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A unified mechanistic model for slug liquid holdup and transition between slug and dispersed bubble flows

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Abstract

A unified mechanistic model for slug liquid holdup is developed based on a balance between the turbulent kinetic energy of the liquid phase and the surface free energy of dispersed spherical gas bubbles. The turbulent kinetic energy is estimated by use of the shear stress at the pipe wall and the momentum exchange (mixing term or acceleration term) between the liquid slug and the liquid film in a slug unit. The momentum exchange term varies significantly with pipe inclination and enables the model to give an accurate prediction of slug liquid holdup for the entire range of pipe inclination angle. The model has been compared with experimental data acquired at TUFFP for slug flows at all inclinations and good agreement has been observed. The model can also be used to predict the slug–dispersed bubble flow pattern transition boundary over the whole range of inclination angles. From comparison with previous experimental results, the model predictions are accurate for gas superficial velocities larger than 0.1 m/s.
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1. Introduction

Slug liquid holdup is needed as a closure relationship when the momentum equations for slug flow are solved to calculate the pressure gradient in pipelines and wellbores. For horizontal and near-horizontal flows, the Gregory et al. (1978) correlation is widely used for prediction of slug liquid holdup as a function of the mixture velocity. However, experimental data from inclined and vertical slug flow tests (Schmidt, 1977; Felizola, 1992) have shown that slug liquid holdup decreases significantly with a change of inclination angle from horizontal to upward vertical.

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Gomez et al. (2000) incorporated both mixture velocity and inclination angle into an empirical correlation for the slug liquid holdup. However, parameters like surface tension and gas–liquid density difference were not considered in their correlation, and the model can not be used for downward flow.

A mechanistic method for prediction of slug liquid holdup was first introduced by Barnea and Brauner (1985). This method is based on a hypothesis that the gas within the developed liquid slugs behaves as dispersed bubbles. Thus, the liquid slugs accommodate the same gas holdup as dispersed bubble flow on the transition boundary with the same mixture velocity. Predictions from the method rely on the correct transition boundary, which is still not available with sufficient accuracy. The Barnea (1987) unified model gives a good prediction for the transition from slug to dispersed bubble flow at low flow rates, but shows an incorrect trend at high gas flow rates. The reason is that the model is based on the Hinze (1955) correlation which is valid for small gas fractions, and the gas fraction is not related to the required turbulent energy for dispersion.

Chen et al. (1997) proposed a general model for the transition to dispersed bubble flow based on a balance between the turbulent kinetic energy of the liquid phase and the surface free energy of dispersed spherical gas bubbles. This concept is employed in the present study, giving more emphasis on the physical mechanism in order to achieve a better prediction of the transition from slug to dispersed bubble flow. The Barnea and Brauner concept is used to calculate slug liquid holdup. However, the non-gravitational pressure gradient in the liquid slug is used to evaluate the turbulent kinetic energy instead of the friction velocity. This pressure gradient includes the frictional pressure gradient and the momentum exchange (mixing term or acceleration term) between the liquid slug and the liquid film. Thus, the slug liquid holdup is interrelated with the slug flow characteristics and can be calculated after solving the momentum and continuity equations for slug flow.

The theoretical development of the model for predicting slug liquid holdup and the transition to dispersed bubble flow will be presented in the next section. Then, the model will be compared with experimental results.

2. Model development

According to the concept first introduced by Barnea and Brauner (1985), the slug liquid holdup corresponds to the highest amount of gas the liquid slug can accommodate. The gas phase is dispersed as spherical bubbles in the liquid phase during fully turbulent flow. Gas bubbles may coalesce when they collide with one another due to turbulent movement. Simultaneously, a gas bubble will be broken up by the turbulent forces exerted on it if its size is larger than a certain value. Therefore, the amount of gas a liquid slug can hold is dependent on the turbulent intensity of the liquid phase. There must be a balance between the total surface free energy of dispersed gas bubbles and the turbulent kinetic energy of the liquid phase.

