Stratified Roll Wave in Horizontal-Pipe Two-Phase Flow

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The flow regime map presented uses dimensionless correlating parameters and allows for the accurate prediction of the occurrence of the stratified roll wave regime in horizontal two-phase pipe flow. Transitional boundary relationships that delineate the roll wave regime from other neighboring patterns, such as the stratified ripple and film plus droplet conditions, are given. The two-phase data followed a relationship that was dependent only on the map correlation parameters and the superficial liquid velocity. This map, together with recent developments by others [e.g., Watterson et al., *Ind. Eng. Chem. Des.*, **2002**, *41*, 6621 and *Dev. Chem. Eng. Min. Process.*, **2003**, *11*, 107; Spedding and Cooper, *Int. J. Heat Mass Transfer*, **2002**, *45*, 219; Spedding et al., *Dev. Chem. Eng. Min. Process.* **2003**, *11*, 95] allows for prediction of the major two-phase parameters, such as holdup and pressure drop, for the stratified roll wave regime.

Introduction

The stratified roll wave regime is one of the more important flow conditions found in horizontal multiphase pipeline flow. Many attempts have been made to predict the presence of the flow pattern. Transitional boundary models and flow regime maps of various types have been proposed to predict the stratified roll wave pattern. However, Spedding and Spence[1] have shown that all models failed when tested against reliable data. One of the main problems was the inability to handle the effect of geometrical changes in diameter. Both McBride[2] and Donnelly[3] have suggested the use of suitable combinations of dimensionless groups as mapping parameters; however, as Spedding et al.[4] have shown, a measure of the effect of diameter still remains. In this work, the problem of devising a regime map that handles geometrical variations is revisited using a new dimensionless group.

The prediction of the main two-phase parameters of holdup and pressure drop has proven to be intractable until recently, when Watterson et al.[5] detailed an iterative momentum balance model that was dependent on an initial rough estimation of both holdup,[6]

$$\left[\frac{\rho_L(V_{SL}/R_L)^2}{\rho_G(V_{SG}/R_G)^2}\right]^{0.5} = 3.65{V_{SL}}^{0.28} \tag{1}$$

and interfacial length,

$$\log\left(\frac{S_i}{S_L}\right) = (0.2626{V_{SL}}^{-0.3501}) \log V_{SG} - 0.4929{V_{SL}}^{0.4059} \tag{2}$$

The iteration was first performed for an assumed angle of wetting, α, using the actual phase velocities, V_G and V_L. Another iteration was then performed to determine the minimum point at the balance of forces for the system where the holdup and pressure drop can be found. Spedding et al.[7] have further details of the method, while Watterson et al.[8] have presented a theoretical basis for eq 1. The method predicted both pressure drop and holdup within a few percent, when tested against a wide range of reliable stratified roll wave data. However, the prediction was possible only because the holdup for the stratified roll wave regime was independent of diameter. This was not the case for other flow patterns such as the film plus droplet or stratified ripple regimes, where the momentum balance model that is outlined ceases to apply. Therefore, to use the above momentum balance method, it is vital to be able to identify correctly the presence of the stratified roll wave regime. This forms the subject of this work.

Flow Regime Map

A universal flow regime map, which enabled the flow patterns to be handled for the entire range of horizontal pipe flow data, was developed. The map was initially determined empirically, using a cluster of dimensionless groups. However, there exists a theoretical basis for the map, which will be the subject of future work.

The mapping parameters and dimensionless groups were as follows:

$$We_{SG} = \frac{\rho_G {V_{SG}}^2 d\sqrt{\beta_G}}{\sigma} \tag{3a}$$

$$We_{SL} = \frac{\rho_L {V_{SL}}^2 d\sqrt{\beta_L}}{\sigma} \tag{3b}$$

$$Re_{SG} = \frac{\rho_G V_{SG} d\sqrt{\beta_G}}{\mu_G} \tag{4a}$$

$$Re_{SL} = \frac{\rho_L V_{SL} d\sqrt{\beta_L}}{\mu_L} \tag{4b}$$

$$Fr_{SG} = \frac{{V_{SG}}^2 \beta_G}{gd} \tag{5a}$$

$$Fr_{SL} = \frac{{V_{SL}}^2 \beta_L}{gd} \tag{5b}$$

$$\beta_G = \frac{Q_G}{Q_L}$$

$$\beta_L = \frac{Q_L}{Q_G} \tag{6}$$

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$$Co = \frac{\sigma \rho_G d}{\mu_G{}^2} \tag{7}$$

