Investigation on average void fraction for air/non-Newtonian power-law fluids two-phase flow in downward inclined pipes

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ABSTRACT

The present work has been carried out to investigate on the average void fraction of gas/non-Newtonian fluids flow in downward inclined pipes. The influences of pipe inclination angle on the average void fraction were studied experimentally. A simple correlation, which incorporated the method of Vlachos et al. for gas/Newtonian fluid horizontal flow, the correction factor of Farooqi and Richardson and the pipe inclination angle, was proposed to predict the average void fraction of gas/non-Newtonian power-law stratified flow in downward inclined pipes. The correlation was based on 470 data points covering a wide range of flow rates for different systems at diverse angles. A good agreement was obtained between theory and data and the fitting results could describe the majority of the experimental data within ±20%.

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1. Introduction

The simultaneous flow of gas–liquid two-phase through downward inclined pipes is encountered in a diverse range of processes industries and particularly in the petroleum industry. Because of the injection of polymeric substance into the well for increasing oil production, crude oil often shows the characteristics of non-Newtonian fluid. Therefore, oil production results in transportation of gas/non-Newtonian fluid two-phase flow over long distances. One of the critical unknown parameters involved in calculating the pressure gradient of two-phase flow is the void fraction. In recent years, considerable effort has been made to develop methods to predict the void fraction for gas/Newtonian fluid flow in inclined pipes [1–10]. Owing to the complexity and lack of understanding of the basic underlying physics of the problem, the majority of the analyses are suggested by using the empirical and semi-empirical correlations. Unlike gas/Newtonian fluid inclined flow [11–13], there are few studies for predicting the void fraction of gas/non-Newtonian fluid flow in inclined pipes [14–16], especially for inclined downward stratified flow. Therefore, the purpose of this work is to study experimentally the gas/non-Newtonian fluid two-phase flow in inclined downward pipe and then to develop a simple model to predict the average void fraction of gas/non-Newtonian stratified downward inclined flow based on experimental data.

2. Experimental set-up and fluid characteristics

The experimental investigation in this work was conducted using Perspex tubing of 60 mm in diameter. The tube includes two 10 m long pipe branches connected by a U-bend that could be inclined to any angle, from a completely horizontal to a fully vertical position. The gamma densitometer installed at 5 m from the entry point measured gamma ray absorption which allowed the mean average void fraction in the pipe to be calculated. The test section was scanned for five separate periods of 60 s to obtain an average value of the void fraction. The gamma ray densitometer was calibrated by scanning a Plexiglass box which contains several water to gas ratios and thus gave different void fraction values to be used as calibration points. Furthermore, to verify the experimental data of the gamma ray densitometer, the results from the gamma densitometer have been compared well with the results obtained using quick closing valves with an average difference for all conditions about 5%. Air originated from a compressor pump and was routed through a gas tank and regulating valve to maintain a constant pressure, after which it passed through a gas mass flow-meter. The liquid phase was conveyed from the liquid phase tank and circulated through the system by a centrifugal pump. The volumetric flow rates of all phases were regulated independently and measured by a thermal mass flow-meter for the gas phase and an electromagnetic flow-meter for the liquid phase, respectively. Flow patterns were recorded using a high-speed video camera, and the flow patterns for each test condition were recorded and observed later in slow motion. The details of the flow-loop could be found in the previous works [14].
Tap water was used as the Newtonian fluid and carboxymethyl cellulose (CMC) solutions with three different concentrations were used as the non/Newtonian fluids. As expected, CMC solutions in the present study were shear-thinning fluids whose rheology could be described by a two-parameter power-law fluid model. For a power-law fluid, the shear stress was related to the shear rate by:

\[ \tau = k(\dot{\gamma})^n \]  

(1)

where \( \dot{\gamma} \), \( k \) and \( n \) were referred to as the shear rate, the fluid consistency coefficient and the flow behaviour index, respectively. The appropriate Reynolds number can be defined as [17]:

\[ \text{Re}_{\text{str}} = \frac{D(Vl - Vc)}{\nu k(1/n)} \]  

(2)

where \( V \), \( D \) and \( \nu \) were the fluid velocity, the pipe diameter and the density of liquid phase, respectively. The values of \( k \), \( n \) and other properties of the CMC solutions were given in Table 1. For the fluids used in this work, the rheological behaviour of CMC solutions was measured before and after each run at constant liquid flow rate. The average deviation of the effective viscosity was less than 4.8%. Thus, the rheological behaviour of CMC solution can be assumed as constant when the concentration is fixed. A total of about 350 experimental data were measured for the average void fraction of five different inclination angles (\( \alpha = -0^\circ, -5^\circ, -15^\circ, -30^\circ, -75^\circ \)) in horizontal and downward pipes.

