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Gas-Liquid Flow Through Coils

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Abstract−Experimental investigations have been carried out to evaluate the two-phase pressure drop and the holdup for flow through helical coils. The coils were made of thick wall transparent PVC tube of diameter 0.01 m and 0.013 m. 24 coils were made at different coil diameter and different helix angles (0^o to 12^o). Three different liquids were used for the experimental studies and air was the gas. Empirical correlations have been developed to predict the two-phase friction factor and the liquid holdup as functions of the physical and dynamic variables of the system. Statistical analyses of the correlations suggest that they are of acceptable accuracy.

Key words: Two-phase, Pressure Drop, Holdup, Friction Factor

INTRODUCTION

Helical coils are extensively used in compact heat exchangers, heat exchanger networks, heating or cooling coils in the piping systems, intake in aircrafts, fluid amplifiers, coil steam generators, refrigerators, nuclear reactors, thermosyphons, other heat transfer equipment involving phase change, chemical plants as well as in food and drug industries. One of the main advantages in the use of helical coiled tubes as chemical reactors or heat exchangers lies in the fact that considerable length of tubing may be contained in a space-saving configuration, which can easily be placed in a temperature-controlled environment. Heat transfer coefficients and mass transfer coefficients are higher in helical coiled tubes than straight tubes. When fluid flows through a curved pipe, the presence of curvature generates the centrifugal force that acts at a right angle to main flow and results in secondary flow. The strength of the secondary flow depends on the curvature of the surface. Literature survey indicated that numerous publications can be found dealing with flow phenomenon and the pressure drop in single phase flow through helical coils and are well summarized in Berger and Talbot [1983] and Das [1996].

Two-phase gas-liquid flow through curved pipes is more complex in nature. When flow enters the curved position, due to the centrifugal action the heavier density phase, i.e., liquid is subjected to larger centrifugal force which causes liquid to move away from the centre of curvature while the gas flows toward the centre of the curvature. This process is a continuous function of coil geometry. Despite varying applications, the literature on two-phase flow through coiled tubes is rather scanty.

Literature review suggested that the analysis of the two-phase pressure drop and holdup is carried out by using the conventional graphical correlation as suggested by Lockhart and Martinelli [1949] for gas-liquid flow through horizontal pipeline [Ripple et al., 1966; Owhadi et al., 1968; Boyce et al., 1969] or modified the Lockhart and Martinelli [1949] correlation [Banerjee et al., 1969; Chen and Zhang, 1984; Rangacharylu and Davis, 1984; Xin et al., 1996] or developed empirical correlation [Akagawa et al., 1971; Kasturi and Stepanek, 1972; Chen and Zhou, 1981]. The purpose of the present work is to generate and study two-phase pressure drop and holdup for gas-Newtonian liquid flow through vertical helical coils.

THE EXPERIMENTAL SETUP

The schematic diagram of the experimental apparatus is shown in Fig. 1. The experimental apparatus consisted of an air supply system, a liquid storage tank ($0.45\ m^3$), centrifugal pumps, a test section, control and measuring systems for flow rate, pressure drop and hold up and other accessories. Detailed dimensions of the coils used in the experiments are given in Table 1.

Thick walled flexible, transparent PVC pipes with internal diameter of 0.013 m and 0.010 m were used for experiments. The PVC pipes were wound round a cylindrical hard PVC frame of known diameter to form a helical coil. Changing the diameter of the frame and the diameter of the tube could vary the coil diameter. The tubes were wound in closed packed fashion so that the pitch was equal to the outer diameter of the tube and maintain constant for all cases. Four helix angles (0^o, 4^o, 8^o and 12^o) were used for experiments.

Pressure drop measurements are known to be difficult due to the inherent variable nature of the two-phase flow. The upstream and downstream pressure taps were mounted after 4 to 6 coils turns from the inlet and outlet, respectively, in order to reduce the entrance and exit effect of the upstream and downstream flows. A simple U-tube manometer containing mercury beneath the water measured the pressure difference. Arrangement for purging the air bubbles/liquid in the manometer line was also provided. At the high air input rates, it was necessary to constrict the manometer lines to reduce fluctuations.