The surface free energy per unit interfacial area is the work necessary to generate this area, and is equal to the interfacial surface tension between a liquid phase and a gas phase (Adamson, 1990). Assuming gas bubbles are all spherical with a diameter of d_b, the total surface free energy of the discrete gas bubbles in the liquid slug is

$$E_S = \frac{6\sigma}{d_b} A(1 - H_{Ls}) l_s, \tag{1}$$

where σ is the interfacial surface tension, A is the internal cross-sectional area of the pipe, H_{Ls} is the liquid holdup in the slug body and l_s is the length of the liquid slug.

The turbulent kinetic energy per unit volume of liquid flowing in a pipe is (White, 1991)

$$e_T = \tfrac{1}{2}\rho_L(\overline{v_r'^2} + \overline{v_\theta'^2} + \overline{v_z'^2}), \tag{2}$$

where ρ_L is liquid density, and v_r', v_θ' and v_z' are the radial, tangential and axial velocity fluctuations, respectively. $\overline{v_r'^2} = \overline{v_\theta'^2} = \overline{v_z'^2}$ if the turbulent flow is assumed to be isotropic. Thus, Eq. (2) is simplified as

$$e_T = \tfrac{3}{2}\rho_L \overline{v_r'^2}. \tag{3}$$

The total turbulent kinetic energy in the liquid slug is

$$E_T = \tfrac{3}{2}\rho_L \overline{v_r'^2} A H_{Ls} l_s. \tag{4}$$

In Taitel and Dukler (1976) and Chen et al. (1997), the root mean square of the radial velocity fluctuation is approximated as the friction velocity, which is

$$v^* = \sqrt{\frac{\tau_s}{\rho_L}}, \tag{5}$$

where τ_s is the shear stress at the pipe wall,

$$\tau_s = \frac{f_s}{2}\rho_s v_m^2 = \left(\frac{dp}{dz}\right)_s \frac{d}{4}. \tag{6}$$

In Eq. (6), d is the pipe diameter, f_s is the friction factor at the pipe wall for the liquid slug, and v_m is the mixture velocity, which is given by

$$v_m = v_{SL} + v_{Sg}. \tag{7}$$

$(dp/dz)_s$ is the pressure gradient in the slug body due to the shear stress. The mixture density in the slug, ρ_s, is

$$\rho_s = \rho_L H_{Ls} + \rho_g(1 - H_{Ls}), \tag{8}$$

where ρ_L and ρ_g are liquid and gas densities.

However, the turbulence in a liquid slug is maintained not only by the shear (or Reynolds stress) between the fluids and the pipe wall, but also by the mixing (or momentum exchange) between the slug body and the film zone of a slug unit. This mixing term was used by Dukler and Hubbard (1975), Nicholson et al. (1978) and Kokal and Stanislav (1989) to calculate the pressure gradient in slug flow. Therefore, the pressure gradient including both the shear term and the mixing term should be used to estimate the velocity fluctuations,

$$\left(\frac{dp}{dz}\right)_{sm} = \left(\frac{dp}{dz}\right)_s + \left(\frac{dp}{dz}\right)_m. \tag{9}$$

The pressure gradient due to momentum exchange between the slug body and the film zone can be expressed as (Zhang et al., 2000),

$$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{m}} = \frac{\rho_{\mathrm{L}} H_{\mathrm{Lf}}(v_{\mathrm{t}} - v_{\mathrm{f}})(v_{\mathrm{m}} - v_{\mathrm{f}})}{l_{\mathrm{s}}}, \tag{10}$$

where H_{Lf} is the liquid holdup in the film zone of a slug unit, v_{t} is the translational velocity at which the slug unit is traveling, and v_{f} is the liquid velocity in the film zone.

