Journal of Engineering and Applied Sciences 9 (4): 97-101, 2014
ISSN: 1816-949X

Frictional Pressure Drop in Vertical Helical Coil Reactor (HCR) Based on Flow Regime

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Abstract: This study presents, the analysis of frictional pressure drop, flow regimes of gas-liquid 2 phase flow in vertical helical column reactor. The analysis is fared based on the Lockhart-Martinelli Model. The Lockhart-Martinelli Model is modified and incorporated to predict the frictional pressure drop of air-non-Newtonian liquid flow in vertical helical coil. The effects of operating variables, such as phase flow rates on frictional pressure drop are investigated. To predict the frictional pressure drop, friction factor of gas-liquid 2 phase flow, correlations have also been developed for different flow regimes, as a function of different dimensionless groups by introducing the operating variables and physical properties.

Key words: Lockhart-Martinelli Model, physical properties, flow regimes, frictional pressure drop, India

INTRODUCTION

In many technological processes when fluid flows through the curved pipe, the curvature generates centrifugal force perpendicular to the main flow, resulting in secondary flow due to which the heat and mass-transfer coefficients in helical coiled tubes are higher than those in straight tubes. Helical coils are frequently used for transferring heat in mixing tanks, heating or cooling coils in piping systems, coil steam generators, refrigerators, nuclear reactor vessels, other heat-transfer equipment involving phase changes and chemical plants, as well as in the food and bio process systems. A detail of review for applications of curved geometries in this regard is reported by Vashisth *et al.* (2008). In 2 phase flow through curved tubes, the heavier phase which is accountable to a larger centrifugal force, moves away from the center of curvature whereas the lighter phase flows toward the center of the curvature. Separation of phases in this way is likely to give rise to significant slip between the phases which is responsible to create different flow regimes. Observations of different flow regimes of gas-liquid flow in vertical helical tube as functions of flow velocity, gas holdup, pressure energy and physical properties of the phases with different geometry in the vertical helical coil are scanty. Commercial simulators usually rely on empirical correlations, such as the classical Lockhart and Martinelli (1949) which are obtained by fitting a significant amount of experimental data, irrespective of the flow patterns. Pressure loss during gas-liquid flow is a function of the gas-liquid ratio and the properties of the phase. A sudden change in the pressure drops due to friction, flow regimes is attributed the phenomenon to the phase fractional holdup. Formulation of analysis tool, simulation of the systems behavior depends on different flow regimes, pressure drop, etc., as a function of fluid properties. Several empirical correlations are also presented by various researchers in the vertical helical coil system (Banerjee *et al.*, 1969; Kasturi and Stepanek, 1972; Mujawar and Rao, 1978; Mishra and Gupta, 1979; Whalley, 1980; Rangacharyulu and Davies, 1984; Saxena *et al.*, 1990; Weisman *et al.*, 1994; Czop *et al.*, 1994; Awwad *et al.*, 1995; Xin *et al.*, 1996; Ali, 2001; Murai *et al.*, 2006; Gupta *et al.*, 2011). To analyze the phenomena of heat and mass transfer in helical coils, it is necessary to know the hydrodynamics like flow regimes frictional pressure drop of the flow in such geometries before installation for industrial applications. The aim of the present study is to examine the effects of fluid flow on pressure gradient and flow regimes in 2 phase, air-water flow in vertical helical coil. Also, the studies involve the analysis of friction factor of air-water 2 phase flow in helical coil. The analysis is sufficed based on the Lockhart-Martinelli principle.

MATERIALS AND METHODS

The schematic of the experimental setup used in the present investigation is shown in Fig. 1. The helical coils were made using transparent thick-walled polythene tube of 2 cm internal diameter with the coil diameter of 20 cm.