The liquid holdup measurements for the tube were made by simultaneously shutting the system of solenoid valves (SV1 & SV2) in the inlet and outlet of the coil, after reaching a steady two-phase flow condition, to trap gas and liquid. The trapped liquid was then blown out of the tube into a graduated cylinder and measured. A previously determined wall wettage was added to the amount col-

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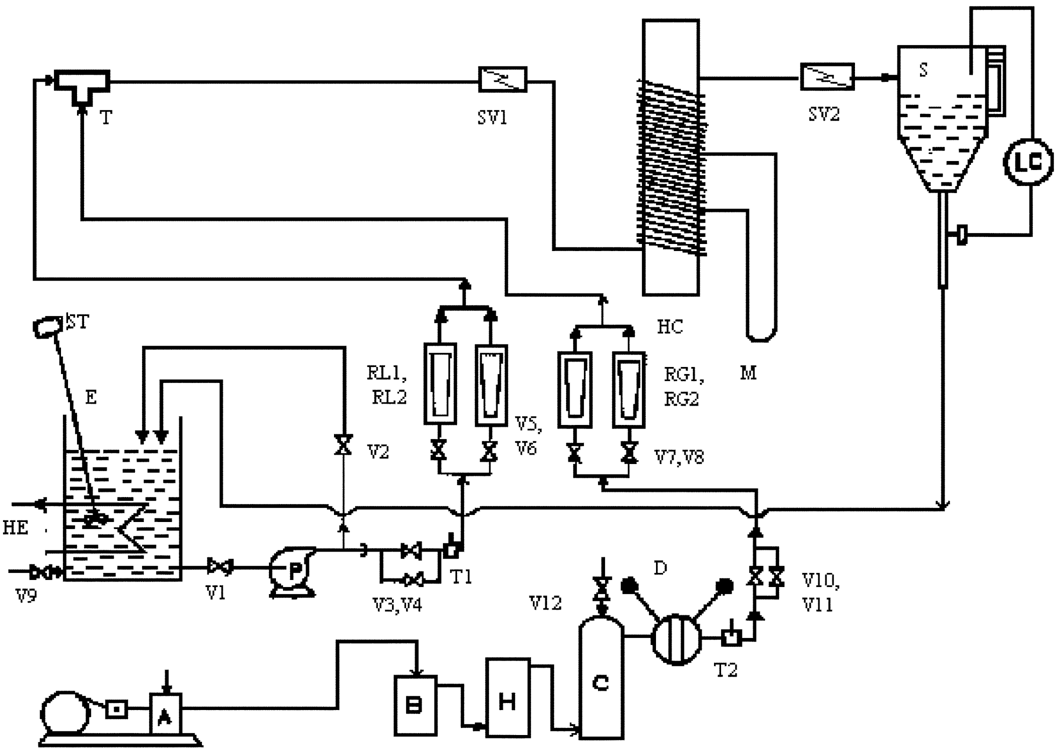

Fig. 1. Schematic diagram of the experimental setup.

A: Compressor	E: Solution tank	S: Separator	ST: Stirrer	RL1-RL2: Liquid rotameters
B: Oil filter	H: Dryer	T: T-Mixer	LC: Level controller	-RG1-RG2: Gas rotameters
C: Gas cylinder	M: Manometer	HC: Helical coil	T1-T2: Thermometers	SV1-SV2: Solenoid valve
D: Gas regulator	P: Pump	HE: Heat exchanger	V1-V14: Valves	

Table 1. Dimension of vertical helical coils

Tube diameter m	Coil diameter m	Helix angle Deg	Turns (n)	
			Total	Manometers
0.01	0.131	0, 4, 8, 12	20	8, 8, 8, 8
0.01	0.185	0, 4, 8, 12	16	6, 6, 6, 6
0.01	0.216	0, 4, 8, 12	13	4, 4, 4, 4
0.013	0.137	0, 4, 8, 12	19	7, 7, 7, 7
0.013	0.191	0, 4, 8, 12	15	5, 5, 5, 5
0.013	0.222	0, 4, 8, 12	12	4, 4, 4, 4

lected to give a liquid holdup. Wall wettage determinations were made by adding a known amount of liquid to the dry tube, blowing out the coil, and determine the differences between the amount collected and that added. Liquid holdups are expressed as the ratio of the amount collected plus wall wettage loss to the total amount held in the tube for single phase liquid flow.

Three different liquids (water, 1% amyl alcohol water solution, 30% glycerin water solution) were used as the experimental fluids. The physical properties of experimental liquids are given in Table 2. Air was drawn from a compressor and its pressure was reduced to 103 kN/m^2 (gauge) before injecting into the pipeline through T-entry.

