EFFECT OF PIPE DIAMETER ON FLOW PATTERN TRANSITION IN VERTICAL OIL WATER FLOWS

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ABSTRACT
This paper investigates the effect of pipe diameter on flow pattern transition boundary in oil water vertical flows, and proposes a model to determine the maximum inner diameter(Din) of a pipe in which the slug flow would not occur. When pipe inner diameter D > D_in, only bubble flow exists, while D < D_in, both bubble flows and slug flows are existent. The method of estimating D_in is validated in oil water two phase flow in two pipes with inner diameters of 19mm and 125mm. The result indicates that fluid property and the pipe diameter play an important role in flow pattern transition from bubble flows to slug flows.
Keywords: two phases flow, pipe diameter, flow pattern

1. INTRODUCTION
The identification and prediction of flow patterns in a multiphase environment are significant. Traditionally, predicting flow patterns was first approached through empirical correlations because of the complex nature of multiphase flows in pipes. From the study history of vertical multiphase flows which was summarized by Brown [11], the majority experiments were performed in mini-type facilities, and the diameters of test pipes were from 1" to 4". Only minority researchers expanded the range of pipe diameter to 6" in local experimentation. Hewitt [21], Taitel [3], and Willis [6] etc. studied flow pattern prediction models and introduced mechanistic approaches. They gave transition models between different flow patterns in air water two-phase flow systems. Their research involved bubble size, bubble velocity and flow pattern in bubble flow, but they didn't specially study the effect of pipe diameter on flow pattern.

Govier et al. [5] experimentally studied and identified four distinct flow patterns for vertical oil and water upward flow in a 1.038in pipe: bubbly, slug, churn, and mist. However, Zavareh et al. [6] also tested oil and water upward flow in a 7.25in pipe. He didn’t observe slug flow, just four bubble flow patterns were observed: bubble, dispersed bubble, inverted bubble, and inverted dispersed bubble. Cheng [7] investigated the structure of upwards air-water flow in different diameter. The result showed that traditional slug flow did not exist in the 150 mm diameter column. Instead, there was a gradual transition and the reason remains unclear. But in 28.9 mm column, bubble flow suddenly transitioned to slug flow as gas rate increasing at constant liquid rate. Zhong [8-9] re-classified oil/water flow patterns by using direct measurement in 125 mm vertical pipe based on multiphase flow loop experiments. The experimental results showed that the proposed flow pattern identification criterion could not be applied to other pipes with different diameters because of the scale effect to flow patterns in different diameter vertical pipes. Because most experimental data were acquired in small diameter air-water systems, and most prior work had been confined to air bubbles in water. It was very difficult using empirical flow pattern maps to predict flow patterns. Thus, the applicability of these results is unknow for most petroleum systems, which are large diameter, producing crude oil water and gas mixtures. Up to now, there are not the flow pattern experiments performed in a full-scale. Therefore, it was discussed that effect of pipe diameter on flow pattern transition in vertical flow.

The main purpose of this study is to develop a model to predict maximum pipe diameter (D_in) in which the slug flow...
will not occur. If the equivalent bubble diameter exceeds the tube diameter, the slug flow will occur. A new criterion of pipe diameter is presented for the transition from bubble to slug flow based on the relationships between bubble property and pipe inner diameter. The proposed model was evaluated by experimental data, and better agreed with the measurement in the pipes of 19mm and 125mm oil-water vertical flow.

2. NUMERICAL METHOD THE RISE VELOCITY OF SIGNAL BUBBLE IN VERTICAL PIPE

Bubble flow is characterized by bubbles which are small compared to the tube inner diameter, dispersed more or less randomly in the liquid continuum within the tube, while slug flow is characterized by Taylor bubble separated by slugs of continuous liquid. The transition between the bubble flow to slug flow does not occur suddenly. The effects of fluid property and pipe condition on flow pattern transition are very complex. For this reason it is especially important that fluid property, bubble size, bubble velocity, and pipe diameter for prediction slug flow occurs.

2.1 Sphere Bubble

The spherical bubble will be formed when surface tension is greater than gravity (or buoyant) and inertia force in two-phase flow. There is a pressure difference between the inside and outside surfaces of a bubble. The greater the pressure difference is, the more spherical the bubble is. The classic work on sphere bubble velocity is that of Stokes. In the Stokes approach the resistance to motion (drag) is taken to be the theoretical expression for a small solid sphere. According to the Archimedes buoyant force principle, when drag forces and buoyant are balance, the single sphere bubble terminal rise velocity is:

\[ V_b = \frac{4 \, g \, \delta \, \rho_s (\rho_b - \rho_l)}{3 \, C_d \, \rho_b} \]  

(1)

Where \( C_d \) is the drag forces coefficient.

2.2 Mushroom Bubble

Neglecting surface tension and viscosity force, the single mushroom bubble rise velocity is\(^{[10]}\)

\[ V_r = 0.715 \sqrt{\frac{g \Delta \rho \, d}{\varepsilon \, \rho_l}} \]  

(2)

This kind of bubble will be happened in the high viscosity continuous phase. The bubble shape will directly transform from sphere to mushroom while bubble size of discrete phase increase. The rise velocity depends on bubble size, fluid density and independent of pipe diameter.