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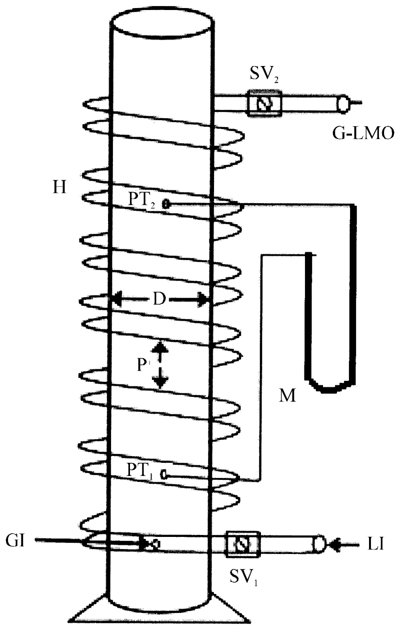

Fig. 1: Schematic diagram of the system: D = Diameter of the coil; H = Helical coil twisted on a pipe; M = U-tube manometer; P = Pitch; PT_1, PT_2 = Pressure taps; $SV_1$and SV_2 = Solenoid valves

The 2 pressure taps (PT_1 and PT_2) at the beginning and end of the coil were provided to measure pressure drop across the coil. The methods for knowing the flow pattern is visualization method and the photographic method.

Liquid and the air are mixed in the starting entry of the coil tube and with the second coil onwards it gets constant flows of air and liquid. Through this test section, the flow regimes (flow patterns) directly can be seen and the photo graph is to be taken to know the flow regimes (flow patterns). Holdup at different flow rates is measured by quick closing valve. There is electrically adjustment for simultaneous closing of the 2 valves to trap the flowing mixture instantaneously. Once the system reaches steady state at particular flow rate of 2 fluids, the flowing mixture is arrested by closing these 2 valves in the test section instantaneously. The liquid was drained out into a previously weighed bottle. To drain the liquid as completely as possible, air from the main line was passed through the coil. By knowing the volume of liquids, holdup is calculated from Eq. 1:

$$\varepsilon_g = \frac{v_T - v_L}{v_T} \tag{1}$$

Where:

ε_g = The gas holdup
V_L = The volume of liquid
V_T = The total volume of gas-liquid mixture

Air-water system was used in the present study. The density of liquid (water) was measured with the help of a specific gravity bottle and the surface tension by tensiometer (K9-MK1, KRUSS GmbH Co., Germany). The present result has been reported within the operating range of the liquid flow rate as 3.33×10^{-5}-3.83×10^{-4} m^3 sec^{-1} and the air flow rate as 1.67×10^{-5}-1.67×10^{-4} m^3 sec^{-1}.

Model: The Lockhart-Martinelli correlation is a recognized tool to describe the 2 phase pressure drop in different flow process system. Originally, Lockhart and Martinelli (1949) had proposed graphically a correlation for the analysis of frictional pressure drop in horizontal 2 phase system. The concept of 2 phase system is used here in the present study. The 2 phase system is considered, as gas-liquid system. As per Lockhart-Martinelli Model, the Lockhart-Martinelli parameters for liquid and gas, ϕ_{sl}, ϕ_{sg} and X are defined as follows:

$$\phi_l^2 = \Delta P_{f2\phi} / \Delta P_{f1\phi l} \tag{2}$$

$$\phi_g^2 = \Delta P_{f2\phi} / \Delta P_{f1\phi g} \tag{3}$$

$$X = \frac{\phi_g}{\phi_l} = \sqrt{\left(\frac{\Delta P_{f1\phi l}}{\Delta P_{f1\phi g}}\right)} \tag{4}$$

The single-phase frictional pressure drop in coil ΔP_{fc} over a distance of ΔL of the pipe can be evaluated by the relation:

$$\Delta P_{fc} = \frac{2 f_c \rho v^2 \Delta L}{d} \tag{5}$$

In the laminar flow range (10<He<3000), the friction factor for non-Newtonian liquid can be calculated as (Mishra and Gupta, 1979):

$$f_c = f_s\left\{1 + 0.033\left(Log_{10}He\right)^4\right\} \tag{6}$$

And for turbulent flow of non-newtonian liquid in the range of $4500<Re<10^5$, $6.7<D/d<346$ and $0<p/D<25.4$:

$$f_c = 0.0791He^{-0.25} + 0.0075\left(d/D\right)^{0.50} \tag{7}$$

$$He = Re\left[\frac{(d/D)}{\left\{1+(p/\pi D)^2\right\}}\right]^{0.5} \quad (8)$$

From each experimental value of the total pressure gradient ($\Delta P/\Delta L_t$), an experimental frictional pressure gradient can be obtained by Eq. 9:

$$\frac{dp}{dL} = g\rho_m + \frac{2f_{2\phi}\rho_m v_m^2}{d} + \frac{2\rho_m v^2 d}{D} \quad (9)$$