The flow pattern is intermittent in nature in the experimental condition. The experiments were repeated a number of times to ensure reproducibility of the data. The gas and liquid flow rates used in the experiments were in the range of 0.15×10^{-4} to 5.25×10^{-4} m^3/s and 3.65×10^{-5} to 14.2×10^{-5} m^3/s, respectively. The temperature of the liquid was maintained in the range of 30±2 °C.

RESULTS AND DISCUSSION

The total pressure drop for gas liquid flow through vertical helical coil of length L, (=n $\pi D_c/\cos\beta$, where n and β are the number of turns and helix angle, respectively) may be the sum of frictional, ΔP_{ftp}, hydrostatic, ΔP_{htp} and accelerational component, ΔP_{atp}. The accelerational component, ΔP_{atp}, is negligible as compared to the total pressure drop in a vertical coil of uniform cross section. Hence,

Table 2. Physical properties of the test liquids

Liquid used	Density ρ_l kg/m^3	Viscosity μ_l kNs/m^2	Surface tension σ_l kN/m	Liquid property group $N_{pl}\times10^{10}$
Water	995.67	0.85	71.23	0.14231
1% Amyl alcohol water solution (% by volume)	996.37	0.84	50.00	0.39215
30% Glycerin water solution (% by volume)	1067.95	2.00	63.38	5.7727

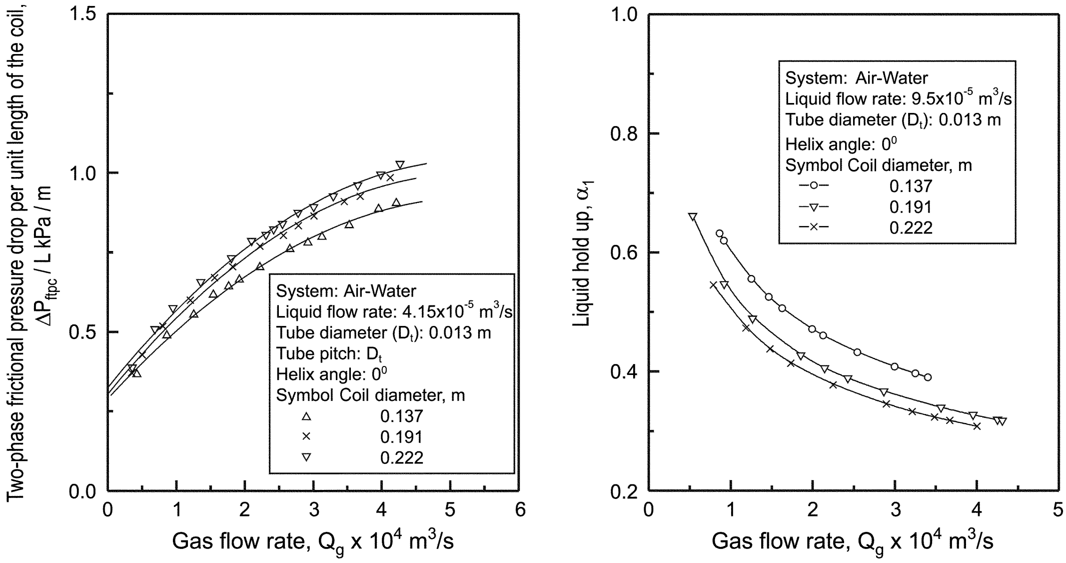

Fig. 2. Variation of two-phase frictional pressure drop per unit length and holdup with gas flow rate at constant liquid flow rate and coil diameter.

$$\Delta P_{tp}=\Delta P_{ftp}+\Delta P_{htp} \tag{1}$$

Literature review suggests that the hydrostatic head component, ΔP_{htp}, may be calculated either by assuming that the gas and liquid form a homogeneous mixture, or by considering the in situ holdup in the system, but for the first case ΔP_{htp}, is relatively straightforward and depends upon the entry flow rates (mass flow rate of liquid and gas, M_1 and M_g, and volumetric flow rate of liquid and gas, Q_1 and Q_g) only, which gives,

$$\Delta P_{htp}=\frac{M_1+M_g}{Q_1+Q_g}hg \tag{2}$$

where, h is the height and g is the acceleration due to gravity. Therefore, in all subsequent analysis the frictional pressure drop is calculated by the following equation:

$$\Delta P_{ftp}=\Delta P_{tp}-\frac{M_1+M_g}{Q_1+Q_g}hg \tag{3}$$

Fig. 2 shows the effect of coil diameter on two-phase frictional pressure drop and liquid holdup. It is clear from the graph that the two-phase pressure drops increases and liquid holdup deceases as the coil diameter increases at constant liquid and gas flow rate, helix angle. It is clear from the figure as gas flow rate increases, the two-phase frictional pressure drop increases and liquid holdup decreases for constant liquid flow rate. The main features of these curves are that the two-phase frictional pressure drop per unit length of the