In summary, the total turbulent kinetic energy in the liquid slug can be estimated as

$$E_{\mathrm{T}} = \frac{3}{2}\left(\frac{f_{\mathrm{s}}}{2}\rho_{\mathrm{s}} v_{\mathrm{m}}^2 + \frac{d}{4}\frac{\rho_{\mathrm{L}} H_{\mathrm{Lf}}(v_{\mathrm{t}} - v_{\mathrm{f}})(v_{\mathrm{m}} - v_{\mathrm{f}})}{l_{\mathrm{s}}}\right) A H_{\mathrm{Ls}} l_{\mathrm{s}}. \tag{11}$$

It is assumed that the total surface free energy of the discrete gas bubbles, based on the maximum amount of gas the liquid slug can hold, is proportional to the total turbulent kinetic energy in the slug body. Then,

$$E_{\mathrm{T}} = C_{\mathrm{e}} E_{\mathrm{S}} \tag{12}$$

or

$$\frac{3}{2}\left(\frac{f_{\mathrm{s}}}{2}\rho_{\mathrm{s}} v_{\mathrm{m}}^2 + \frac{d}{4}\frac{\rho_{\mathrm{L}} H_{\mathrm{Lf}}(v_{\mathrm{t}} - v_{\mathrm{f}})(v_{\mathrm{m}} - v_{\mathrm{f}})}{l_{\mathrm{s}}}\right) H_{\mathrm{Ls}} = C_{\mathrm{e}}\frac{6\sigma}{d_{\mathrm{b}}}(1 - H_{\mathrm{Ls}}). \tag{13}$$

As mentioned previously, the gas phase is accommodated in the slug body as dispersed spherical bubbles. There is a critical bubble diameter above which the bubbles will be deformed (or broken up by the turbulent forces) and the rise velocity is constant. This critical diameter was first proposed by Brodkey (1967) and then modified by Barnea et al. (1982) as

$$d_{\mathrm{c}} = 2\left(\frac{0.4\sigma}{(\rho_{\mathrm{L}} - \rho_{\mathrm{g}})g}\right)^{1/2}, \tag{14}$$

where g is the gravity acceleration. Corresponding to the maximum amount of gas the liquid slug can accommodate, the above critical diameter is taken as the average diameter of the bubbles dispersed in the slug body. Then, from Eqs. (13) and (14), the liquid holdup in the slug body can be calculated with

$$H_{\mathrm{Ls}} = \frac{1}{1 + \frac{T_{\mathrm{sm}}}{3.16[(\rho_{\mathrm{L}} - \rho_{\mathrm{g}})g\sigma]^{1/2}}}, \tag{15}$$

where

$$T_{\mathrm{sm}} = \frac{1}{C_{\mathrm{e}}}\left[\frac{f_{\mathrm{s}}}{2}\rho_{\mathrm{s}} v_{\mathrm{m}}^2 + \frac{d}{4}\frac{\rho_{\mathrm{L}} H_{\mathrm{Lf}}(v_{\mathrm{t}} - v_{\mathrm{f}})(v_{\mathrm{m}} - v_{\mathrm{f}})}{l_{\mathrm{s}}}\right]. \tag{16}$$

T_{sm} has the same units as shear stress and includes the wall shear stress and the contribution from momentum exchange between the liquid slug and the liquid film in a slug unit.

Liquid holdup (H_{Lf}) and velocity in the film zone (v_{f}) of a slug unit are required in order to calculate the slug liquid holdup by use of Eq. (15). These parameters can be obtained by solving the momentum and continuity equations for slug flow. At the same time, the slug translational velocity, slug length, friction factors (wall and interfacial) must be given for both slug dynamics and calculation of the slug liquid holdup. The detailed solution procedures and the selection of all the closure relationships can be found in Zhang et al. (2000).

