}\right)^p \left(\frac{\mu_A}{\mu_W}\right)^q\right\}\right] \quad (14)$$

To determine the values of the leading coefficient (C) and the exponents (m, n, p, q, r) in equation (14), the single phase and two phase heat transfer data was used. Total 26 data points were used for the correlation, by changing the flow rates of water and air. Polymath software with least square method was used to calculate the leading coefficient and constants in the correlation.

III. Results and discussion

The experimental results of single phase heat transfer (water) were presented in the form of a plot between single phase heat transfer coefficient and Reynolds number for water in figure 4. From figure, it was observed that single phase heat transfer coefficient increases with increase in Reynolds number.

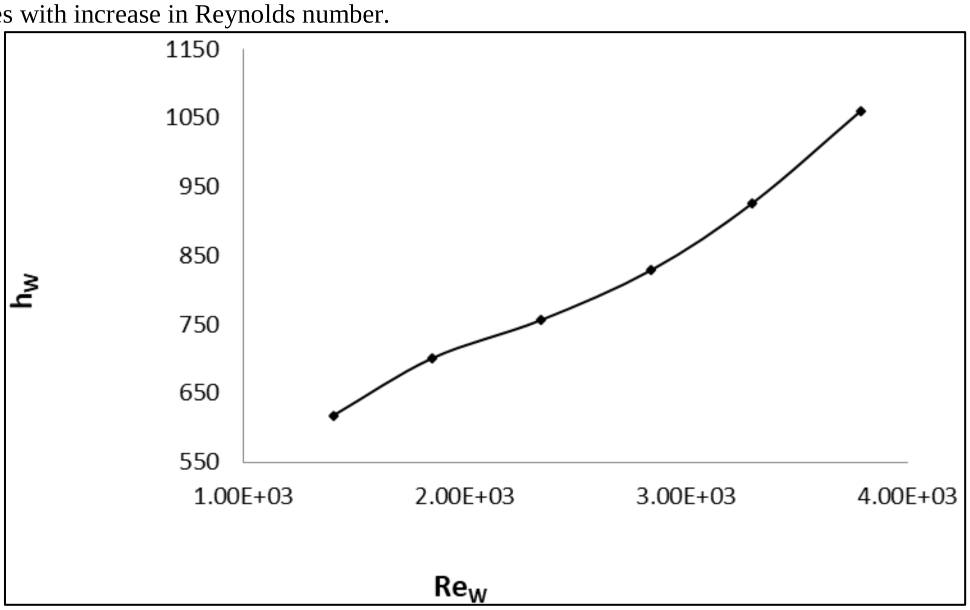

Fig. 4: Single Phase (water) Heat Transfer Coefficient (h_W) vs Water Reynolds Number(Re_W).

As mentioned earlier, one of the objectives of this study was to systematically gather gas–liquid non-boiling flow heat transfer data for a stratified flow pattern in a horizontal pipe and use this data for better understand the non-boiling two-phase flow heat transfer behavior. The two-phase heat transfer data was obtained by systematically varying the air and water flow rates. All superficial Reynolds number and thermo physical properties used in these calculations were calculated at the bulk average temperatures of the fluid.