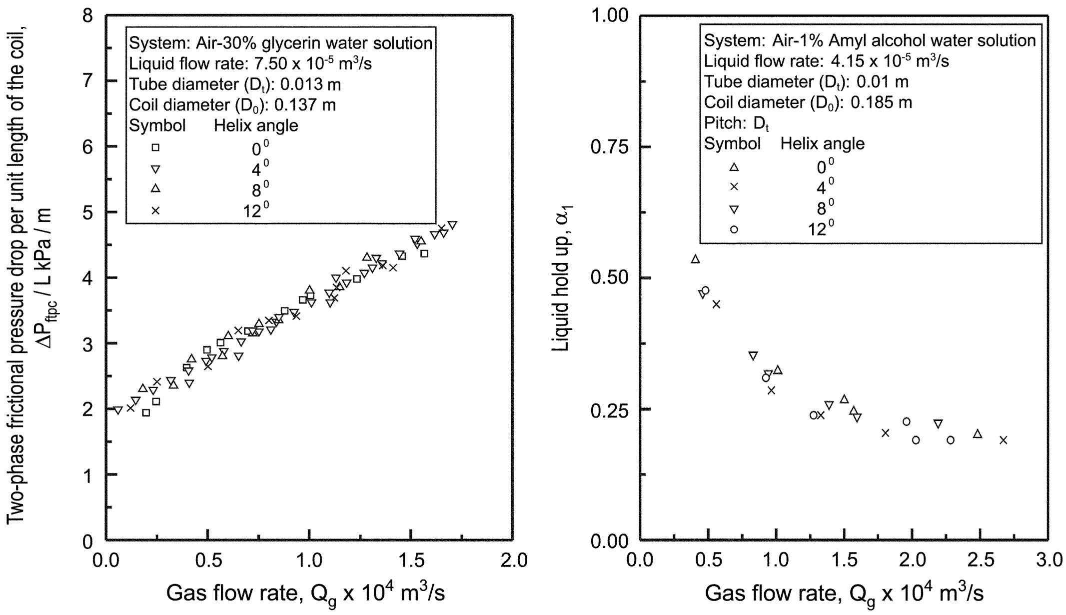

Fig. 3. Variation of two-phase frictional pressure drop per unit length and liquid holdup with gas flow rate at constant liquid flow rate and different helix angle.

coil is more and liquid holdup is less for larger coil diameter. The reason for this can be explained with the introduction of slip effect in two-phase flow condition. Since liquid density is at least more than 600 times higher than gas density and overall gas flow rate is nearly 10 times higher than liquid flow rate. So centrifugal forces acting on liquid phase are much higher than that of gas phase at a particular coil diameter. The liquid is accelerated because of the slip existing between the gas and liquid phase. As coil diameter decreases the slip increases, i.e., liquid is more accelerated, and hence, the pressure drop for liquid phase decreases. As gas phase pressure drop is very small compared to that of liquid phase, the net effect is decreased in two-phase pressure drop. As coil diameter decreases due to slip effect the two-phase pressure drop decreases. In small diameter coil, the number of turns is greater, i.e., the flow path is greater, the effect of slip and gravity as it increases with increasing number of turns acts in the opposite direction. This combined effect is responsible for slightly more liquid holdup for smaller coil diameter.

Fig. 3 shows that the two-phase frictional pressure drop increases and liquid holdup decreases with increase in gas flow rate at constant liquid flow rate and coil diameter, but independent of helix angle. Banerjee et al. [1969] and Xin et al. [1996] also obtained similar results.