It appears that the coefficient C_e in Eq. (12) is dependent on pipe inclination angle. Due to the buoyancy of the gas bubbles in the liquid slug, it is easier for the gas phase to be kept in the slug body during vertical flow than during horizontal flow. Therefore, based on experimental results it is proposed that

$$C_e = \frac{2.5 - |\sin(\theta)|}{2}, \tag{17}$$

where θ is the pipe inclination angle from horizontal. Clearly, C_e will change from 0.75 to 1.25 and then to 0.75, corresponding to vertical downward to horizontal and then to vertical upward flow.

According to the analyses of Taitel et al. (1980) and Barnea and Brauner (1985), slug lengths of $32d$ and $16d$ are used for horizontal and vertical flows, respectively. For inclined flow, the slug length is estimated as

$$l_s = \lfloor 32.0\cos^2(\theta) + 16.0\sin^2(\theta) \rfloor d. \tag{18}$$

Liquid holdup in the slug body is also a required closure relationship to solve the momentum and continuity equations of slug flow. An initial estimation for the slug liquid holdup is made by use of the Gregory et al. (1978) correlation,

$$H_{Ls} = \frac{1}{1 + \left(\frac{v_m}{8.66}\right)^{1.39}}, \tag{19}$$

where v_m is in m/s. Two to three iterations are necessary to obtain a converged value from the initial estimate.

3. Comparisons with experimental results

3.1. Slug liquid holdup

The model for slug liquid holdup developed in the last section is compared with experimental results acquired at TUFFP from 1977 to 1996 for slug flows at different inclination angles. The experimental results include data from Schmidt (1977) for vertical upward flows in a 51-mm (2-in.) diameter pipe, Kouba (1986) for horizontal flows in a 77.9-mm (3-in.) diameter and 425-m long pipe, Felizola (1992) for upward inclined flows in a 51-mm (2-in.) diameter pipe, and Roumazeilles (1994) and Yang (1996) for horizontal and downward inclined flows in a 51-mm (2-in.) diameter pipe. All these studies used kerosene and air as the two phases and the tests were carried out with ambient temperature and atmospheric pressure at the gas/oil separator. The kerosene and air densities at the test sections were $\rho_L = 814$ kg/m^3 and $\rho_g = 3$ kg/m^3, respectively. The dynamic viscosities of the two phases were $\mu_L = 0.0019$ kg/ms and $\mu_g = 0.000019$ kg/ms. The surface tension of kerosene was $\sigma = 29$ dyn/cm. The slug liquid holdups were measured with capacitance sensors.

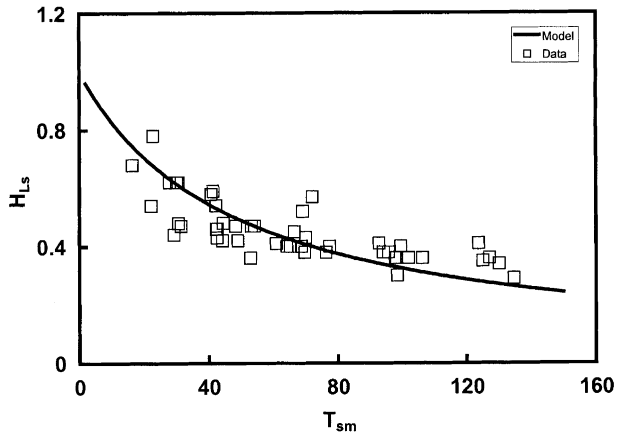

Fig. 1. Model prediction of slug liquid holdup compared with Schmidt (1977) data ($d = 51$ mm, $\theta = 90°$).

Fig. 1 shows a comparison between predicted slug liquid holdup and the measured values by Schmidt (1977) for vertical upward slug flows. Although the experimental data appear scattered, the trends of the model and the data agree very well. Good agreement is also observed between model prediction and Kouba (1986) measurements for horizontal slug flows (see Fig. 2).

Felizola (1992) measured slug liquid holdup in upward inclined flows from horizontal to vertical. In Fig. 3, comparison is made between the model and data for upward inclination angles of 10°, 30°, 50° and 70°. Most of the measurements are slightly lower than the model predictions.