### Table 1

<table>
<thead>
<tr>
<th>Liquid phase</th>
<th>Concentration (kg/m)</th>
<th>Density, ( \rho ) (kg/m$^3$)</th>
<th>Surface tension, ( \sigma ) (N/m)</th>
<th>Fluid consistency coefficient, ( k ) (Pa.s$^n$)</th>
<th>Flow behaviour index, ( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>-</td>
<td>999.0</td>
<td>0.0712</td>
<td>0.001</td>
<td>1.000</td>
</tr>
<tr>
<td>CMC-1 solution</td>
<td>1.0</td>
<td>999.9</td>
<td>0.0714</td>
<td>0.089</td>
<td>0.798</td>
</tr>
<tr>
<td>CMC-2 solution</td>
<td>2.0</td>
<td>1000.0</td>
<td>0.0718</td>
<td>0.460</td>
<td>0.658</td>
</tr>
<tr>
<td>CMC-3 solution</td>
<td>3.0</td>
<td>1000.4</td>
<td>0.0727</td>
<td>0.972</td>
<td>0.615</td>
</tr>
</tbody>
</table>

\[ \text{Re}_{\text{str}} = \frac{Dq_{\text{sl}}}{Vc}n + \frac{\rho_l\bar{v}_{\text{eff}}}{\mu_l} = \text{Re}_{\text{str}} \]  

where \( q_{\text{sl}} \) and \( \bar{v}_{\text{eff}} \) are the superficial liquid velocity and the effective average void fraction in practical engineering applications.

### 3.2. Predicting model

One of the methods used mostly to predict the average void fraction in a gas–liquid stratified flow is the model of Taitel and Dukler [18] for gas/Newtonian liquid flow and extended by Heywood and Charles [19] and Xu et al. [14] for gas/non-Newtonian liquid horizontal and inclined flows, respectively. Due to the computational complexity, they are inconvenient for estimating the average void fraction in practical engineering applications. In the present work, we attempt to develop a simple method to predict the average void fraction for gas–liquid stratified inclined flow. The model suggested in this work bases on the method of Vlachos et al. [20] in horizontal stratified flow and accounts for the characteristics of non-Newtonian power-law fluid to predict the average void fraction.

For gas/Newtonian fluid two-phase stratified flow in horizontal pipes, Vlachos et al. suggested the dimensionless film thickness at the pipe bottom using the following empirical correlation:
Air/CMC-1 solution flow, \( V_{sl} = 0.75 \) m/s

\[ h = \frac{h}{D} = f(k, V_{sl}, V_{sg}) = k \left( \frac{V_{sl}^{0.35}}{V_{sg}^{0.65}} \right) \]  

where \( k = 1.5(m/s)^{0.33} \) and \( \hat{h} = h/D \) is the dimensionless film thickness in stratified flow. \( h \) and \( D \) are the average film thickness and the pipe diameter. Once the dimensionless film thickness is obtained, the average void fraction can be calculated by:

\[ \varepsilon = \frac{1}{\pi} \left[ \cos^{-1}(2\hat{h} - 1) - (2\hat{h} - 1)\sqrt{1 - (2\hat{h} - 1)^2} \right] \]  

For gas/non-Newtonian fluid horizontal flow, Farooqi and Richardson [21] modified the Lockhart–Martinelli parameter [22] to analyse experimental data. They proposed a correction factor defined as:

\[ J = \left( \frac{V_{sl}}{V_{c}} \right)^{1-n} \]  

where \( V_{c} \) is the critical value of superficial liquid velocity when laminar flow ceases to exist. This value can be estimated by setting the Reynolds number, calculated by using Eq. (2), equal to 2000. By introducing the correction factor \( J \) into the Lockhart–Martinelli parameter, they caused the holdup data of gas/non-Newtonian fluid to be corrected for annular flow.

\[ \epsilon = \frac{1}{\pi} \left[ \cos^{-1}(2\hat{h} - 1) - (2\hat{h} - 1)\sqrt{1 - (2\hat{h} - 1)^2} \right] \]  

Fig. 1. The average void fraction measured for air/CMC-3 solution flow in different downward inclined pipes at constant superficial liquid velocity.

Fig. 2. The average void fraction against inclination angles for air/CMC-3 solution flow at constant superficial velocities.

Fig. 3. Effects of viscosity on the dimensionless film thickness (\( \hat{h} \)) for gas–liquid downward inclined stratified flow at \( \alpha = -15^\circ \).

Fig. 4. Influences of both fluid viscosity and superficial liquid velocity on the correction factor of Farooqi and Richardson.

Fig. 5. The average void fraction predicted by the model against the average void fraction experimentally obtained in this work and for others systems reported in the literature: gas/Newtonian fluid system.
void fraction of gas/non-Newtonian fluid flow in downward inclined pipes. The correlation incorporated the method of Vlachos et al. for gas/Newtonian fluid horizontal flow, the correction factor of Farooqi and Richardson and the pipe inclination angle. The correlation was based on 470 data points covering a wide range of flow rates for different systems at diverse angles. A good agreement was obtained between the predicted and experimental results.

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References