Prediction of Liquid Holdup in Horizontal Stratified Two-Phase Flow

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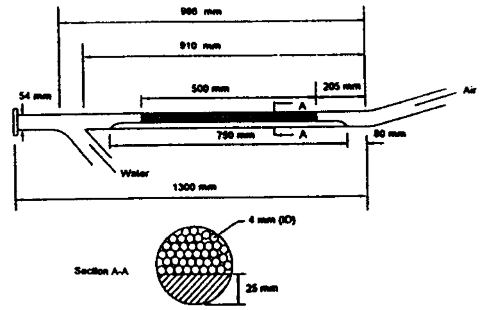
Abstract

This paper provides a combined theoretical and experimental investigation into the prediction of hold-up for a stratified two-phase concurrent flow in a horizontal circular pipe. The test section, 10 m long, with an inside diameter 54 mm was made of transparent acrylic glass to permit visual observation of the flow patterns. The experiments were carried out under various air and water flow rates in the regime of smooth and wavy stratified flows. Stainless ring electrodes were mounted flush in the tube wall for measuring the liquid hold-up which is defined as the ratio of the cross-sectional area filled with liquid to the total crossectional area of the pipe. Calculation method for predicting the liquid hold-up was developed by using the Taitel and Dukler momentum balance.The ratio of interfacial friction factor and superficial gas-wall friction factor,(f_i/f_{SG}) was assumed to be constant. Hold-up curves calculated by this method are compared with present experimental data and those of other researchers. A ratio of f_i/f_{SG} ,which corresponds with the flow conditions, (laminar or turbulent) are presented.

Key Words: Two-Phase Flow, Co-Current Flow, Stratified Flow, Liquid Hold-Up

1. Introduction

Stratified two-phase flow regime is frequently encountered in various chemical and industrial processes; e.g. the flows of steam and water, or oil and natural gas in pipelines etc. One of the main problems in two-phase flow is the calculation to determine the liquid hold-up and pressure loss. Lockhart and Martinelli [1] have developed a procedure for calculating the frictional pressure loss for adiabatic two-phase flow using their data on the horizontal flow of air and water and various other liquids at atmospheric pressure. Their correlations have been applied to all regions of two-phase flow both by the originators and by several other investigators. Chisholm [2] has developed the Martinelli models in such a way that the original Martinelli curves for the various flow regimes can be fitted quite well by selecting a fixed value of a parameter for each flow regime. Johannessen [3] has developed a theoretical solution of the original Lockhart and Martinelli flow model for calculating two-phase pressure drop and holdup in the stratified and wavy flow region. He has shown that his theoretical solutions of pressure drop and holdup agree much better than those of Lockhart and Martinelli in the separated flow region.



Mixing section

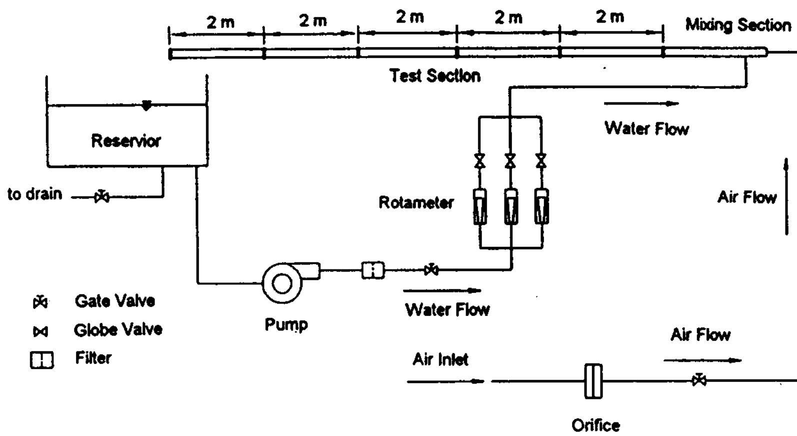


Figure 1. Test facility

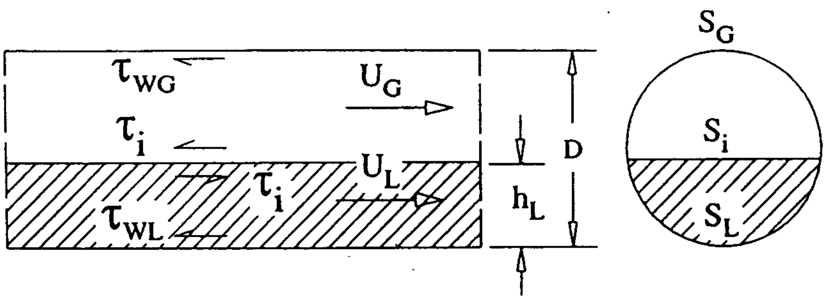


Figure 2. Stratified co-current two-phase flow

The semi-empirical methods for calculating the two-phase flow pressure drop have been proposed by numerous investigators. Wallis [4] correlation which has been improved further by Hewitt and Hall-Taylor [5] can be used in the annular flow region. Hughmark [6] developed a semi-empirical pressure drop correlation independently which is applicable in slug flow region. Kadambi [7] proposed an analytical procedure to determine the pressure drop and void fraction in two-phase stratified flow between parallel plates.