Fig. 4 shows the effect of different liquid properties on two-phase frictional pressure drop and liquid holdup. It is clear from the graph that the two-phase pressure drop increases and liquid holdup decreases with an increase of the viscosity of the liquid at constant liquid flow rate and helix angle. The liquid has a retarding effect as its viscosity increases and also slip is expected to be higher in viscose liquid. Hence, two-phase pressure drop increases and liquid holdup decreases. Surface tension also has a pronounced effect on two-phase pressure drop. In case of air-1% amyl alcohol water solution, liquid surface tension reduction and slight foaming has been observed compared with the air-water two-phase case. It reduces the slip between the phases and creates a tendency to retain the gas phase. Due to continuous changes of centrifugal forces, liquid is continuously pushing to the outer wall and gas phase is in inside wall. The probable effect of centrifugal force is more than the retarding effect of gas phase. Hence, the pressure drop is slightly more in case of air-1% amyl alcohol water solution than that of air-water system. Effect of surface tension on the liquid holdup is negligible.

Lockhart and Martinelli [1949] proposed graphical correlations for the analysis of the frictional pressure drop for horizontal two-phase gas-Newtonian liquid flow. They presented the frictional pressure drop in the form of log-log plots between the pressure ratio, ϕ_l and a parameter X, defined as

$$\phi_l = \sqrt{\frac{\Delta P_{ftp}/L}{\Delta P_{fl}/L}} \tag{4}$$

$$X = \sqrt{\frac{\Delta P_{fl}/L}{\Delta P_{fg}/L}} \tag{5}$$

Comparison with the existing methods is carried out and shown in Figs. 5 to 8. It is clear from all graphs that large deviation exists.

Govier et al. [1957] developed an expression for two-phase friction factor (f_{tplc}) for vertical gas-liquid flow as,

$$f_{tplc} = (1+R_v)\left(\frac{\Delta P_{ftp}}{\rho_l g L}\right)\left(\frac{g D_t}{2V_l^2}\right) \tag{6}$$

The values of f_{tplc} have been calculated by the above equation using the experimental data. Friedel [1980] pointed out that determination of the hydrodynamic parameters is not possible by the theoretical analysis alone because the phenomenon of the momentum transfer between the two phases, the wall friction, the shear at phase interface, and the secondary flow due to centrifugal action cannot be specified quantitatively. Therefore, theoretical analysis is difficult. Further, it has been suggested that since the physical pro-

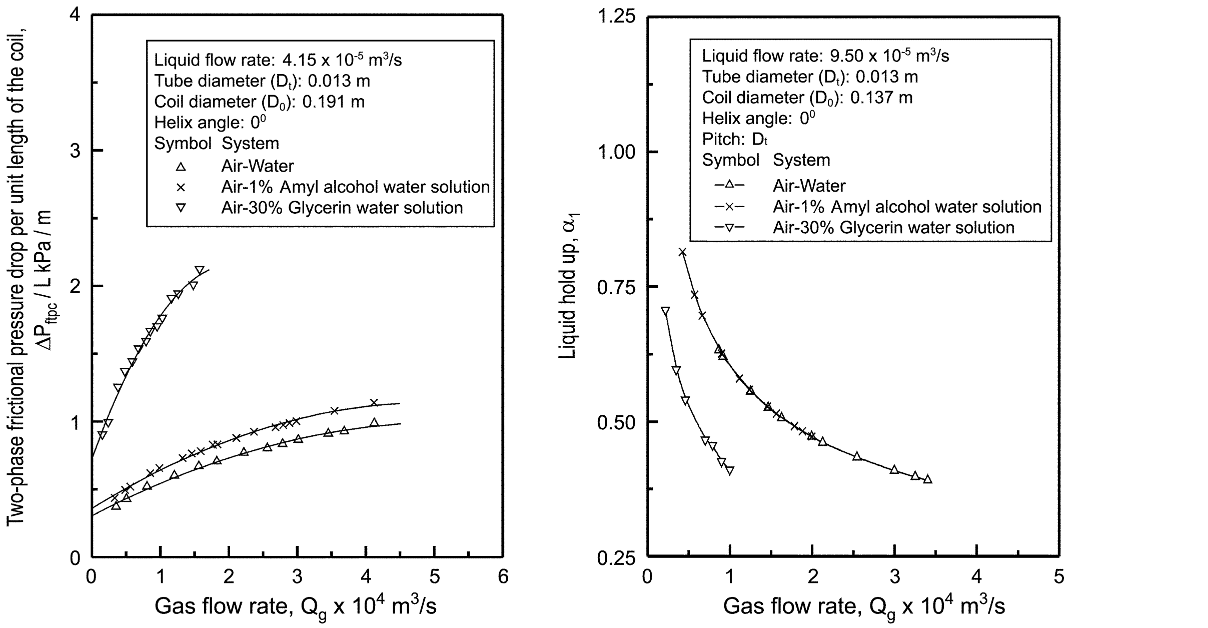

Fig. 4. Variation of two-phase frictional pressure drop per unit length and liquid holdup with gas flow rate at constant liquid flow rate for different system.