$$X = \left[\frac{(We_{SG} Re_{SG} Fr_{SG} \beta_G{}^{1.5})^{0.5}}{Re_{SL}}\right]^{0.8} Co^{1/3} \tag{8}$$

$$Y = \frac{(We_{SL} Re_{SL} Fr_{SL} \beta_L{}^{1.5})^{0.5}}{Co^{1/3}} \tag{9}$$

Figure 1 gives the relevant truncated form of the map with the stratified roll wave data obtained under various conditions for diameters of 0.09525 and 0.02515 m,[9] 0.0935 m,[10] 0.052 m,[11] 0.0508 m,[12] 0.0454 m,[13,14] and 0.0259 m.[1,2]

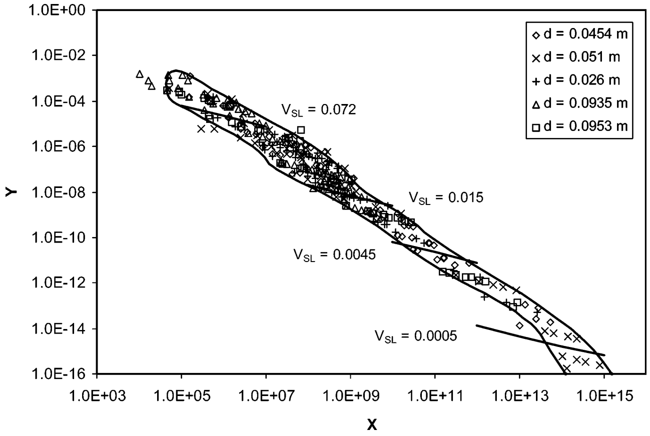

Figure 1. Universal flow regime map for a horizontal stratified roll wave. Constant superficial liquid velocity data fall on the oblique full lines.

The stratified roll wave data were contained in a narrow band extending over a wide range of the mapping parameters, thus allowing for a considerable accuracy in prediction. The transitional boundaries enclosing the map area included the stratified ripple to stratified roll wave and the film plus droplet to stratified roll wave.

A. Stratified Ripple to Stratified Roll Wave.

$$\log Y = -\frac{7}{6} \log X + 1.5 \tag{10}$$

for Y values in the range of $10^{-3}-10^{-13}$, and

$$\log Y = -2.31 \log X + 16.45 \tag{11}$$

for Y values of $10^{-13}-10^{-16}$ and below.

B. Film plus Droplet to Stratified Roll Wave.

$$\log Y = -1.25 \log X + 4.0 \tag{12}$$

for Y values in the range of $10^{-3}-10^{-13}$, and

$$\log Y = -2.486 \log X + 21.802 \tag{13}$$

for Y values of $10^{-13}-10^{-16}$ and below. Beyond $Y = 10^{-3}$, the slug and blow-through annular slug regimes were in evidence.

The stratified roll wave data lay on obliquely sloped lines across the mapped region, which were dependent only on the liquid velocity (and not on diameter). These formed the relation

$$\log Y = -0.4775 \log X + 3.017 \log V_{SL} + 1.6593 \tag{14}$$

Conclusions

A detailed examination of existing flow regime maps, using reliable two-phase data obtained for widely varying conditions, has shown that none can yield accurate predictions. It proved particularly difficult to accommodate the geometrical effect of varying pipe diameter. A universal map that correctly predicts the horizontal pipe stratified roll wave regime is presented. This pattern was chosen because recent development allows for accurate prediction of both holdup and pressure drop using a momentum balance. It was possible to obtain the balance because the holdup proved to be independent of pipe diameter.

Detail is presented for the transitional boundaries of the stratified roll wave regime. In addition, the data are shown to follow a general relation linking the mapping parameter with superficial liquid velocity.

Nomenclature

Co = diameter correction factor
d = diameter (m)
Fr = Froude number
g = acceleration due to gravity (m/s^2)
Q = volumetric flow rate (m^3/s)
R = holdup
Re = Reynolds number
S = perimeter length (m)
V = velocity (m/s)
We = Weber number
X = mapping parameter, as given by eq 8
Y = mapping parameter, as given by eq 9
α = suspended angle of wetting (degrees)
β = input volumetric ratio
μ = viscosity (kg/(ms))
ρ = density (kg/m^3)
σ = surface tension (kg/s^2)

Subscripts

G = gas
i = interface
L = liquid
S = superficial

Acknowledgment

Thanks are due to Jonathan Cole.

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