Roumazeilles (1994) and Yang (1996) measured liquid holdup and pressure drop for horizontal and downward slug flows. Fully developed slug flow was not observed from −50° to −90° for the investigated flow rate ranges. Fig. 4 shows the comparison between their measurements of slug liquid holdup and the model predictions for horizontal flows. The agreement is excellent. For flows at downward −30°, Fig. 5 also shows good agreement, except the experimental results are slightly lower than model predictions.

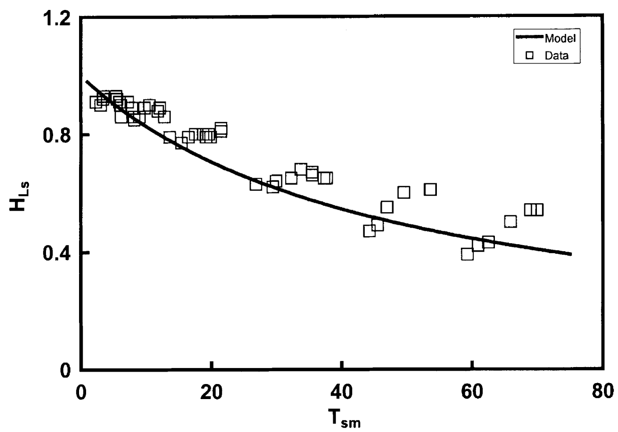

Fig. 2. Model prediction of slug liquid holdup compared with Kouba (1986) data ($d = 77.9$ mm, $\theta = 0°$).

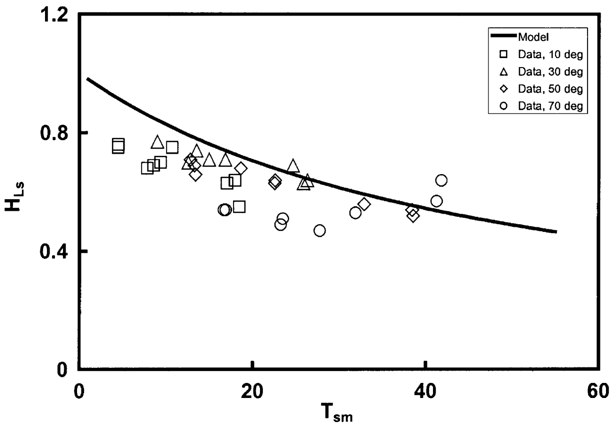

Fig. 3. Model prediction of slug liquid holdup compared with Felizola's (1992) data ($d = 51$ mm, upward inclined).

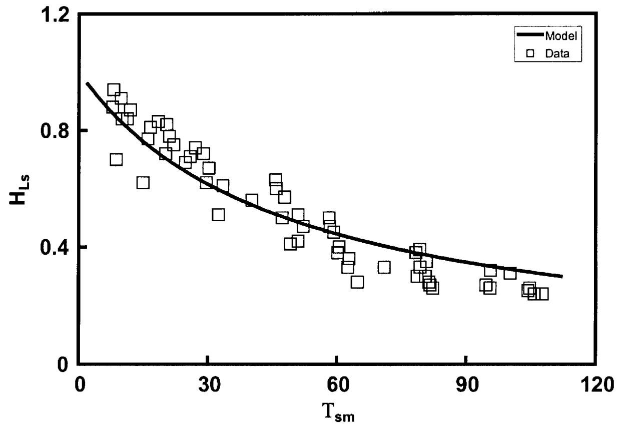

Fig. 4. Model prediction of slug liquid holdup compared with Yang (1996) and Roumazeilles (1994) ($d = 51$ mm, $\theta = 0°$).

