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Pressure drop and bubble–liquid interfacial shear stress in a modified gas non-Newtonian liquid downflow bubble column

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Abstract

A functional form of equation for predicting pressure drop in a modified non-Newtonian downflow bubble column has been formulated. The equation has been developed based on the bubble formation, drag at interface and the wettability effect of the liquid. Also the bubble–liquid interfacial shear stress in two-phase flow is analyzed and correlated with the dynamic, geometric and physical variables. The functional form of equation appears to predict the pressure drop satisfactorily for two-phase dispersed flow in the co-current modified downflow bubble column with carboxy methyl cellulose (CMC) solution in water with different concentrations.

Keywords: Non-Newtonian fluid; Pressure drop; Downflow bubble column; Interfacial shear stress; Friction factor

1. Introduction

Bubble column have been employed extensively in a large number of gas–liquid reactions such as chlorination and oxidation of organic compounds, biological waste water treatment fermentation processes etc. Most of the literature concerned with continuous systems has gas dispersed from the bottom with liquid flowing either co-currently or counter-currently to the gas phase. One of the major drawbacks of such systems is the limitation of the gas phase residence time which arises owing to the rise velocity of the bubbles. The gas phase residence time can be considerably increased by introducing the gas from the top into a liquid flowing co-currently, so that the bubbles are forced downwards in a direction opposite to their buoyancy. Conditions in the downflow system can be so manipulated by variation in the liquid velocity that the mean residence time of the gas phase can be extended to a point almost approaching a state of suspension. The downflow bubble column concept offers a novel means of contacting and reacting in gas–liquid system.

1.1. Background of two-phase pressure drop

Pressure drop is an important parameter from a design standpoint since it not only affects the gas phase residence time but it also indirectly relates to the interfacial area. The knowledge of pressure drop also gives the pattern of energy dissipation, helps in modeling the system and forms the basis of assessment of performance of the equipment. Wang et al. (2004) present data on the interfacial friction factor and relative interfacial roughness on the gas–liquid interface for an air–water annular flow in a tube. Motil et al. (2003) report experimental data on flow regime transitions, pressure drop, and flow characteristics for co-current gas–liquid flow through packed columns in microgravity. Earlier, Bousman et al. (1996) presented data on two-phase gas–liquid flow in the reduced gravity aircraft for void fraction, liquid film thickness and pressure drop. Takamasa et al. (2003) present data which they claim can be used for the development of reliable constitutive relations which reflect the true transfer mechanisms in two-phase flow in microgravity. These relations can be used to determine the pressure drop across the pipe section. Kamp et al. (2001) developed a mechanistic model for bubble coalescence in turbulent flow. Their model can be used to predict pressure drop in pipes. Iguchi and Terauchi (2001) reported wettability of the pipe did not

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affect the mean rising velocity of bubbles in microgravity. Taitel and Witte (1996) present a model to predict slug flow in microgravity. Colin and Fabre (1995) reported how coalescence and the wall friction factor affect pressure drop. Mandal et al. (2004) reported the frictional pressure drop in downflow bubble column without considering the bubble–liquid interaction. The detailed literature survey regarding the pressure drop has been cited in our earlier study (Majumder et al., 2006a). From the literature review, it is seen that correlations based on experiments exist for predicting the pressure drop, but none of these approaches have taken into account the contacting mechanism between the phases, effect of bubble formation, phase interaction due to interaction of bubbles and the wettability effect on pressure drop in downflow bubble column with non-Newtonian system. In our earlier study (Majumder et al., 2006a), prediction of pressure drop characteristics in the downflow bubble column with only air–water system has been reported.

In the present study, the same model (Majumder et al., 2006a) for pressure drop with a refinement in the ejector induced downflow bubble column with non-Newtonian liquids has been incorporated. The model which is based on mechanical energy balance within the framework of dynamic interaction of the phases has been formulated. The model includes the effect of bubble formation, phase interaction at interface and the wettability effect of liquid on the pressure drop. The theoretical model proposed in the present study appears to predict the pressure drop satisfactorily for gas–liquid dispersed flow in the cocurrent gas non-Newtonian liquid downflow bubble column.