Most stratified flow models were based on an iterative solution of the two phase momentum balance, but differed in the model of the interfacial shear stress. To solve this problem, Taitel and Dukler [8] made the assumption that the interface was smooth and interfacial friction factor equal to the gas-wall friction factor and the gas interfacial shear stress was evaluated with the same equation as the gas wall shear stress.

In another paper (Taitel and Dukler [9]), they demonstrated that the hold up and the dimensionless pressure drop for stratified flow are unique functions of X under the assumption that $f_G/f_i \cong$ constant. Kawaji [10] predicted holdup successfully by substituting the ratio of the gas-wall friction factor and the gas interfacial shear stress into the Taitel and Dukler momentum balance.

Inaccuracies in previous stratified flow models are found to be a result of the interfacial shear stress used in the model. In the present study, the method for prediction of liquid hold-up will be presented. The method is based on that of Spedding et al. [11,12] and Wongwises [13] where the ratio of the interfacial friction factor and gas-wall friction factor is assumed to be a constant. With this technique a mathematical model of interfacial friction factor is not necessary. The value of the constant depends on whether the phases are in turbulent or laminar flow.

2. Experimental Apparatus and Method

The experimental facility used is shown schematically in Fig 1.The main components of the system consisted of the test section, air supply, water supply, instrumentation, and data acquisition system.The horizontal test section, with an inside diameter of 54 mm and length of 10 m was made of transparent acrylic glass to permit visual observation of the flow patterns.Water was pumped from the storage tank through the rotameter to the water inlet section at the bottom of the pipe. Air was supplied to the test section by a suction-type blower. The air flow could be controlled by a valve at the outlet of the blower. Many small rods were used as guide vanes at the air inlet section to maintain a uniform flow. Both the air and water streams were brought together in a mixer and then passed through the test section concurrently.The inlet flow rate of air was measured by means of a round-type orifice and that of water was measured by two sets of rotameters.

The temperature of the air and water was measured by thermocouples. Stainless ring electrodes were mounted flush in the tube wall for measuring the liquid hold up. They operate on the principle of the variation of electrical resistance following changes in the water level between two parallel electrode rings. The same description of the calibration procedures for stratified flow can be found in Andreussi [14]. Due to the variation of conductivity caused by temperature change and coating of the electrodes with impurities, the gauges were calibrated before and after each run.

Experiments were conducted with various flow rates of air and water at ambient condition. In the experiments the air flow rate was increased by small increments while the water flow rate was kept constant at a preselected value. After each change in inlet air flow rate, both the air and water flow rates were recorded. The liquid hold-up was registered through the transducers. The flow phenomena was detected by visual observation.

3. Mathematical Model

Consider an equilibrium horizontal stratified flow as shown in Fig. 2. A momentum balance on each phase yields:

$$-A_L\left(\frac{dP}{dx}\right)-\tau_{WL}S_L+\tau_iS_i=0 \quad (1)$$

$$-A_G\left(\frac{dP}{dx}\right)-\tau_{WG}S_G-\tau_iS_i=0 \quad (2)$$

Equating pressure drop in the two phases and assuming that the hydraulic gradient in the liquid is negligible, the following result is obtained;

$$\tau_{WG}\frac{S_G}{A_G}-\tau_{WL}\frac{S_L}{A_L}+\tau_iS_i\left(\frac{1}{A_L}+\frac{1}{A_G}\right)=0 \quad (3)$$

The shear stresses are evaluated in a conventional manner

$$\tau_{WL}=f_L\frac{\rho_L u_L^2}{2} \quad (4)$$

$$\tau_{WG}=f_G\frac{\rho_G u_G^2}{2} \quad (5)$$

$$\tau_i=f_i\frac{\rho_G(u_G-u_L)^2}{2} \quad (6)$$

Normally for equilibrium flow $u_G \geq u_L$ such that u_L in eq.(6) can be neglected. A widely used method for the correlation of the liquid and gas friction factors is in the form of Blasius equation:

$$f_L=C_L\left(\frac{D_Lu_L}{\upsilon_L}\right)^{-n} \quad (7)$$

$$f_G=C_G\left(\frac{D_Gu_G}{\upsilon_G}\right)^{-m} \quad (8)$$

where D_L and D_G are the hydraulic diameter evaluated in the manner as suggested by Agrawal et al.[15]. The liquid is visualized as if it was flowing in an open channel .