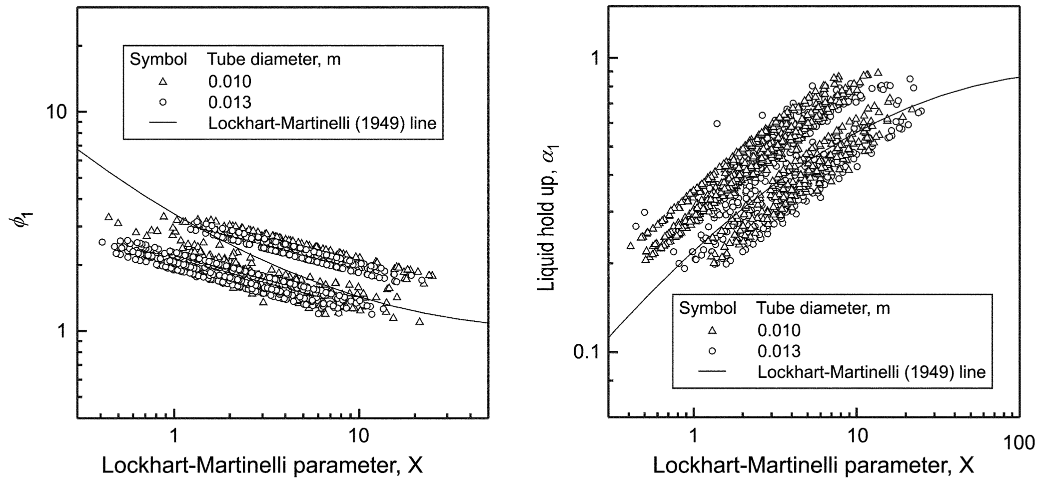

Fig. 5. Comparison of experimental two-phase frictional pressure drop and liquid holdup with Lockhart and Martinelli [1949] correlation.

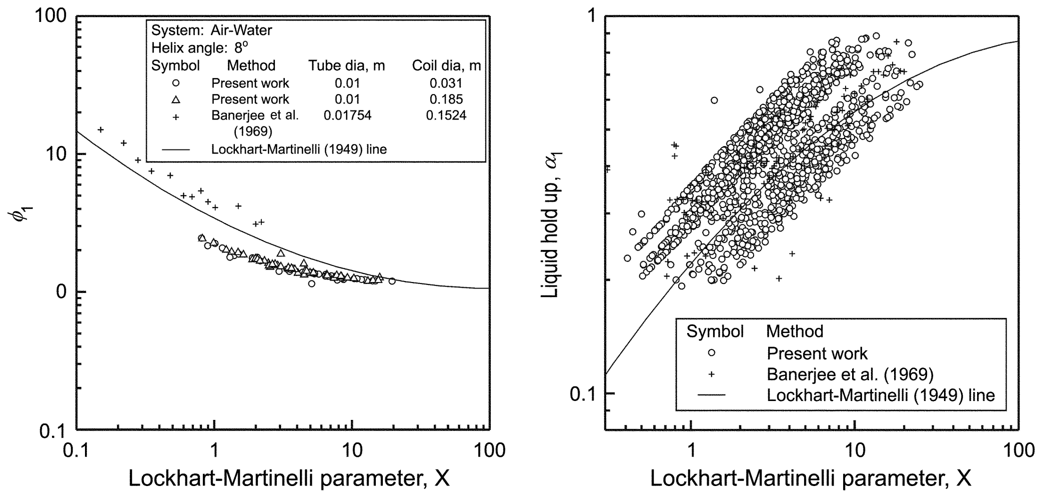

Fig. 6. Comparison of experimental two-phase frictional pressure drop and liquid holdup with Banerjee et al. [1969] data.