Chisholm (1967) developed equations in terms of the Lockhart-Martinelli correlating groups for the frictional pressure gradient during the flow of gas-liquid or vapor-liquid mixtures in straight pipes. He developed a simplified equation for multiplier for use in engineering design, as a function of L-M parameter. The value of parametric constant dependents on the liquid and gas phases flow conditions. In the present study for the helical or curved pipe system, the complex phenomena of multiphase flow gradients vary the parameter which is enunciated by developing the correlation based on different dynamic, geometric and physical properties as variables.

RESULTS AND DISCUSSION

The flow pattern in vertical coiled tubes changes very little relative to the horizontal coiled tubes. The 3 types flow patterns were identified, such as Plug (P), Slug (S) and Stratified flow (ST) under the present experimental conditions. The Stratified flow pattern (ST), occurs within the lower mixture velocity conditions. At the slug flow condition, the gas phase, characterized by different size of bubbles, exists within the continuous liquid phase. This flow pattern occurs under higher mixture velocity and lower gas holdup conditions. The plug flow appeared with the higher liquid reynolds number and with lower gas reynolds number. The stratified flow observed with the lower liquid reynolds number and higher gas reynolds number. In this process, slug flow will also got effected when the changes of plug and stratified flow happened.

Variations of frictional pressure drop with different variables: The 2 phase frictional pressure drop per unit length of coil tube length increases with increasing Reynolds number at constant coil diameter, tube diameter and pitch. It is obvious that the fluid flow rate increases the frictional pressure drop as the momentum increases. The 2 phase frictional pressure drops per unit length of coil decreases with increasing coil diameter as shown in Fig. 2. As the centrifugal forces acting on the liquid phase

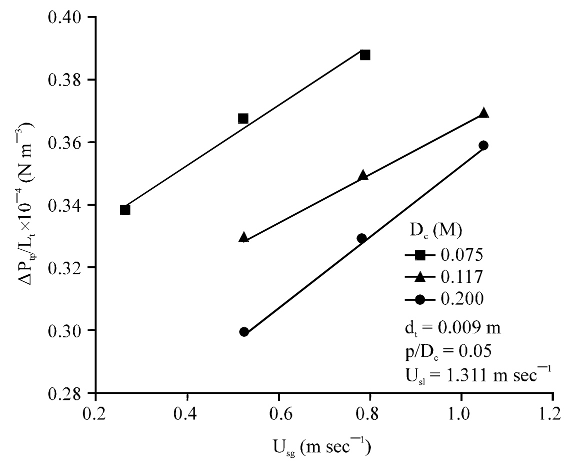

Fig. 2: Frictional pressure drop as a function of coil diameter

are much higher than those acting on the gas phase at any particular coil diameter, the relative momentum of the 2 phases is increased because of the slip existing between the gas and liquid phases. As the coil diameter decreases, the slip increases and hence, the pressure drop for the liquid phase decreases. The liquid momentum is more than the gas momentum due to the density difference of the phases which consequences the gas-phase pressure drop lower compared to that of the liquid phase. This results in overall a decrease in the 2 phase frictional pressure drop per unit length of coil. The 2 phase frictional pressure drops per unit length of coil increases with increasing gas flow rate at constant liquid flow rate and coil diameter.

Analysis of frictional pressure drop by Lockhart-Martinelli (L-M) Model: Earlier in theoretical conditions, it is seen that there exist a functional relationship between liquid multiplier (ϕ_l) and gas multiplier (ϕ_g) and L-M parameter (X). To establish such a relationship the experimental results are shown in Fig. 3 for a helical coil with air-Newtonian and air-non-Newtonian liquid systems. Based on the Lockhart-Martinelli concept in the present case the parameters, ϕ_l and ϕ_g have been correlated by incorporating the effect of different variables like geometric variables like coil diameter, tube diameter and pitch length and the physical properties of the fluid by dimensional analysis as:

$$\phi_l^2 = \lambda'\left(\frac{\mu_m}{\rho_m Us_m d_t}\right)^{a'}\left(\frac{\sigma_L}{\rho_m Us_m d_t}\right)^{b} \left(\frac{D_c}{d_t}\right)^{c'}\left(\frac{L_p}{d_t}\right)^{d'}\left(\frac{L_t}{d_t}\right)^{e'}(X)^{f'} \quad (10)$$