$$D_L=\frac{4A_L}{S_L} \quad (9)$$

The gas is visualized as flowing in a closed duct and thus

$$D_G=\frac{4A_G}{S_G+S_i} \quad (10)$$

Furthermore, the coefficients C_L, n, C_G and m used in Eq. (7) and Eq. (8) are those used by Taitel and Dukler [8] in their co-current studies,

in turbulent flows; $C_G = C_L = 0.046$, $m = n = 0.20$

in laminar flows; $C_G = C_L = 16$, $m = n = 1.0$.

Turbulent or laminar flow conditions in each phase are identified by calculating the Reynolds number for each phase using the superficial velocity and diameter of the pipe, i.e.

$$\mathrm{Re}_{SK}=\frac{U_{SK}D}{\upsilon_K}$$

where K = G, L

Laminar flow is also assumed for superficial Reynold number < 2000.
Substituting τ_{WL}, τ_{WG}, τ_i from Eq.(4), Eq.(5) and Eq.(6) into Eq.(3),the following equation is obtained;

$$\frac{f_G\rho_Gu_G^2S_G}{2A_G}-\frac{f_L\rho_Lu_L^2S_L}{2A_L}+\frac{f_i\rho_Gu_G^2S_i}{2}\left[\frac{1}{A_L}+\frac{1}{A_G}\right]=0 \quad (11)$$

In the case of the single phase flow, the pressure gradient is determined from;

$$\left(\frac{dP}{dx}\right)_{SG}=\frac{2f_{SG}\rho_Gu_{SG}^2}{D} \quad (12)$$

where $f_{SG} = C_G \left(\frac{D u_{SG}}{\upsilon_G} \right)^{-m}$

Equation (11) is non-dimensionalized by dividing by $\left(\frac{dP}{dx} \right)_{SG}$

Finally the following equation is obtained;

$$\frac{f_G u_G^2 S_G D}{4 f_{SG} A_G u_{SG}^2} - \frac{f_L \rho_L u_L^2 S_L D}{4 f_{SG} \rho_G A_L u_{SG}^2} + \frac{f_i \rho_G u_G^2 S_i D}{4 f_{SG} \rho_G u_{SG}^2} \left[\frac{1}{A_L} + \frac{1}{A_G} \right] = 0 \quad (13)$$

or in dimensionless form

$$(\tilde{u}_G)^2 (\tilde{D}_G \tilde{u}_G)^{-m} \frac{\tilde{S}_G}{\tilde{A}_G} - \left[(\tilde{u}_L)^2 (\tilde{D}_L \tilde{u}_L)^{-n} \frac{\tilde{S}_L}{\tilde{A}_L} \right] X^2 + \frac{f_i}{f_{SG}} (\tilde{u}_G)^2 \left[\frac{\tilde{S}_i}{\tilde{A}_L} + \frac{\tilde{S}_i}{\tilde{A}_G} \right] = 0 \quad (14)$$

where $X^2 = (dP/dx)_{SL} / (dP/dx)_{SG}$ is the ratio of the frictional pressure gradient of the liquid to that of the gas when each phase flows along in the pipe.

$$X^2 = \frac{\frac{4C_L}{D} \left(\frac{u_{SL} D}{\upsilon_L} \right)^{-n} \frac{\rho_L (u_{SL})^2}{2}}{\frac{4C_G}{D} \left(\frac{u_{SG} D}{\upsilon_G} \right)^{-m} \frac{\rho_G (u_{SG})^2}{2}} \quad (15)$$

X is recognized as the parameter introduced by Lockhart and Martinelli [1] and can be calculated unambiguously with the knowledge of the flow rate, fluid properties and tube diameter.Liquid hold up can be calculated from h_L/D which is in the form of $\tilde{A}_G, \tilde{A}_L$.