1.2. Theoretical background

In the earlier study (Majumder et al., 2006a), the hydrodynamics of two-phase downflow on the basis of mechanical energy balance has been theoretically considered. The model is presented with the following assumptions:

(i) isothermal steady flow of phases through column,
(ii) the holdup is considered as average for particular gas and liquid flowrate,
(iii) acceleration effects are negligible due to absence of interphase mass transfer,
(iv) for a particular gas and liquid flowrate, frictional loss is considered as uniform throughout the column.

1.3. Energy balance equation

The mechanical energy balance equation for the gas is given by

$$\Delta P_{lg}\varepsilon_g A_c V_{sg} + g\Delta Z A_c \varepsilon_g \rho_g V_{sg} + E_g = 0. \tag{1}$$

In Eq. (1), the first term is "energy due to two-phase pressure", second term is "potential energy" and the third term is "energy dissipation due to friction".

Similarly for the liquid

$$\Delta P_{lg}(1-\varepsilon_g)A_c V_{sl} + g\Delta Z A_c(1-\varepsilon_g)\rho_l V_{sl} + E_l = 0. \tag{2}$$

Adding Eqs. (1) and (2) one gets

$$\Delta P_{lg}[(1-\varepsilon_g)V_{sl} + \varepsilon_g V_{sg}] + [(1-\varepsilon_g)\rho_l V_{sl} + \varepsilon_g \rho_g V_{sg}]g\Delta Z = -(E_l + E_g)/A_c. \tag{3}$$

The energy dissipation in gas–liquid two-phase flow occurs from the frictional losses of individual phase, formation and breakage of bubbles and wettability of liquid. Therefore, total energy dissipation of the two phases is equal to the sum of frictional loss due to each of the phases and the loss due to bubble formation and wettability.

Therefore an expression for $(E_l + E_g)$ can be obtained as

$$\Delta P_{fl} A_c(1-\varepsilon_g)V_{sl} + \Delta P_{fg} A_c \varepsilon_g V_{sg} + E_b + E_w = (E_l + E_g), \tag{4}$$

where ΔP_{fl} is the frictional pressure loss due to liquid in two-phase flow and ΔP_{fg} is the frictional pressure loss due to gas in two-phase flow. E_b is the energy loss due to bubble formation and E_w is the energy loss due to wetting of thin liquid layer with the solid wall.

Substituting Eq. (4) for $(E_l + E_g)$ in Eq. (3) one gets

$$\Delta P_{lg}[L/\rho_l + G/\rho_g] + [L + G]g\Delta Z + \Delta P_{fg} G/\rho_g + \Delta P_{fl} L/\rho_l + E_b/A_c + E_w/A_c = 0, \tag{5}$$

where L and G are the mass flux of liquid and gas, respectively, and these have been defined as, $L = (1-\varepsilon_g)V_{sl}\rho_l$ and $G = \varepsilon_g V_{sg}\rho_g$, respectively.

The frictional losses due to each gas and liquid phase in two-phase flow can be calculated by equations as given by Majumder et al. (2006a):

$$\frac{\Delta P_{fl}}{\Delta P_{fl0}} = \frac{\alpha_l}{(1-\varepsilon_g)^3}, \tag{6}$$

$$\frac{\Delta P_{fg}}{\Delta P_{fg0}} = \frac{\alpha_g}{\varepsilon_g^3}. \tag{7}$$

1.4. Pressure drop due to phase interaction

A bubble imbedded in a flowing fluid is influenced by a number of mechanisms, which act on it through the traction at the gas–liquid interface. The bubbles moving through the fluid experiences pressure forces that affect its motion (Joshi, 2001). The formulation of the pressure force due to phase interaction can be expressed as (Majumder et al., 2006a)

$$\Delta P_{\mathrm{FD}} = \tfrac{1}{8} C_D \rho_l V_s^2, \tag{8}$$

where C_D is the drag coefficient, V_s is the slip velocity. The interaction force depends on the size and shape of the bubble and the nature of the gas–liquid interface. The drag coefficient and slip velocity was calculated as reported by Majumder et al. (2006a).

1.5. Energy loss due to formation of bubble

To account for dynamic interaction, it is necessary to first calculate the additional pressure drop due to formation of bubbles.