Table 1: The parameters for Eq. 10 of liquid multiplier of air-water 2 phase flow in helical coil

Flow pattrens	Flow cond.	λ'	a'	b'	c'	d'	e'	f'	R^2	SE	Range (Re_{cm})
Plug flow	Laminar	0.280	0.072	-0.220	0.316	-0.043	0.051	-0.043	0.922	0.077	420-1811
	Turbulent	2.05×10^{12}	1.887	-1.254	-0.063	-0.083	-1.136	-3.560	0.999	0.068	33417-197702
Slug flow	Laminar	4.787	0.347	-0.565	-0.130	-0.006	0.580	-0.893	0.946	0.056	74-2039
	Turbulent	1.13×10^{3}	-0.286	-0.200	-0.155	-0.345	-1.378	-0.775	0.998	0.055	14148-214584
Stratified flow	Laminar	5.096	0.390	-0.606	0.043	-0.024	0.585	-1.004	0.904	0.058	87-1839
	Turbulent	0.196	-1.422	1.302	-0.586	-0.111	-0.670	-0.084	0.988	0.055	17084-95449
Mixed flow	Turbulent	0.357	-0.552	0.870	0.000	-0.034	0.000	0.006	0.938	0.035	80931-170942

Table 2: The parameters for Eq. 11 of friction factor of air-water 2 phase flow in helical coil

Flow pattrens	Flow cond.	λ''	a''	b''	c''	d''	e''	R^2	SE	Range (Re_{cm})
Plug flow	Laminar	0.568	-0.337	-0.014	-0.191	0.020	-0.146	0.988	0.006	226-648
	Turbulent	9.731×10^{3}	1.583	-1.208	-0.731	-0.240	-0.473	0.996	0.067	20337-102519
Slug flow	Laminar	0.364	-0.240	-0.044	-0.105	0.020	-0.068	0.928	0.023	96-1039
	Turbulent	1.379×10^{4}	1.401	-1.129	-0.337	-0.342	-1.042	0.997	0.061	13151-205371
Stratified flow	Laminar	0.863	-0.160	-0.124	-0.195	0.024	0.008	0.973	0.012	88-641
	Turbulent	3.664×10^{2}	-0.359	1.969	-0.223	-0.117	-0.975	0.996	0.179	33417-212347
Mixed flow	Turbulent	1.110×10^{5}	1.267	0.785	0.000	-0.211	0.000	0.942	0.142	80931-1103334

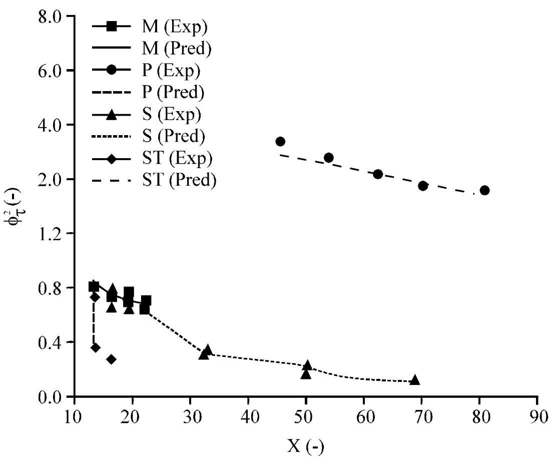

Fig. 3: Parity plot of experimental and predicted values of L-M multiplier; Mixed flow (M): $L_t/d_t = 275.556$ m, $D_c/d_t = 8.333$ m; Plug flow (P): $L_t/d_t = 5.850$ m, $D_c/d_t = 58.500$ m; Slug flow (S): $Lt/dt = 275.556$ m, $D_c/d_t = 13.00$ m and Stratified flow (ST): $L_t/d_t = 275.556$ m, $D_c/d_t = 8.333$ m

The values of constants with correlation coefficient (R^2) and the Standard Error (SE) of Eq. 10 for different flow patterns found are shown in Table 1. From Fig. 3, it is seen that with the parameter X, the frictional pressure drop multiplier gives the satisfactory prediction for frictional pressure drop in the 2 phase gas-liquid flow of the present system for the range of $2.00\times10^{-0.5} \leq \mu_m/\rho_m Us_m d_t \leq 1.800\times10^{-0.4}$, $0.003 \leq \sigma_L/\rho_m Us_m d_t \leq 0.016$, $3.750 \leq D_c/d_t \leq 22.22$, $1.875 \leq L_p/d_t \leq 33.333$, $58.500 \leq L_t/d_t \leq 275.556$, $5.239 \leq X \leq 126.876$ and $0.103 \leq \phi_l^2 \leq 12.461$ within ±10% of error.