All dimensionless variables with the superscript can be seen from

$$\begin{aligned} \tilde{A} &= \pi / 4, \\ \tilde{A}_L &= A_L / D^2, \\ \tilde{S}_L &= S_L / D, \\ \tilde{A}_G &= A_G / D^2, \\ \tilde{S}_G &= S_G / D, \\ \tilde{S}_i &= S_i / D, \\ \tilde{D}_L &= D_L / D, \\ \tilde{D}_G &= D_G / D, \\ \tilde{h}_L &= h_L / D \end{aligned} \quad (13)$$

$$\begin{aligned} \tilde{S}_L &= \pi - \cos^{-1}(2\tilde{h}_L - 1), \\ \tilde{S}_G &= \cos^{-1}(2\tilde{h}_L - 1), \\ \tilde{S}_i &= \sqrt{1 - (2\tilde{h}_L - 1)^2}, \\ \tilde{U}_G &= \frac{\tilde{A}}{\tilde{A}_G}, \\ \tilde{U}_L &= \frac{\tilde{A}}{\tilde{A}_L} \end{aligned}$$

$$\tilde{A}_L = 0.25\left[\pi - \cos^{-1}(2\tilde{h}_L - 1) \right] + 0.25\left[(2\tilde{h}_L - 1)\sqrt{1 - (2\tilde{h}_L - 1)^2} \right]$$

$$A_G = 0.25\left[\cos^{-1}(2\tilde{h}_L - 1) \right] - 0.25\left[(2\tilde{h}_L - 1)\sqrt{1 - (2\tilde{h}_L - 1)^2} \right]$$

In order to solve Eq.(14) for liquid hold up, gas hold up and pressure drop, an iterative computer program is required. A flow chart of this program is shown in Fig 3.

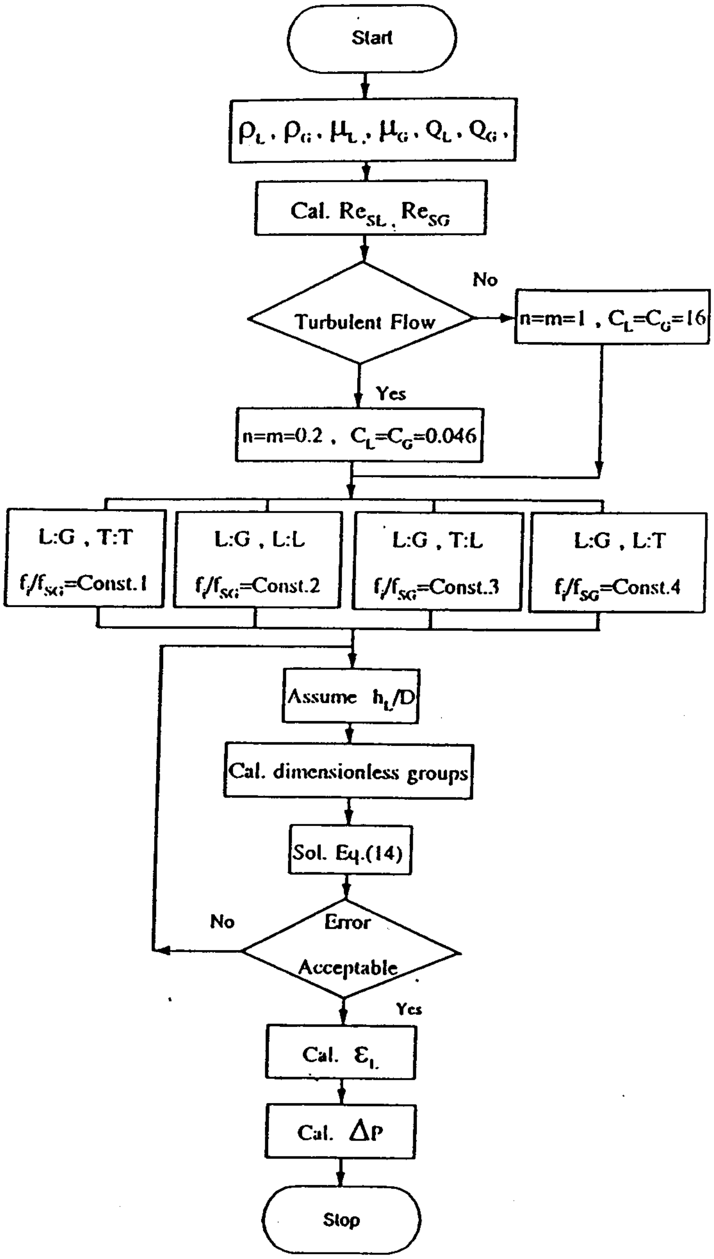


Figure 3. Flow chart for calculation of liquid hold-up and pressure drop

4. Results and Discussion

To handle practical problems, it is necessary to gain a better understanding of flow characteristics. Visual observation shows that different flow patterns may occur with gas-liquid cocurrent flow in horizontal pipes. In accordance with results obtained from this experiment, the following flow patterns were obtained :

a) Stratified flow: The water flows in the lower part of the pipe and the air over it with a smooth interface between the two phases.

b) Two-dimensional wavy flow: Similar to stratified flow except for a wavy interface, due to a velocity difference between the two phases and two-dimensional steady waves travel with a relatively regular pitch.

c) Three-dimensional wavy flow: At a higher air flow rate, the water surface is disturbed and three-dimensional waves occur, which have small irregular ripples on the fundamental waves.

d) Violent wavy flow: The interface is violently disturbed by the air stream. This flow pattern occurs at a relatively high air flow rate.