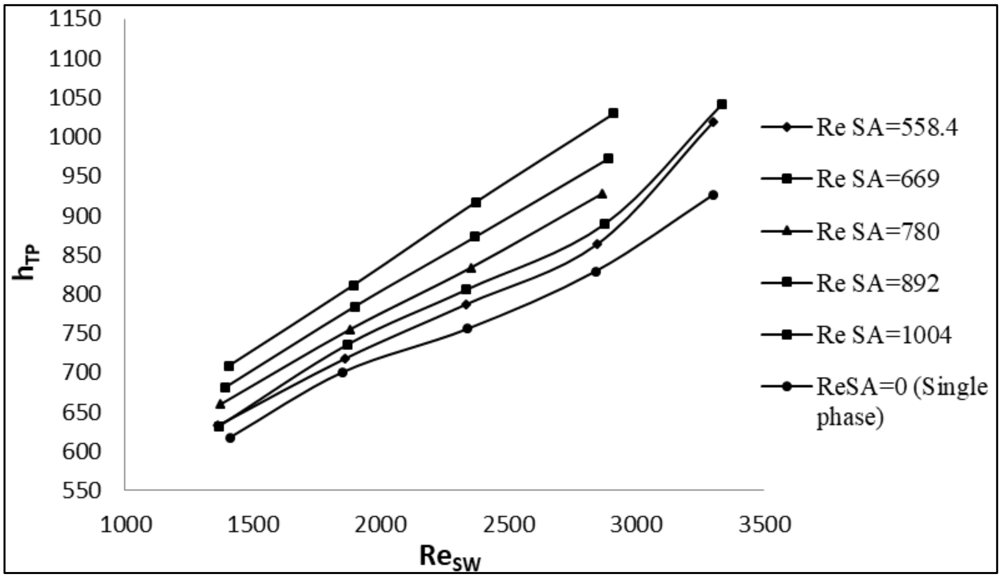

Fig. 5: Two Phase Heat Transfer Coefficient (h_{TP}) vs Superficial Gas Reynolds Number (Re_{SA}).

From figure 5, it was observed that, the introduction of air even at low flow rate into the water flow increases the heat transfer coefficient in the range of 3% to 33%. Because, as air flow rate increases the turbulence in water flow increases. Flow pattern, superficial water Reynolds number and superficial air Reynolds number have pronounced influence on the two phase heat transfer coefficient.

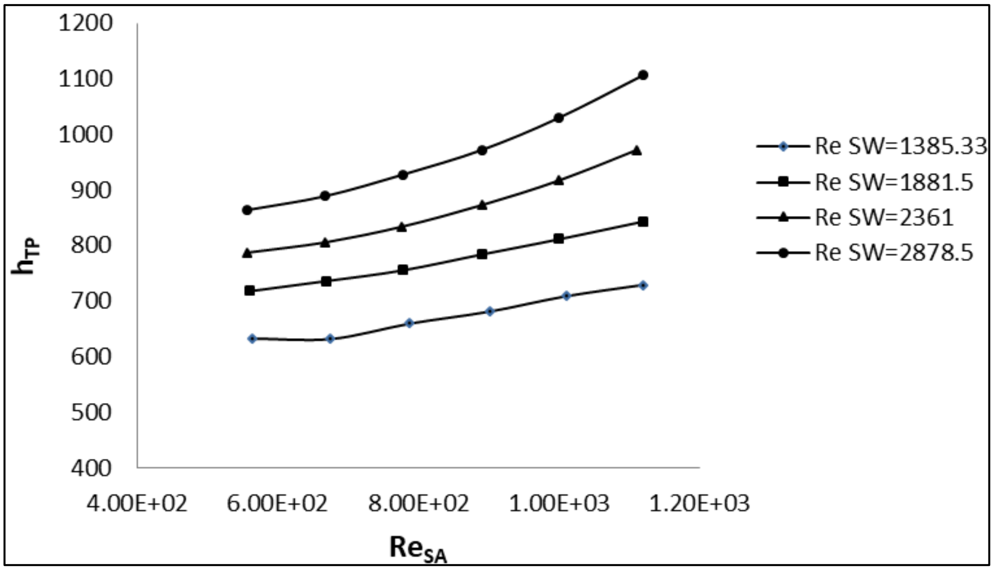

Fig. 6: Two Phase Heat Transfer Coefficient (h_{TP}) vs Superficial Water Reynolds Number (Re_{SW}).

Figure 5 & 6 shows the influence of the superficial water Reynolds number and superficial air Reynolds number on the two-phase heat transfer coefficient in horizontal pipe flow. The results presented in Figure 5 clearly show that, the two-phase heat transfer coefficients were strongly influenced by the superficial water Reynolds number. The two phase heat transfer coefficient increases proportionally up to superficial water Reynolds number equal to 3000 and increases drastically after it. In addition, for a fixed superficial water Reynolds number, the two-phase heat transfer coefficients were also influenced by the superficial air Reynolds number, however, the influence of superficial air Reynolds number on the two phase heat transfer coefficients was not as strong as that of superficial water Reynolds number.

