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A Simple Model for Predicting the Void Fraction of Gas/Non-Newtonian Fluid Intermittent Flows in Upward Inclined Pipes

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In this work, a simple correlation, which incorporates the mixture velocity, drift velocity, and the correction factor of Farooqi and Richardson, was proposed to predict the void fraction of gas/non-Newtonian intermittent flow in upward inclined pipes. The correlation was based on 352 data points covering a wide range of flow rates for different CMC solutions at diverse angles. A good agreement was obtained between the predicted and experimental results. These results substantiated the general validity of the model presented for gas/non-Newtonian two-phase intermittent flows.

Keywords Multiphase flow; Non-Newtonian fluids; Upward inclined flow; Void fraction

Introduction

Prediction of the holdup is of great importance in process industries, especially in the petroleum industry, in which the estimate of production is intimately related with this parameter. It is well known that the holdup depends on the flow pattern. In recent years, considerable effort has been paid to develop methods to calculate the holdup for the intermittent flows of gas and Newtonian fluid (Lockhart and Martinelli, 1949; Zuber and Findlay, 1965; Bonnecaze et al., 1971; Mattar and Gregory, 1974; García et al., 2003, 2005). In these studies, empirical and semi-empirical correlations for predicting the holdup were presented depending on experimental data and diverse theoretical models. Unlike gas/Newtonian fluid two-phase flow, there are very few studies for predicting the holdup of the mixture flow of gas/non-Newtonian liquid due to its complexity (Farooqi and Richardson, 1982a,b; Das et al., 1992; Xu et al., 2007). In the chemical process industries, non-Newtonian liquids, especially pseudo-plastic (power-law) liquids, are encountered frequently. Several industrial applications utilize these liquid-gas mixtures flowing through horizontal and inclined pipes. Therefore, there is a need to understand in depth the hydrodynamics and transport behavior of non-Newtonian liquid-gas systems. The purpose of this work is to develop a simple model to predict the void fraction of gas/non-Newtonian intermittent flow in upward inclined pipes based on experimental data.

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Experimental Setup and Procedure

The experimental investigations were conducted using the setup shown in Figure 1. The multiphase flow pipeline was constructed using Perspex tubing 60 mm in diameter. The tube includes two 10 m long pipe branches connected by a U-bend that can be inclined to any angle, from a completely horizontal to a fully vertical position. Flow patterns were recorded using a high-speed video camera, and the flow patterns for each test condition were recorded to be observed later in slow motion. The gamma densitometer was installed 5 m from the entry point, which provides sufficient entrance length to stabilize the flow. The gamma densitometer measures gamma ray absorption, which allows the mean void fraction in the pipe to be calculated. During the measurement the device was aligned perpendicular to the flow with a ^{137}Cs source on the bottom half of the pipe; the detector, with an 8 mm diameter collimator on the top, is shown in Figure 2. The gamma ray densitometer was calibrated by scanning a Plexiglas box that contains several water-to-gas ratios and thus gives different void fraction values to be used as calibration points. The counting rate was integrated over 80 energy bands centered at the peak energy band of the 662 keV value generated from the ^{137}Cs scattering. The test section was scanned for five separate periods of 60 s to obtain an average value of void fraction. Due to the effect that different flow patterns have on the measurement, the experimental data has been further amended using the method proposed by Stahl and von Rohr (2004). Furthermore, the average void fractions from the gamma densitometer have been compared well with the results obtained using quick-closing valves with an average difference for all conditions of less than 5%.

Air originates from a compressor pump and is routed through a gas tank and a regulating valve to maintain a constant pressure, after which it passes through a gas