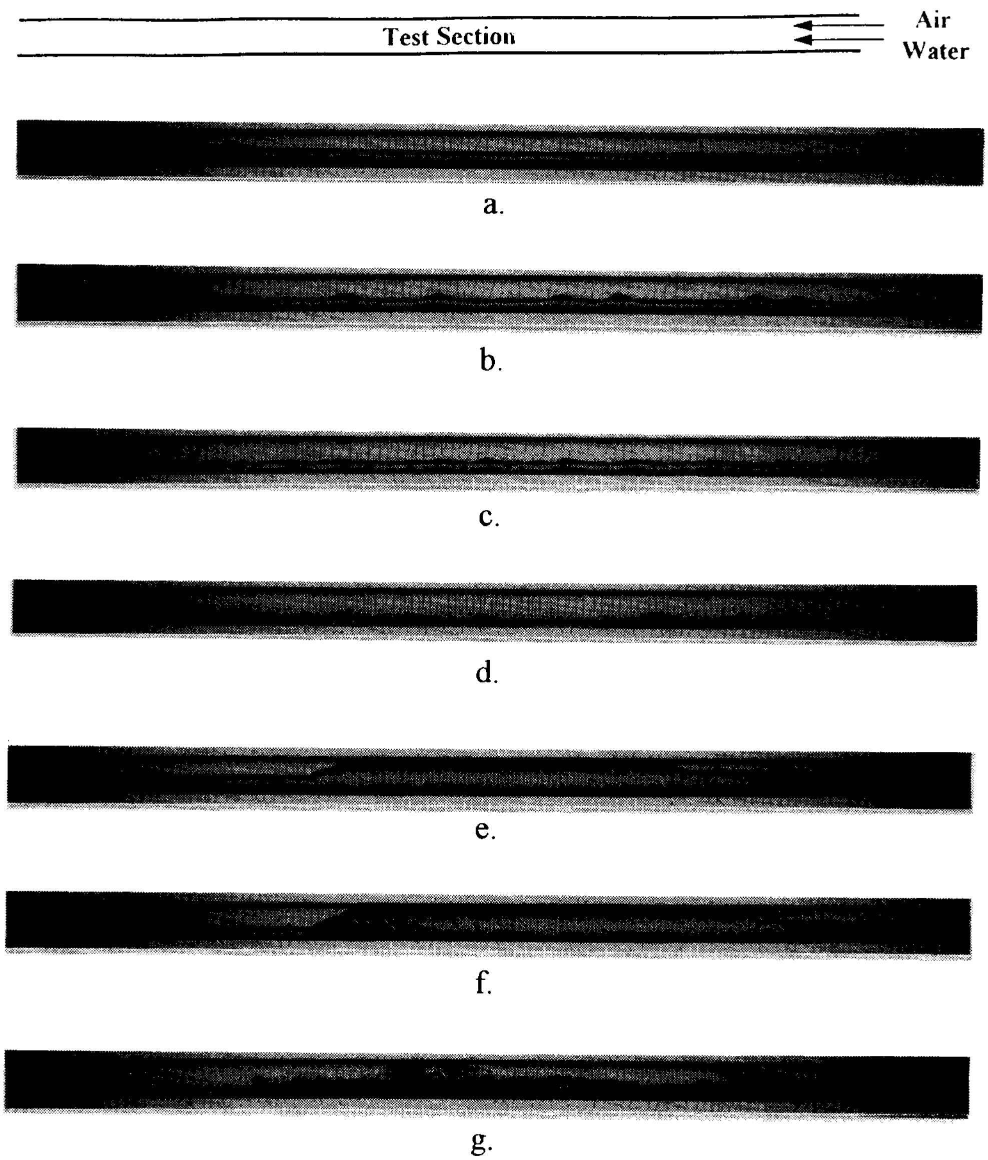
e) Plug flow: Air moves along the upperside of the pipe. This flow pattern occurs at a relatively low air flow rate. The interface is smooth and no bubbles are contained in a water plug.

f) Slug flow: Splashes or slugs of water occasionally pass through the pipe with a higher velocity than the bulk of the water. The tail of water slug is relatively smooth and sometimes contains some small bubbles. The upstream portion of the water slug is similar to the wavy flow, and the downstream portion to the stratified flow or wavy flow.

g) Pseudo slug flow: The semi-slug is defined as a highly agitated long wave which contains many bubbles. Its upstream and downstream portions are similar to the wavy flow.