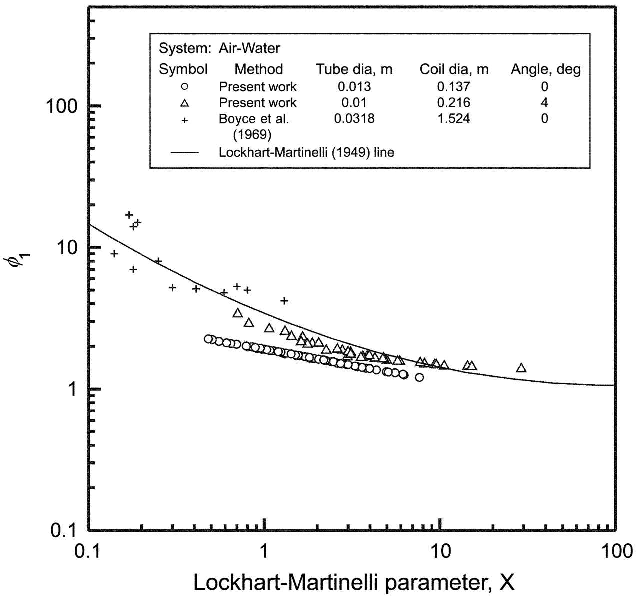

Fig. 7. Comparison of experimental two-phase frictional pressure drop with Boyce et al. [1969] data.

cess of two-phase flow is not clearly understood the alternative method generally used is dimensional analysis. Therefore, the pressure drop and holdup data have been analyzed in terms of the two-phase friction factor and liquid holdup as a function of various physical and dynamic variables of the system.

Dimensional analysis yields the following functional relationship:

$$f_{tplc} = F(Re_1, Re_g, N_{p1}, D_t/D_c) \quad (7)$$

$$\alpha_1 = F(Re_1, Re_g, N_{p1}, D_t/D_c) \quad (8)$$

Where, Re_1, Re_g and N_{p1} are the Reynolds number of liquid and gas and liquid property group. The liquid property group ($N_{p1}=\mu_1^4 g/\rho_1\sigma_1^3$) signifies some complex balance between viscous, surface tension and gravitational forces. On the basis of Eqs. (7) and (8) the multiple linear regression analysis for the two-phase friction factor and liquid holdup data in vertical helical coil for 0° helix angle was carried out, which yielded the following correlation,

$$f_{tplc}=5.8853\, Re_1^{-1.1829\pm0.0215}\, Re_g^{0.9520\pm0.0142}\, N_{p1}^{0.0220\pm0.0086}\, (D_t/D_c)^{-0.2820\pm0.0369} \quad (9)$$

$$\alpha_1=0.1723\, Re_1^{0.4620\pm0.0077}\, Re_g^{-0.3632\pm0.0051}\, N_{p1}^{-0.0068\pm0.0030}\, (D_t/D_c)^{0.3712\pm0.0142} \quad (10)$$

The correlation plots have been shown as in Fig. 9. The vari-

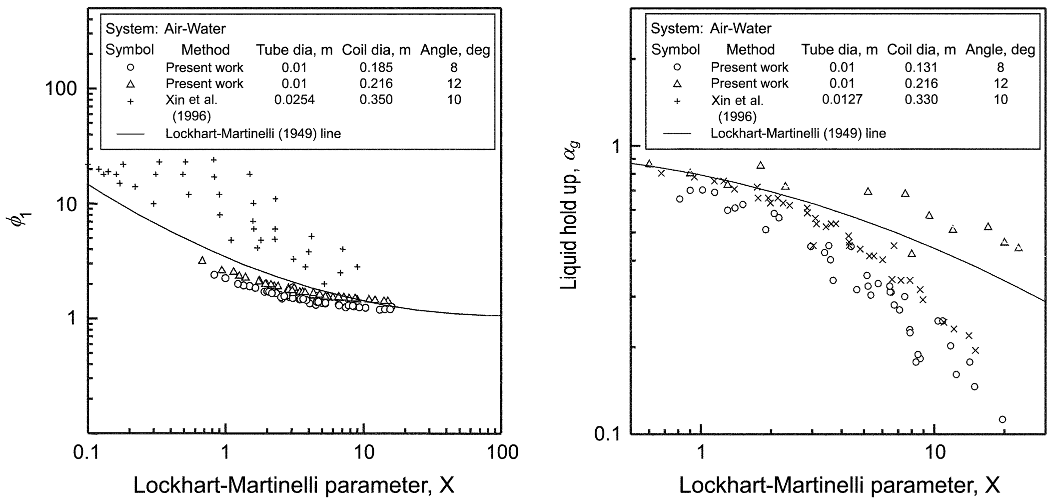

Fig. 8. Comparison of experimental two-phase frictional pressure drop and liquid holdup with Xin et al. [1996] data.