It should be mentioned that the accuracy of the capacitance sensors in measuring liquid holdup depends on the phase distribution of the flow, and fluid and environmental temperatures. If the phase distribution is different from the calibration condition or the fluid and environmental temperatures change during the test, a significant shift can occur in the output from the capacitance sensor. These influences were inevitable during the tests and measurement uncertainties were possible, especially for the early studies. However, it is shown from the comparisons that the model can predict the change trends of slug liquid holdup with respect to the turbulent intensity in the liquid slug as a result of the overall dynamics of the slug flow.

3.2. Boundary of dispersed bubble flow

The unified model for slug liquid holdup can also be used to predict the flow pattern boundary between slug and dispersed bubble flows. This follows the Barnea and Brauner (1985) approach of

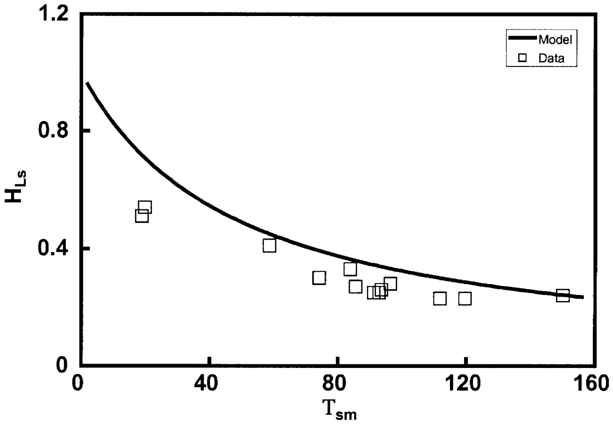

Fig. 5. Model prediction of slug liquid holdup compared with Yang (1996) and Roumazeilles (1994) ($d = 51$ mm, $\theta = -30°$).

using the slug–dispersed bubble flow boundary model to predict slug liquid holdup based on a hypothesis that the gas within the developed liquid slugs behaves as (saturated) dispersed bubbles. The liquid slugs accommodate the same gas holdup as the dispersed bubble flow on the transition boundary with the same mixture velocity. At the transition boundary between slug and dispersed bubble flows, the film zone of slug flow disappears. Therefore, the mixing term in Eq. (11) becomes zero. Corresponding to a superficial gas velocity, the superficial liquid velocity can be obtained by solving Eq. (13). The slug liquid holdup is then the liquid holdup of dispersed bubble flow, which is calculated assuming the gas and liquid phases flow with the same velocity.

In Fig. 6, the predicted transition boundaries are compared with experimental data for an air–water system in a 25.4-mm (1-in.) diameter pipe (Shoham, 1982) over the entire range of inclination angles, including horizontal, upward inclined, upward vertical, downward inclined and downward vertical flows. The model gives good predictions for the transition to dispersed bubble flow when the superficial gas velocities are greater than 0.1 m/s.

Good agreement is also observed between model predictions and experimental results for flows in a 51-mm (2-in.) diameter pipe at different inclination angles (see Fig. 7) when the superficial gas velocities are larger than 0.1 m/s. At superficial gas velocities below 0.1 m/s, the transition boundary can be predicted using Barnea (1987) model, which is based on Hinze's (1955) correlation at negligible gas holdup. Since the superficial gas velocity is normally greater than 0.1 m/s, the unified model proposed in this study can be applied for most situations.

4. Concluding remarks

Slug liquid holdup changes significantly from downward to horizontal, and to upward flows. The present unified mechanistic model is based on the balance between the turbulent kinetic energy of the liquid phase and the surface free energy of dispersed spherical gas bubbles that the turbulent liquid can hold. The momentum exchange between the liquid slug and the liquid film in a slug unit is employed in addition to the wall shear stress in estimating the turbulent kinetic