2.3 Taylor Bubble

A Taylor bubble is a constant pressure surface, whose shape is that of a cylinder bounded on top by a spherical cap or a bullet shaped nose, and at the bottom by a distorted flat tail. The mean diameter of the bubble cylinder is almost equal to tube diameter (about 0.75D), and the length is at least one tube diameter. Between the Taylor bubble and the pipe wall, liquid flows downward in the form of a thin falling film. There are often small bubbles in the slug of liquid following the Taylor bubble. The rise velocity of the Taylor bubble on the other hand is given by\(^{[5]}\)

\[ V_T = 0.328 \sqrt{gD} \]  

(3)

The rise velocity of Taylor bubble depends on gravity acceleration, pipe diameter but independent of bubble size.

2.4 The Maximum Rise Velocity of Bubble

The terminal rise velocity could be predicted by an equation of the form\(^{[10]}\)

\[ V_\infty = 1.5 \sqrt{g \Delta \rho \sigma / \rho_b^2} \]  

(4)

Some early works were that the density difference alone would be sufficient for estimation of terminal rise velocity. A very important aspect of equation (4) is that it is independent of bubble diameter. Fig. 1 shows that effect of bubble size on terminal velocity in static water\(^{[11]}\). The experimental result shows that there is a value of critical bubble size at which the terminal velocity has a maximum in liquid-liquid two-phase flow. When bubble diameter is about 0.7 cm, the measured velocity has a maximum of 14.8 cm/s. The measured velocity is smaller than estimated velocity of 15.2 cm/s.
(\(\rho = 1.002 \text{g/cm}^3, \sigma = 0.773 \text{g/cm}^3, \sigma = 0.0435 \text{N/m}\)). In other words, the maximum velocity can be estimated from equation (4).

3. THE EFFECT OF PIPE DIAMETER ON TRANSITION FROM BUBBLE TO SLUG FLOW

Table 1 shows the effect of pipe diameter on flow patterns. Schleumberger tested the result of oil/water flow pattern in four pipes with internal diameter D of 4", 5.5" and 7.625", and 9.625"\(^{(11)}\). Flow pattern from O/W to W/O depends on relative flow rate in the same pipe. While water flow rate keeps a constant and change oil flow rate, the transition boundary of W/O and O/W is changeable in different pipe. Furthermore, the more oil flow rate is needed when the pipe diameter is increasing if the flow patterns change from W/O to O/W. For bubble flow, the experiment shows that there is a maximum or minimum pipe diameter express as the existence criterion. This criterion is based on the comparison between rise velocity of elongated bubbles and small bubbles. When equivalent bubble diameter is greater than pipe’s, slug flow will occur. Fig. 2 illustrates the schematic graph of one kind of bubble flow has a different flow pattern in different pipe diameter. There are two critical pipe diameter, the smaller one is the minimum pipe diameter (\(D_{\text{bubble}}\)) and the larger one is the maximum pipe diameter \(D_{\text{slug}}\). While \(D_{\text{bubble}} < D < D_{\text{slug}}\), both of bubble and slug flow exist in the pipe. The flow patterns mainly depend on individual phase flow rate and pipe condition. But when \(D > D_{\text{slug}}\), only bubble flow occurs, and \(D < D_{\text{bubble}}\) only slug flow exists. Therefore, bubble flow is observed only in relative large-diameter pipe and slug flow is observed only in relative small-diameter pipe.

<table>
<thead>
<tr>
<th>Table 1 Effect of pipe diameter on flow pattern</th>
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<tr>
<td>Pipe size &quot;</td>
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<tr>
<td>-------------</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5 1/2</td>
</tr>
<tr>
<td>7 5/8</td>
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<tr>
<td>9 5/8</td>
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</table>

1 \(b/d = 0.159 \text{m}^3/\text{d}\)

\(K_w\): water cut.

W/O: Oil is continuous phase.
O/W: Water is continuous phase.

4. DETERMINING MAXIMUM PIPE DIAMETER \(D_{\ast}\)

Taitel et al.\(^{(3)}\) suggested that whenever terminal velocity \(V_{\ast}\) is greater than Taylor bubble \(V_T\), the discrete bubble approaches the back of the Taylor bubble and coalescence occurs. Under these conditions bubble flow cannot exist. On the other hand when \(V_{\ast} < V_T\), the Taylor bubble rise through an array of discrete bubble and the relative motion of liquid at the nose of Taylor bubble sweep the small bubbles around the large one, and coalescence does not take place. This phenomenon allows the existence of the bubble flow pattern. Assumed \(D_{\ast}\) is the corresponding maximum pipe diameter in which slug flow does not exist. Therefore, combining equation (3) and (4), only the bubble flow exists in pipe when \(D > D_{\ast}\), \(D_{\ast}\) is given by
Therefore, equation (5) may be used to predict the upper-limit pipe diameter between bubble and slug flow for vertical upward flow conditions. Fig. 3 shows the relationship between \( D_{\text{ub}} \) and fluid density difference. The boundary shown in Fig. 3 can served as a basis for an upper-limit pipe diameter estimation. According to Fig. 3, the bubble property and, more importantly, the difference in density between the light and heavy-fluid phases seem to determine the upper-limit pipe diameter.