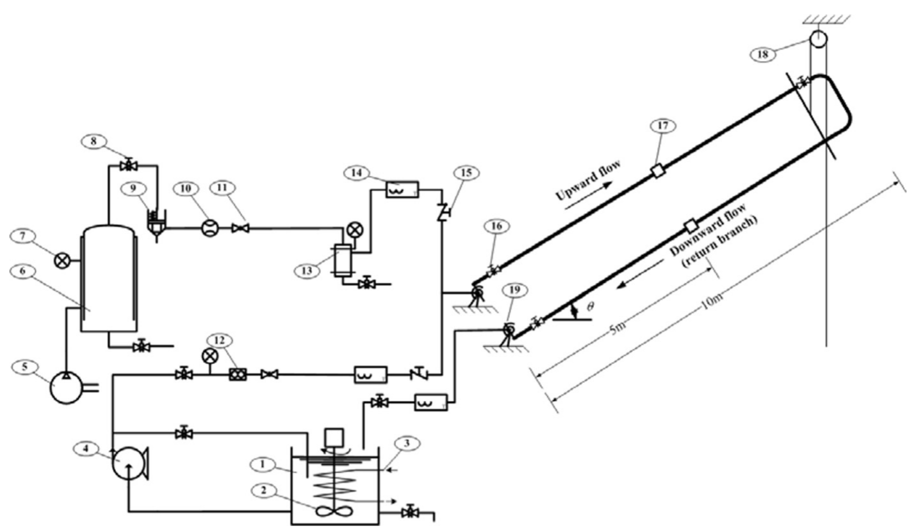

Figure 1. Schematic of the test facility: 1, liquid tank; 2, blender; 3, coils; 4, centrifugal pump; 5, air compressor; 6, gas tank; 7, pressure gauge; 8, control valves; 9, regulating valve; 10, thermal mass flow meter; 11, electromagnetic valve; 12, electromagnetic flow meter; 13, water trap; 14, thermometer; 15, check valve; 16, control valve; 17, gamma densitometer; 18, block and tackle; 19, gear wheel.

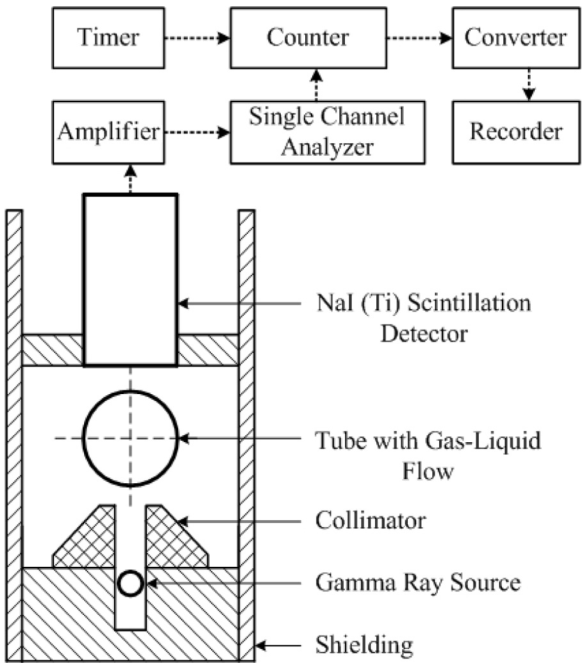

Figure 2. Schematic of the gamma densitometer.

mass flow meter. The liquid phase is conveyed from the liquid phase tank and circulated through the system by a centrifugal pump. The liquid phase and the gas phase are fed into the pipeline via a T-junction. The volumetric flow rates of all phases can be regulated independently and are measured by a thermal mass flow meter for the gas phase and an electromagnetic flow meter for the liquid phase. The details of the flow loop can be found in previous works (Xu et al., 2007).

Tap water is used as the Newtonian liquid phase and CMC (carboxymethyl cellulose) solutions with three different concentrations are used as the non-Newtonian liquid phases. As expected, CMC solutions in this study are shear-thinning fluids whose rheology can be described by a two-parameter power-law fluid model. For a power-law fluid, the shear stress is related to the shear rate by:

$$\tau = k(\dot{\gamma})^n \tag{1}$$

where $\dot{\gamma}$ is the shear rate, and k and n are two empirical curve-fitting parameters known as the fluid consistency coefficient and the flow behavior index, respectively. The appropriate Reynolds number can be defined as (Metzner and Reed, 1955):

$$\mathrm{Re}_{MR} = \frac{u \cdot \rho \cdot D}{\mu_{eff}} \tag{2}$$

where the effective viscosity, μ_{eff}, of the solution is measured in a pipeline viscometer and defined by the well-known equation:

$$\mu_{eff} = 8^{n-1} u^{n-1} D^{1-n} k \left(\frac{1+3n}{4n}\right)^n \tag{3}$$

Table I. Physical properties of the fluid measured at 20°C and 0.101 MPa

Liquid phase	Concentration C (Kg/mg^3)	Density, ρ (kg/m^3)	Surface tension, σ (N/m)	Fluid consistency coefficient, k (Pa·s^n)	Flow behavior index, n
Water	—	999.0	0.0712	0.001	1.000
CMC-1 solution	1.0	999.9	0.0714	0.089	0.798
CMC-2 solution	2.0	1000.0	0.0718	0.469	0.658
CMC-3 solution	3.0	1000.4	0.0727	0.972	0.615

The values of k, n, and other properties of the CMC solutions are given in Table I. A total of 352 experimental data were measured for the average void fraction of intermittent flow regimes in horizontal and upward inclined pipes, as shown in Table II.

Furthermore, the rheological behavior of CMC solutions was measured before and after each run at constant liquid flow rate. The average deviation of the effective viscosity, μ_{eff}, did not exceed 5%. Thus, the rheological behavior of CMC solution can be assumed as constant when the concentration is fixed.