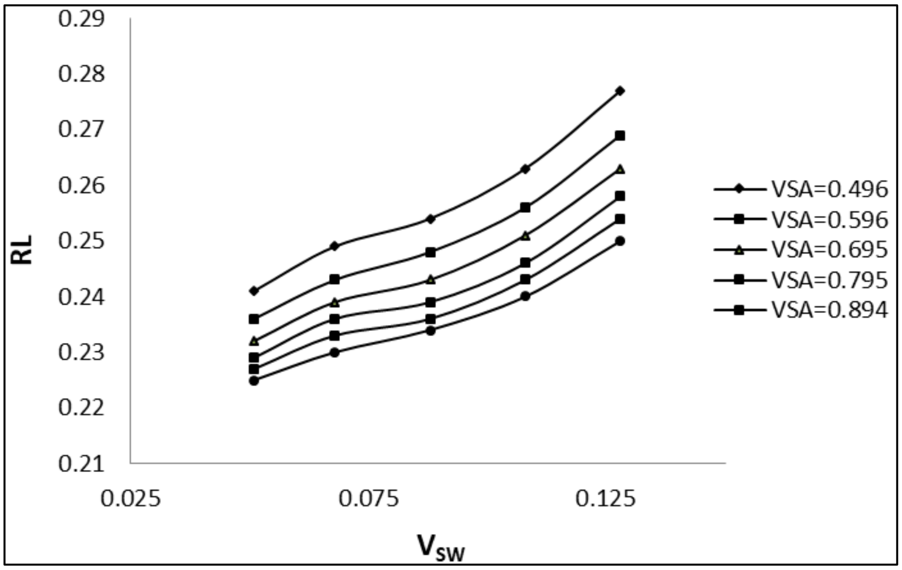

Fig. 7: Liquid Holdup vs. Superficial Water Velocity.

From figure 7 it was observed that, at constant superficial air velocity, the liquid holdup values were increases with the superficial water velocity. The relationship between liquid hold up and superficial water velocity is nonlinear. The water local velocity also increases with increasing superficial water velocity. The overall effect results in faster moving water phase covering a larger portion of the pipe cross-section and wetting a larger fraction of the pipe wall. Due to which two phase heat transfer coefficient increases.

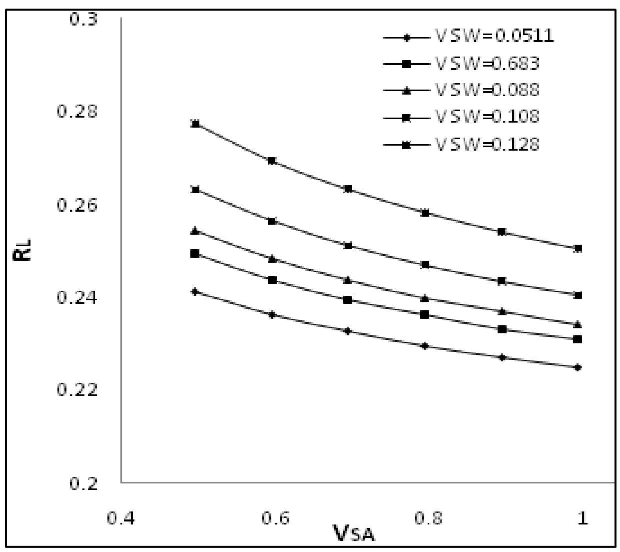

Fig. 8: Liquid Holdup Vs Superficial Air Velocity.

Figure 8 shows that, Lower liquid holdup values were observed as the superficial air velocity was increased at constant superficial water velocity. The increase in superficial water velocity is observed due to the higher drag exerted on the water phase at the interface by the faster moving air. The water moves faster, leaving a smaller amount of water in the pipe at any given time. The increase in superficial air velocity increases the superficial water velocity and due to this two phase heat transfer coefficient increases.