The typical photographs of flow patterns are shown in Figure 4. The focus of the study was on the stratified and small wavy flow. Figures 5 and 6 show the relation between the liquid holdup,ε_L against the Lockhart-Martinelli parameter, X for a laminar liquid-turbulent gas flow in the 0.054 m. diameter pipe and Q_L = 1.67 $\times 10^{-5}$, 6.67×10^{-5}.m^3/s respectively. The values C_G=C_L=0.046, n=m=0.2 for turbulent flow and C_G=C_L=16,n=m=1.0 for laminar flow are used. The figures show a comparison of the experimental data with the present model where the ratio, f_i/f_{SG} is assumed. It is found that an agreement of the present model with the experimental data is obtained by using f_i/f_{SG} = 0.30-1.0. The data obtained by Spedding et al. [11] who tested the model against wavy and stratified flow data from 93.5 and 45.5 mm diameter pipes are compared with the predictions from the present model. Their data points were taken from log scale, thus were a cause of some uncertainties. Their data can be accurately predicted with f_i/f_{SG} = 0.6 for laminar liquid-turbulent gas flow. Their predicted f_i/f_{SG} are in the recommended range in this work. The scatter of Spedding et al. data for the smaller diameter pipe is much greater than the large diameter.

Figures 7 and 8 show also the relation between ε_L against X for a turbulent liquid-turbulent gas flow for $Q_L = 8.3\times10^{-5}$ and 1.67×1 0^{-4}.m^3/s respectively. They show that the liquid holdup can be accurately predicted by assuming f_i/f_{SG} = 2.0-4.0. The data shows that the assumption of f_i/f_{SG} = 1.0 overpredicted liquid holdup for the stratified flows.The results correspond to those from Kawaji [10] who predicted holdup successfully by substituting f_i/f_{SG} = 3.0 and also from Spedding et.al.[11] by substituting f_i/f_{SG} = 4 for turbulent liquid-turbulent gas flow into the Taitel and Dukler [8] momemtum balance. Their predicted f_i/f_{SG} are also in the recommended range in this work. However, for Spedding et al. results, a discrepancy is found between the present recommended ratio of f_i/f_{SG} and the experimental data at greater Lockhart Martinelli Parameter. This is because of a change of interfacial phenomena. The amplitude of the water layer fluctuation increases slightly with



a. Stratified flow
b. Two-dimensional wavy flow
c. Three-dimensional wavy flow
d. Violent wavy flow
e. Plug flow
f. Slug Flow
g. Pseudo slug flow

Figure 4. Photographs of flow Patterns

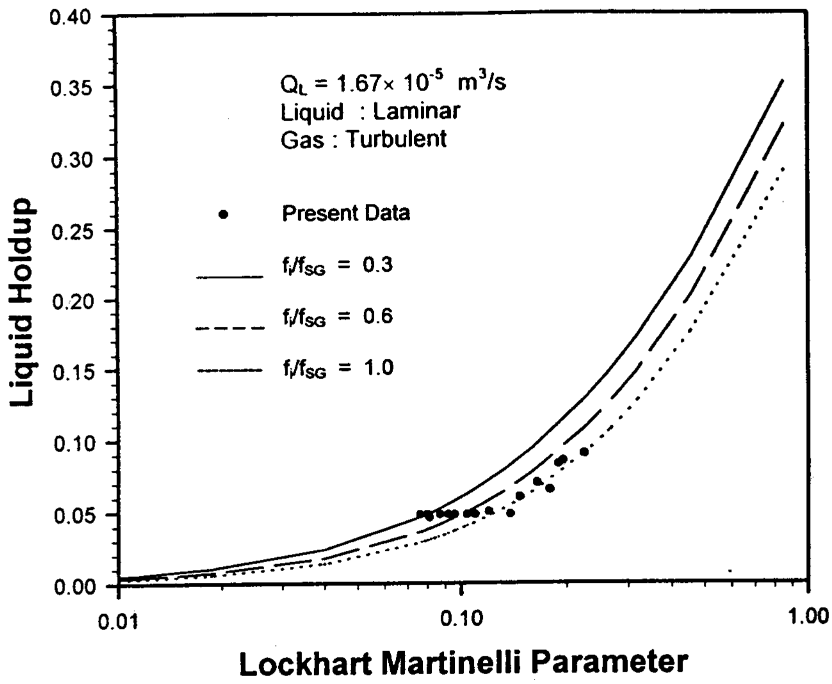


Figure 5. ε_L against log (X) for $Q_L = 1.67\times10^{-5}$ m^3/s ; Liquid-Laminar and Gas-Turbulent