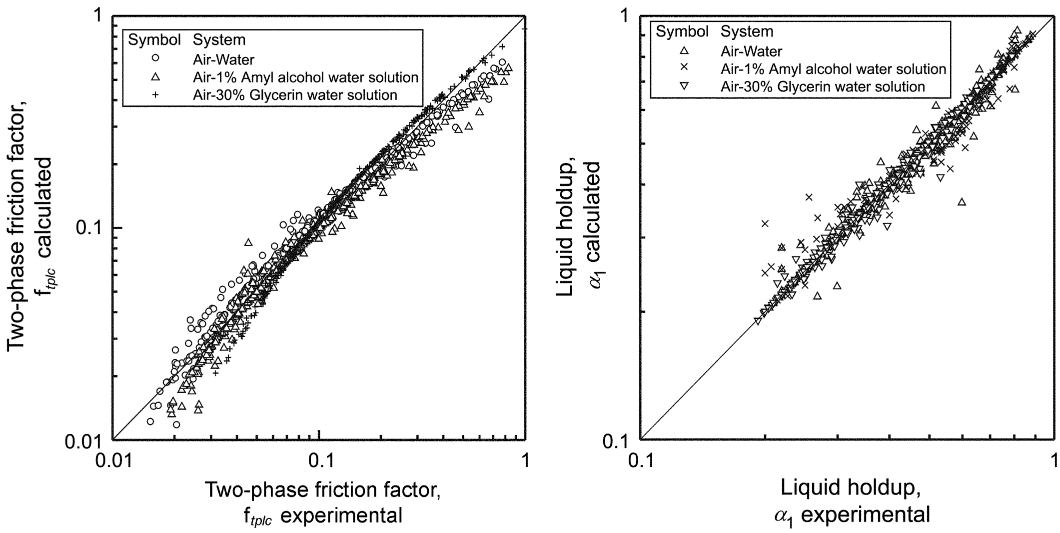

Fig. 9. Correlation plot for two-phase friction factor and liquid holdup.

ance of estimate and correlation coefficient of the above equations are 2.158×10^{-2} and 0.9855, 2.0725×10^{-3} and 0.9876 respectively, for a 't' value of 1.98 for 1074 degrees of freedom at 0.05 probability level and 95% confidence range.

CONCLUSIONS

Experiments have been performed to measure two-phase pressure drop and liquid holdup for different helical coils in vertical orientation. The coils were made of thick wall PVC tube of diameter 0.01 m and 0.013 m. Twenty four coils were made at different coil diameter and different helix angles (0^o to 12^o). Three different liquids and air were used for the experimental studies. The two-phase pressure drop was measured by U-tube manometer and holdup by displacement techniques. It was observed that the effect of helix angle (0^o to 12^o) has no effect on the two-phase pressure drop and holdup.

The experimental data on two-phase pressure drop and holdup have been analyzed by different methods available in literature. Empirical correlations, Eqs. (9) and (10), have been developed to calculate the two-phase friction factor and liquid holdup by using experimental data of 0^o helix angle. Detailed statistical analysis has shown that correlations, i.e., Eqs. (9) and (10), are of acceptable accuracy.

NOMENCLATURE

D : diameter [m]
F : function, dimensionless
f : friction factor, dimensionless
g : acceleration due to gravity [m/s^2]
h : height [m]
L : length [m]
M : mass flow rate [kg/s]
n : no. of coil turns
N : number of data points, dimensionless
N_{p1} : liquid property group ($\mu_1^4 g/\rho_1\sigma_1^3$), dimensionless
ΔP : pressure drop [Pa]

Q : flow rate [m^3/s]
R : radius [m]
R_v : input gas/liquid volumetric flow ratio, dimensionless
Re : Reynolds number, $VD\rho/\mu$, dimensionless
X : Lockhart-Martinelli parameter, dimensionless

Greek Letters

α : holdup, dimensionless
β : helix angle [degree]
μ : viscosity [Ns/m^2]
ρ : density [kg/m^3]
σ : surface tension [N/m]
ϕ : two-phase multiplier, dimensionless

Subscripts

c : coil
g : gas
l : liquid
t : tube
tp : two-phase
fg : frictional gas
fl : frictional liquid
atp : accelerational two-phase
ftp : frictional two-phase
htp : hydrostatic two-phase
expt : experimental
tplc : two-phase based on liquid for coil

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