Prediction of friction factor at different flow patterns by correlation model: A general correlation to predict the frictional pressure drop is developed with the operating variables as shown in Eq. 11 for different flow patterns.

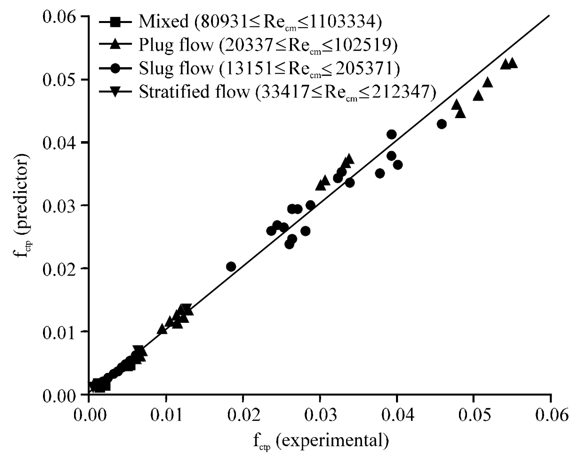

Fig. 4: Parity plot of experimental and predicted values of friction factor

The parameters in the equation with the correlation coefficients and standard error are shown in tabular format as shown in Table 2.

$$f_{c,tp} = \lambda'' \left(\frac{\mu_m}{\rho_m Us_m d_t}\right)^{a''} \left(\frac{\sigma_L}{\rho_m Us_m d_t}\right)^{b''} \left(\frac{D_c}{d_t}\right)^{c''} \left(\frac{L_p}{d_t}\right)^{d''} \left(\frac{L_t}{d_t}\right)^{e''} \quad (11)$$

The 2 phase friction factor with the reynolds number at different flow conditions for a plug flow condition is shown in Fig. 4 by comparing with the predicted values calculated by correlation.

CONCLUSION

The present study focuses on the flow pattern and hydrodynamics of gas-liquid two-phase flow in a vertical helical coil. The 3 different flow patterns:

- Plug flow
- Slug flow
- Stratified flow are observed within a wide range of experimental conditions

Comparing all experimental data plug flow is observed with higher liquid reynolds number with lower gas reynolds number. The effect of coil diameter and pitch difference on flow patterns mostly depends on the secondary flow which is caused by the centrifugal force. The friction factor increases with the increase in tube diameter whereas it decreases as the coil diameter increases. But, there is no pitch effect for the friction factor with the present data. A correlation is developed for friction factor of air-liquid 2 phase flow in vertical helical coil. The correlation developed follows a good agreement with the present experimental data. The martinelli parameter has been modified by incorporating different dimensionless number obtained by dimensional analysis with the help of different operating variables. This study may be useful tool for further understanding of multiphase flow in chemical process systems possible scale up of three-phase column for different chemical processes.

NOMENCLATURE

d_t = Tube diameter (m)
D_c = Coil diameter (m)
f = Fanning friction factor (-)
L_p = Pitch length (m)
L_t = Tube length (m)
P = Pressure
p = Pitch of the coil (m)
p/D_c = Pitch difference (-)
U_{sg} = Gas superficial velocity (m sec^{-1})
U_{sl} = Liquid superficial velocity (m sec^{-1})
U_m = Mixed velocity (m sec^{-1})
X = Lockhart Martinelli parameter (-)
He = Helical number
Re = Reynolds number ($d_tU\rho/\mu$)

Greek letters:
ρ = Density (kg m^{-3})
μ = Viscosity (kg m.sec)
α_g = Gas holdup (-)
σ = Surface tension (N m^{-1})
ϕ = Pressure drop multiplier (-)

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