Results and Discussion

To calculate the gas volume fraction and interpret holdup data in a gas and Newtonian fluid system, Zuber and Findlay (1965) proposed the drift-flux model, which correlates the actual gas velocity, u_g, and the mixture velocity, u_m, using two parameters, c_0 and u_d:

$$u_g = c_0 \cdot u_{\mathrm{m}} + u_d \tag{4}$$

where $u_m = u_{sl} + u_{sg}$ is the mixture velocity of the superficial gas and liquid phase, and c_0 is referred to as the distribution parameter. It accounts for the effects of the nonuniform distribution of both velocity and concentration profiles. If the two phases are uniformly mixed, the concentration profile will be flat and c_0 should be equal to one. u_d is the drift velocity. For upward inclined pipe flows, following Bendiksen's (1984) proposition:

$$u_d = (g \cdot D)^{0.5} \cdot (0.35 \cdot \sin\theta + 0.54 \cdot \cos\theta) \tag{5}$$

where θ, g, and D refer to the angle of inclination from the horizontal, the acceleration due to gravity, and pipe diameter, respectively. With the two parameters and

Table II. Experimental test matrix (number of data points)

Pipe inclination	Air-water flow	Air-CMC-1 solution flow	Air-CMC-2 solution flow	Air-CMC-3 solution flow
0°	18	16	16	18
5°	18	18	18	15
15°	18	18	17	18
30°	18	18	18	18
75°	18	18	18	17

superficial velocities, the void fraction of gas/Newtonian fluid systems in inclined pipes, ε, can be calculated as:

$$\varepsilon = \frac{u_{sg}}{c_0 \cdot u_m + u_d} \tag{6}$$

For gas/non-Newtonian fluid flow in horizontal pipes, Farooqi and Richardson (1982a,b) modified the Lockhart–Martinelli (1949) parameter (χ) to analyze their holdup data. They proposed a correction factor, J, defined as:

$$J = (u_{sl}/u_{cl})^{1-n} \tag{7}$$

where u_{cl} is the critical value of superficial liquid velocity when laminar flow ceases to exist (this value can be estimated by setting the Reynolds number equal to 2000). Figure 3 shows the effects of the flow behavior index (n) and superficial liquid velocity (u_{sl}) on the correction factor, J. It can be seen in Figure 3(a) that J decreases quickly with a decrease at n. In Figure 3(b), for a given n, J changes slightly as u_{sl} is increased and u_{sl} has a minimal effect on J. Moreover, the previous experimental works (Xu et al., 2007) show that the average void fraction decreases for a given u_{sg} as the liquid phase becomes more shear-thinning (i.e., lower value of n). Thus, it can be found that there is a similar trend between Figure 3 and the above phenomena. By introducing the correction factor into the drift-flux model, we can cause the void fraction data of gas/Newtonian fluid horizontal flow to be close to those of gas/non-Newtonian fluid flow. Furthermore, considering the exponential correlation proposed by Farooqi and Richardson (1982a,b) for predicting the holdup of gas/non-Newtonian horizontal flow, a general structure of the correlation can be defined by incorporating the mixture velocity, drift velocity, and the correction factor for upward inclined flow:

$$\varepsilon = f(\varepsilon_{Newtonian}, J) = a_1 \left(\frac{u_{sg}}{u_m + u_d} \right)^{b_1} \cdot J^{b_2} \tag{8}$$

where a_1, b_1, and b_2 are constant. The multiple regression analysis of the 352 experimental data gives the following correlation:

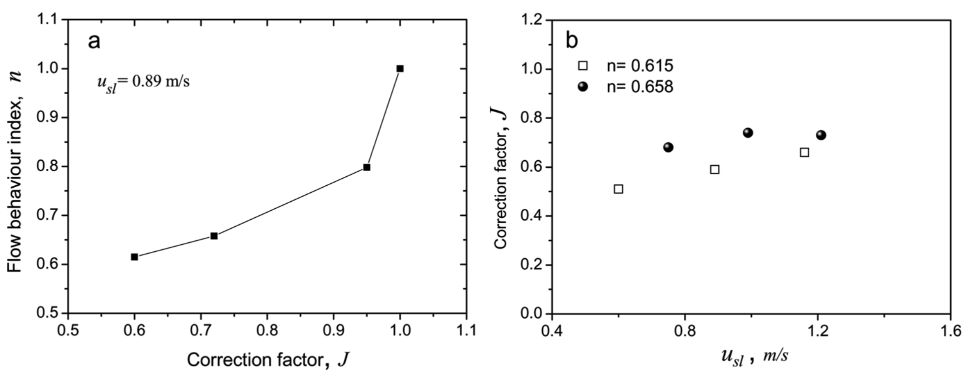

Figure 3. Effects of flow behavior index (n) and superficial liquid velocity (u_{sl}) on the correction factor of Farooqi and Richardson (J).