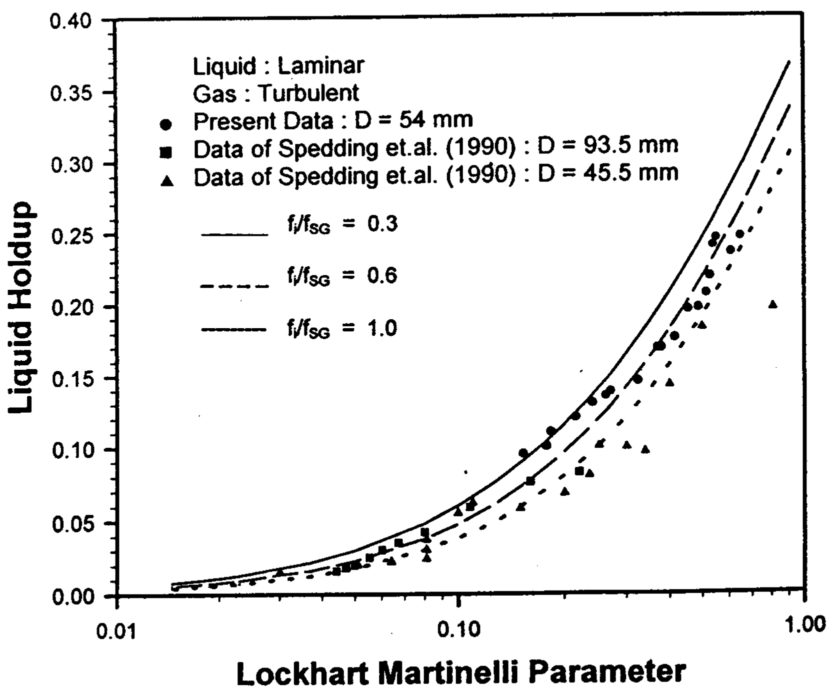


Figure 6. ε_L against log (X) for $Q_L = 6.67\times10^{-5}$ m^3/s ; Liquid-Laminar and Gas-Turbulent

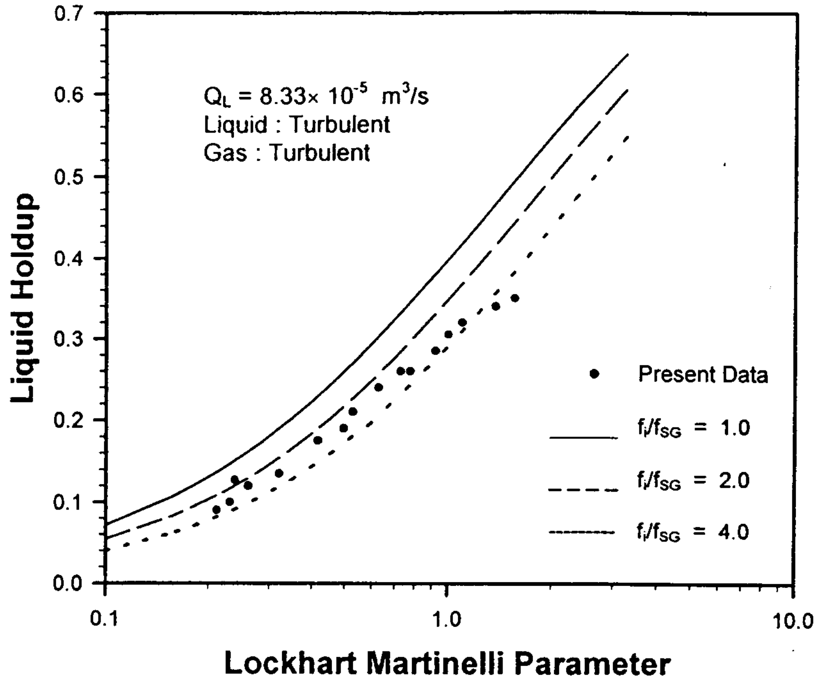


Figure 7. ε_L against log (X) for Q_L= 8.33×10^{-5} m^3/s ; Liquid-Turbulent and Gas-Turbulent