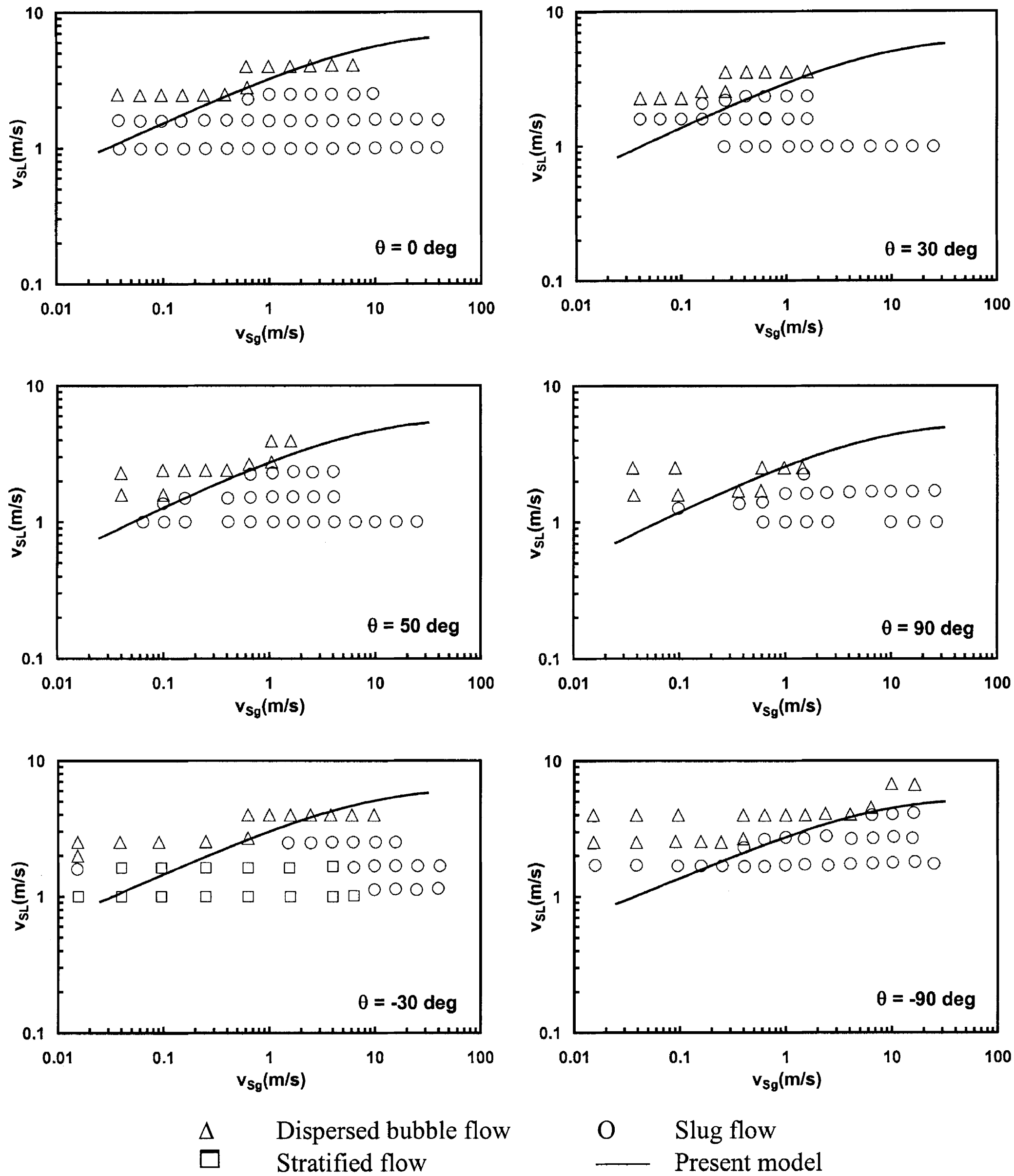

Fig. 6. Model predicted flow pattern transition boundaries from slug to dispersed bubble flows compared with experimental results of Shoham (1982) (air–water, 25.4 mm ID, 1.0 bar, 25 °C).

energy. At different inclination angles, the liquid film holdup and the velocity difference between film and slug are very different. Therefore, the momentum exchange term varies significantly with the pipe inclination. Introduction of the momentum exchange term enables the model to give an accurate prediction of slug liquid holdup for the entire range of pipe inclination angle and at different flow rates.