5. EXPERIMENTAL RESULTS AND ANALYSIS

Two sets of experiments data were obtained from a full-scale pipe located at DLTS (Daqing Logging and Test Service Company). The bubble rise velocity is estimated by water holdup, and water holdup is measured by fast close valve. The bubble velocity approximates to terminal velocity \( V_m \) as water hold up increasing. The test fluid is water and kerosene, and \( \rho = 1.002 \text{g/cm}^3 \), \( \mu = 0.890 \text{ Pa \cdot s} \), \( \sigma = 0.07125 \text{N/m} \), \( \rho = 0.834 \text{g/cm}^3 \), \( \mu = 3.0 \times 10^{-3} \text{ Pa \cdot s} \), \( \sigma = 0.02862 \text{N/m} \), \( \sigma = 0.0486 \text{N/m} \). The estimated equivalent diameter of mushroom bubble from equation (2) is 14.95 mm at the average bubble velocity is 11.14 cm/s when water hold up greater than 0.98. From equation (5) and fluid parameters, we can estimate maximum pipe diameter \( D_{\text{ub}} = 19.6 \text{mm} \). In another words, when pipe diameter is greater than 19.6 mm, only bubble exists. According to definition of Taylor bubble, the equivalent bubble diameter greater 0.75D=14.7 mm if slug flow occurs in 19.6 mm pipe.

![Fig. 3 The relationship between upper-limit pipe diameter and fluid density difference](image)

![Fig. 4 oil and water in 125mm vertical pipe](image)

Fig 4 shows the interface oil water bubble flow in 125 mm vertical pipe. Only bubble flow was observed in 125 mm pipe. The experimental diameter of spherical oil bubble from photograph is 1–6 mm, and mushroom bubble is 10–15 mm. The experimental results showed the maximum diameter 19.6 mm predicted from equation (5) has a good agreement with test pipe. Only bubble flow exists in 125 mm pipe, both bubble and slug flow exist in 19 mm pipe. The pipe diameter predicted from equation (5) can served as a flow pattern boundary between bubble and slug flow in oil water vertical flow. The improved relationships between pipe diameter and fluid property should be better to predict slug flow does not exist in a pipe. Both theoretical studies and experiments indicate that the fluid properties are not only the factors affecting flow pattern, flow pattern depends on pipe diameter, as well. If we look at the basic equation for sphere and mushroom bubble, we see that it is in fact related to bubble size, as it is to individual phase density. As the phase density or pipe diameter vary, it has been found that the flow pattern must adjust themselves to an equilibrium situation consistent with the densities, viscosities, and interracial tension of the fluids.

6. CONCLUSION

Based on the experimental results and qualitative analyses, it is found that the flow pattern transition from bubble to slug depends on the pipe diameter and fluid property. When pipe diameter \( D > D_{\text{ub}} \), only bubble flow exists. When \( D < D_{\text{ub}} < D_{\text{sb}} \), both of bubble and slug flow exist. From the improved model for predicting maximum diameter \( (D_{\text{ub}}) \), we
can estimate \( D_e \) and know whether slug flow will occur or not in the pipe. This study has confirmed that fluid property and pipe diameter is the key factor that causes the bubble-to-slug or slug-to-bubble transition in oil water upward vertical pipe.

REFERENCES


NOMENCLATURE

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<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>( C_d )</td>
<td>the drag forces coefficient</td>
<td>B (bubble)</td>
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<tr>
<td>( D )</td>
<td>pipe diameter</td>
<td>d (drag)</td>
</tr>
<tr>
<td>( D_{eq}, D_e )</td>
<td>the equi-pipe diameter</td>
<td>e (equivalent)</td>
</tr>
<tr>
<td>( d_e )</td>
<td>equivalent bubble diameter</td>
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<tr>
<td>( g )</td>
<td>acceleration of gravity</td>
<td>l (light)</td>
</tr>
<tr>
<td>( V_r )</td>
<td>the mushroom bubble rise velocity</td>
<td>r (mushroom)</td>
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<tr>
<td>( V_T )</td>
<td>Taylor bubble rise velocity</td>
<td>s (slug)</td>
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<tr>
<td>( V_\infty )</td>
<td>the maximum velocity at critical bubble size</td>
<td>T (Taylor)</td>
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<tr>
<td>( \rho_\infty )</td>
<td>heavy phase density</td>
<td>∞ (infinite)</td>
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<tr>
<td>( \rho_l )</td>
<td>light phase density</td>
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<tr>
<td>( \Delta \rho )</td>
<td>density difference ( (\rho_\infty - \rho_l) )</td>
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