A. Formation of Heat Transfer Correlation

To determine the values of the leading coefficient (C) and the exponents $(m, n, p, q\ and\ r)$ in equation (14), the horizontal pipe single and two phase heat transfer data was used. Polymath software with least square method was used to calculate the leading coefficient and constants in the correlation. The modified form of general correlation is,

$$h_{TP} = (1-\alpha)\, h_L \left[1 + 9.786 \left\{ \left(\frac{x}{1-x}\right)^{-2.18} \left(\frac{\alpha}{1-\alpha}\right)^{5.288} \left(\frac{Pr_G}{Pr_L}\right)^{-12.9} \left(\frac{\mu_G}{\mu_L}\right)^{11.24} \right\}\right] \qquad (15)$$

The equation (15) predicted the experimental data with an overall mean deviation of –4.51%, and a deviation range of –10.56% to 12%.

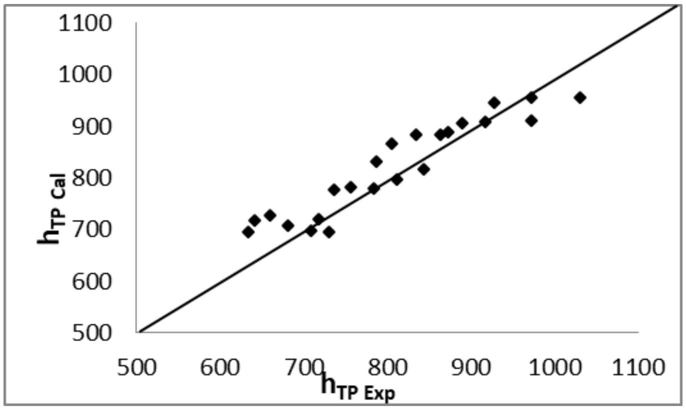

Fig. 9: Calculated Two Phase Heat Transfer Coefficient $(h_{TP\ Cal})$ vs Experimental Two Phase Heat Transfer Coefficient $(h_{TP\ Exp})$.

Figure (9) shows the graphical relation between experimental and predicted two phase heat transfer coefficients. Eighty five percent of all the experimental data are predicted by developed correlation within ±7% deviation. This equation is useful for prediction of two phase heat transfer coefficient for the stratified flow regime in the range of superficial water Reynolds from 2720 to 5740 and superficial air Reynolds number from 563 to 1120.

IV. CONCLUSION

In this experimental work two phase heat transfer coefficient for stratified flow was studied. The experimental data was curved fitted using polymath software. The following conclusions were observed from single and two phase heat transfer experiments.

- The introduction of air in water flow rate increases the heat transfer coefficient from 3% to 33% based on air flow rates.
- Both water and air superficial Reynolds number affects two phase heat transfer coefficient but the influence of superficial water Reynolds number is more than superficial air Reynolds number.
- The developed correlation predicts the two phase heat transfer coefficient with a deviation range of –10.56% to 12%. These results were useful to calculate the two phase heat transfer coefficient for the stratified flow regime. This equation was useful in the superficial water Reynolds number range of 2720 to 5740 and superficial air Reynolds number range of 563 to 1120.

REFERENCES

[1] Kim J, & Ghajar A J, International Journal of Multiphase flow, 32, (2006) 447
[2] Ishii M & Hibiki T, Thermo fluid-dynamics of Two-phase Flow, (Springer New York), 2006, 1
[3] Govier G W & Aziz K, The flow of complex mixtures in pipes, (Van Nostrand Reinhold, New York), 1973, 2
[4] Ghajar A J, Journal of the Brazilian society of mechanical science and engineering, 27, (2005) 46
[5] Cheremisinoff N P, Gas-Liquid flows: Encyclopedia of fluid mechanics, (Gulf publishing company), 3, 1985, 404
[6] Cheng L, Ribatski G & Thome J R, Applied Mechanics Reviews ASME, 61, (2008)
[7] Richardson J F, Coulson J M, Backhurst J R & Harker J H, Chemical Engineering: Fluid flow, Heat transfer and Mass transfer, (Elsevier), 1, 1999, 183
[8] Azzopardi B J, Chemical engineering and chemical process technology: Encyclopedia of life support system (EOLSS), 1
[9] Ghajar A J & Tang C C, Heat transfer engineering, 31, (2010) 715
[10] Ghajar A J & Kim J, A non-boiling two-phase flow heat transfer correlation for different flow patterns and pipe inclination angles, Proceeding, ASME Summer Heat transfer conference, 2005.