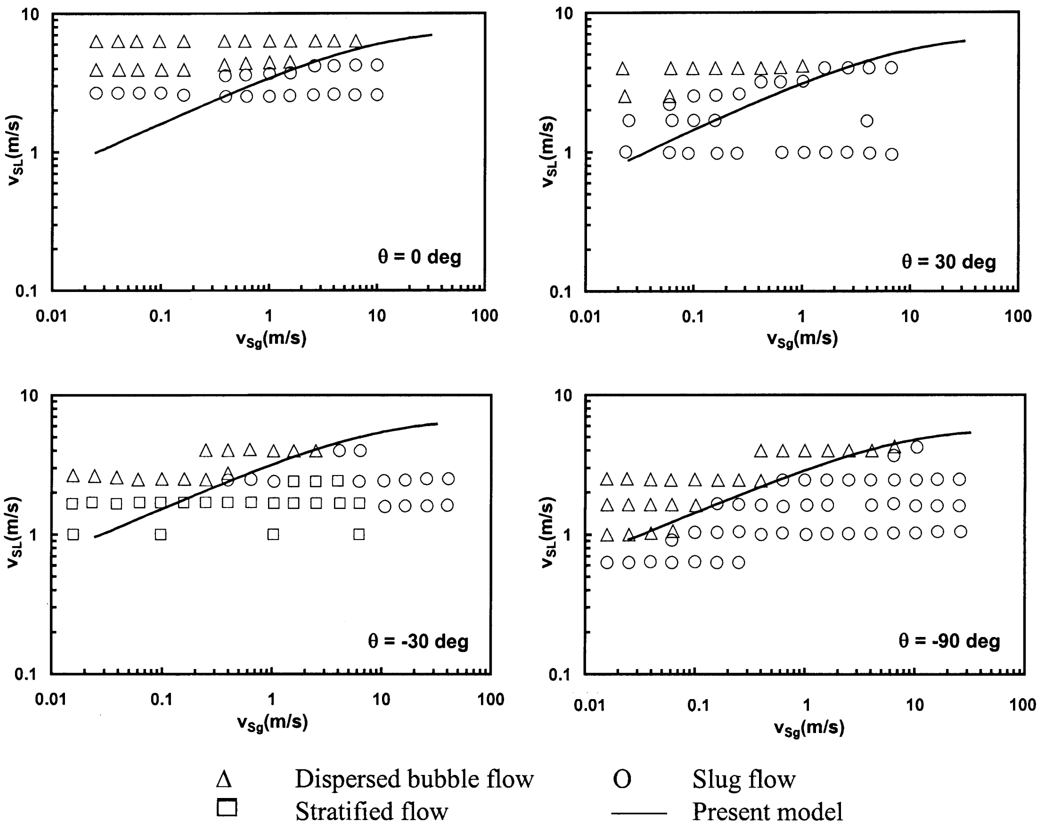

Fig. 7. Model predicted flow pattern transition boundaries from slug to dispersed bubble flows compared with experimental results of Shoham (1982) (air–water, 51 mm ID, 1.0 bar, 25 °C).

In the present model, slug liquid holdup is interrelated with slug flow characteristics and can be calculated after solving the momentum and continuity equations for slug flow. The model can also be used to predict the transition boundaries between slug and dispersed bubble flows at different inclination angles and flow rates based on the hypothesis that the liquid slugs accommodate the same gas holdup as the dispersed bubble flow on the transition boundary with the same mixture velocity.

The model has been compared with experimental data for different pipe diameters and inclinations from downward, horizontal to upward vertical. Good agreement has been observed in predictions of slug liquid holdup as well as the transition boundaries between slug and dispersed bubble flows.

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