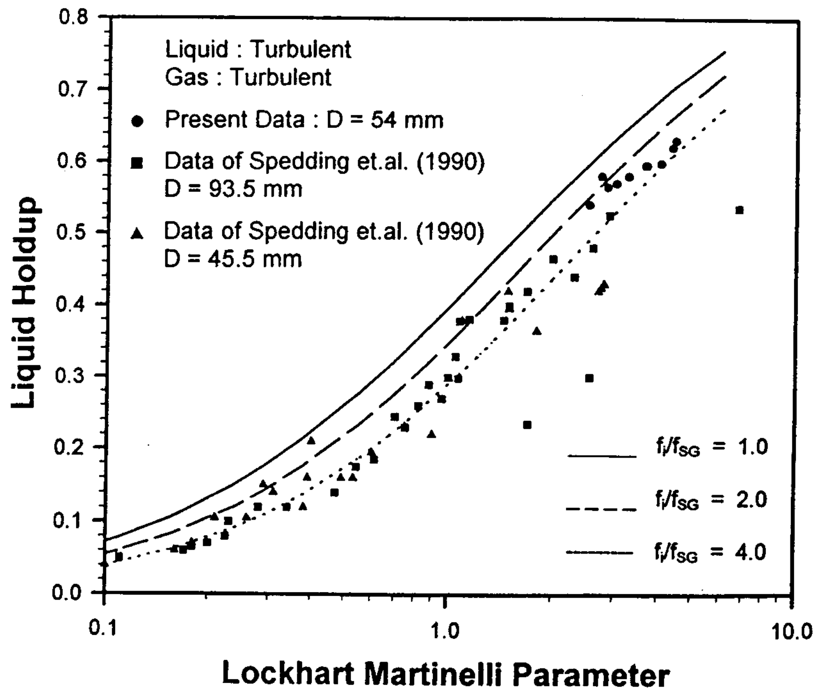


Figure 8. ε_L against log (X) for Q_L= 1.67×10^{-4} m^3/s ; Liquid- Turbulent and Gas-Turbulent

air flow. Two-phase pressure drop can be determined further by substituting h_L/D into Eq. (1) or (2). In this work, the situation when gas flow was laminar, was not considered.

5. Conclusion

This paper presents new data to predict the liquid holdup in horizontal concurrent stratified flow in a circular pipe. It has been demonstrated that the liquid holdup can be predicted by using Taitel and Dukler momemtum balance between both phases. The ratio of the friction factor of the gas at the interface and the gas at the pipe wall, f_i/f_{SG} is assumed to be constant. The constant depends on the phase being either turbulent or laminar. With this method a model of interfacial friction factor is not necessary. For turbulent liquid-turbulent gas flows, the former assumption that $f_i = f_{SG}$ is shown to give a result which does not agree with the experimental data.Future work should examine the effect of pipe diameter. It may be also worthwhile to study in countercurrent flow for comparison with concurrent flow data.

Nomenclature

A	Crossectional area of pipe, m^2
A_G, A_L	Crossectional area of gas and liquid phase, m^2
C_G, C_L	Constant in Eq.(7) and (8)
D	Pipe diameter,m
D_G, D_L	Hydraulic diameter of gas and liquid phase, m
f_G, f_L	Gas-wall and liquid-wall friction factor
f_i	Interfacial friction factor
f_{SG}	Superficial gas-wall friction factor
g	Gravitational acceleration, m/s^2
h	Liquid height, m
n,m	Constant in Eq.(7) and (8)
P	Pressure, N/m^2
dP/dx	Two phase pressure gradient, N/m^3
$(dP/dx)_{SG}$	Pressure gradient of single gas phase, N/m^3
$(dP/dx)_{SL}$	Pressure gradient of single liquid phase, N/m^3
Q_G	Volume flow rate of gas,m^3/s
Q_L	Volume flow rate of liquid,m^3/s
Re_G	Gas phase Reynolds number
Re_L	Liquid phase Reynolds number
Re_{SG}	Superficial gas phase Reynolds number
Re_{SL}	Superficial liquid phase Reynolds number
S_G	Gas phase perimeter,m
S_L	Liquid phase perimeter,m
S_i	Interfacial width,m
U_G	Average velocity of gas, m/s
U_L	Average velocity of liquid, m/s
U_{SG}	Superficial velocity of gas, m/s
U_{SL}	Superficial velocity of liquid, m/s
X	Lockhart-Martinelli parameter

Greek Symbols

ρ	Density, kg/m^3
υ	Kinematic viscosity, m^2/s
τ	Shear stress, N/m^2
ε	Liquid hold up

Subscripts

G	Gas phase
L	Liquid phase
i	Interface
WL	Liquid-wall
WG	Gas-wall
SG	Superficial gas
SL	Superficial liquid

Superscripts

~	dimensionless term

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