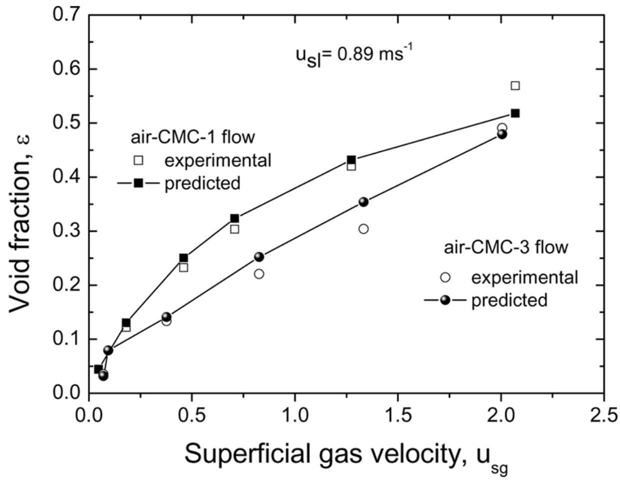

Figure 4. Average void fraction vs. superficial gas velocity at constant superficial liquid velocity in horizontal pipes.

$$\varepsilon = 0.7892 \cdot \left(\frac{u_{sg}}{u_m + u_d}\right)^{0.87} \cdot J^{0.2682} \tag{9}$$

The average void fraction versus superficial gas velocity at constant superficial liquid velocity in horizontal pipes is shown in Figure 4. As can be seen, Equation (9) captures the main trends of the data, namely that the void fraction increases with increasing superficial gas velocity and the void fraction decreases with decreasing value of *n*. A typical comparison between experimental data and the

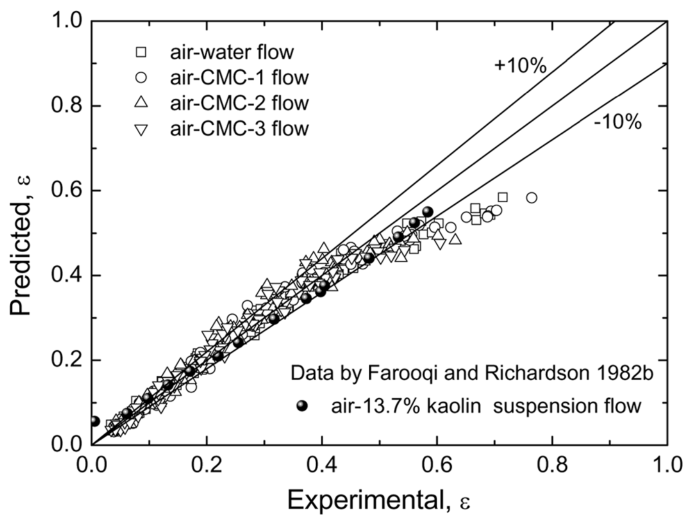

Figure 5. Comparison of the average void fraction data on air-water and air-CMC solutions in this work and for another system reported in the literature for inclined intermittent flow regimes.

Table III. Statistical parameters for experimental and predicted void fraction for horizontal and upward intermittent flows

Gas-liquid systems	Average error, E1, (%)	Average absolution error, E2, (%)
Air-water flow	−0.06	10.05
Air-CMC-1 solution flow	−0.99	10.48
Air-CMC-2 solution flow	3.78	10.48
Air-CMC-3 solution flow	0.61	8.79

prediction of the proposed correlation by Equation (9) is given in Figure 5. Good agreement is obtained between theory and data. Statistical parameters for experimental and predicted void fraction for horizontal and upward intermittent flows are presented in Table III. It can be found that the fitting results are within an average absolute error of 10.5%. Furthermore, the experimental data of Farooqi and Richardson (1982a,b) were also used to validate the model, as shown in Figure 5. These results substantiate the general validity of the model presented for gas/non-Newtonian two-phase intermittent flows.

Conclusions

A new correlation for the average void fraction was proposed for gas/power-law fluid upward inclined flows in intermittent flow regimes. The correlation incorporated the mixture velocity, drift velocity, and the correction factor of Farooqi and Richardson. The correlation was based on 352 data points covering a wide range of flow rates for different CMC solutions at diverse angles. Good agreement was obtained between the predicted and experimental results.

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Nomenclature

c_0	distribution parameter
D	pipe diameter, m
g	acceleration due to gravity, m/s^2
J	correction factor of Farooqi and Richardson
k	fluid consistency coefficient, Pa $\cdot$ s^{n_1}
n	flow behavior index
u	mean velocity, m/s
u_{cl}	critical value of superficial liquid velocity, m/s
u_d	drift velocity, m/s
u_{sg}	superficial gas velocity, m/s
u_{sl}	superficial liquid velocity, m/s

Greek Letters

ε	average void fraction
θ	angle of inclination from the horizontal
μ_{eff}	effective viscosity
τ	shear stress, Pa
χ	Lockhart-Martinelli parameter

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