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Gas holdup and hydrodynamic flow regime transition in bubble columns

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ABSTRACT

The homogeneous-to-heterogeneous flow regime transition point dependence on gas and liquid properties was investigated in a semi-cylindrical bubble column of 1.8 m height and 0.21 m inner diameter operating as a semi-batch system. He, air, and CO_2 gases were injected at superficial gas velocities of up to 239 mm/s. The batch liquids included water, aqueous ethanol solutions, and aqueous glycerol solutions, all with a gas-free liquid height settled at 1 m. When the gas density increased, the gas holdup increased at all superficial gas velocities, delaying the flow regime transition. The gas holdups in the liquid mixtures were higher than those for tap water. The transition gas holdup for the ethanol solutions increased to a sharp maximum and then decreased as the surface tension increased. Also, the glycerol solutions showed similar behavior with respect to increasing liquid viscosity, but with a shallower maximum. The transition gas holdup was empirically correlated as a function of the gas density, surface tension, and liquid viscosity, employing dimensional constants. The measured transition gas holdups for liquid mixtures, as well as some data from the literature, were fitted by the correlation.

Introduction

Bubble columns provide a classical operational method for contacting liquids with continuous gas flow, and are widely used in chemical, biochemical, and petrochemical processes. Gas holdup control in bubble columns is critical in reactor design and modeling.

In a solids-free bubble column, two main flow regimes are observed — homogeneous and heterogeneous. The homogeneous regime is characterized by relatively small uniform gas bubbles, and the gas holdup increases almost linearly with increasing superficial gas velocity. On the other hand, the heterogeneous regime or churn-turbulent regime is characterized by vigorous bubble coalescence and break-up, high bubble rise velocities, and much larger, less-uniform bubbles. When the homogeneous regime undergoes transition to the heterogeneous regime as the superficial gas velocity is increased, the slope of the gas holdup vs. gas velocity changes substantially [1]. Demarcation of the transition between the homogeneous and heterogeneous flow regimes is essential for operators of bubble columns.

According to Zahradnik et al. [2] and Ruzicka et al. [3], the flow regime transition region clearly depends on the orifice diameter and open area fraction of the gas distributor. After comparing flow regimes from the distributors that have hole sizes of 0.5 and 1.6 mm, for a fixed open ratio of 0.5%, Zahradnik et al. [2] reported that the flow regime transition and heterogeneous regime are difficult to characterize. Camarasa et al. [4] identified the change of flow regime when using a porous plate, as well as for single- and multiple-orifice nozzles. For the porous plate and multiple-orifice nozzle distributor, the gas holdup increased and then decreased with increasing superficial gas velocity in the range of the flow regime transition. Kazakis et al. [5] classified the flow in this region into three regimes: pseudo-homogeneous regime, transition regime, and heterogeneous regime. They considered the pseudo-homogeneous regime as the case where a linear increase of gas holdup occurs with increasing, yet low, superficial gas velocity.

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Nomenclature

A, B, C, D	Constants for empirical correlation (–)
D_c	Diameter of column (m)
d_0	Orifice diameter in gas distributor (mm)
g	Acceleration of gravity (m/s^2)
H	Length of column (m)
i	Number of experiments
n	Richardson-Zaki index (–)
N	Total number of experiments
P	Pressure (N/m^2)
U_g	Superficial gas velocity (mm/s)
U_w	Drift flux velocity (mm/s)
Z	Axial coordinate (m)

Greek symbols

δ_1, δ_2	Mean percentage error (–)
ε	Holdup (–)
ε_{trans}	Gas holdup at flow regime transition point (–)
ρ	Density (kg/m^3)
σ_l	Surface tension (N/m)
μ_l	Viscosity of liquid ($mPa \cdot s$)

Subscripts

c	Critical value
g	Gas
l	Liquid

Finch and Dobby [6] and Bennet et al. [7] identified the transition as the point where the slope of the gas holdup vs. superficial gas velocity changes abruptly.

The drift flux model by Wallis [8] is commonly used to identify the flow regime transition. This model introduces the critical point, which initiates the flow regime transition when the stability of the homogeneous regime begins to diminish. In the range of superficial gas velocities in the homogeneous regime, the data show a negative parabolic form when the drift flux (explained in Section **Drift flux theory**) is plotted vs. the superficial gas velocity. When the bubble stability diminishes, the drift flux no longer increases linearly with gas holdup.

The flow regime transition depends on various factors: the gas distributor type, gas density, liquid viscosity, and surface tension. Numerous empirical correlations for gas holdup have been proposed which do not distinguish between the separate homogeneous and heterogeneous regimes [9–12].

A number of research groups have determined the flow regime transition experimentally. Table 1 shows the operating and design conditions for various previous studies on the flow regime transition. The empirical correlations by Reilly et al. [13] and Wilkinson et al. [14] are the most widely used flow regime transition correlations for bubble column reactors. However, these equations do not match the data for liquid mixtures, especially at low solute concentrations. Moreover, liquid viscosity was not considered in the flow regime transition gas holdup correlation by Reilly et al. [13], and the equation by Wilkinson et al. [14] does not provide a good fit to data that show the effect of liquid viscosity.

In the current study, in order to improve the ability to predict the gas holdup at the flow regime transition, we varied the liquid surface tension and viscosity, using aqueous ethanol and glycerol solutions. In addition, to investigate the effect of gas density, several different gases were tested. An empirical correlation is proposed which considers these properties.

Experimental

Fig. 1 shows a schematic of the experimental equipment. Gas holdup and axial pressure drop estimation were carried out with a semi-cylindrical acrylic column of a 1.8 m height and 0.21 m inner diameter. The column was filled with the water or aqueous solutions up to a 1 m height and the liquid temperature was fixed at 20 ± 2 °C. The upper surface of the liquid in the column was exposed to the atmosphere. A gas distributor was positioned at the bottom of the test section to distribute the gas flow uniformly.

Fig. 2 shows a cross-sectional diagram of the rectangular pitch type distributor which has 35 holes of 2 mm diameter. Additionally, the thick channel inside the distributor (shown as a red circle) was blocked to enhance the gas distribution. The pseudo-homogeneous regime and the heterogeneous regime were observed in our tests.

To determine the effect of gas density on flow regime transition, three different gases were tested at atmospheric pressure: air ($\rho_g = 1.2\ kg/m^3$), helium ($\rho_g = 0.18\ kg/m^3$), and carbon dioxide ($\rho_g = 1.85\ kg/m^3$). All three gases were supplied by JC gas. In addition, various aqueous ethanol, and glycerol solutions were employed to examine the influence of the liquid viscosity and surface tension on the flow regime transition. The properties of the gases and liquids used in this study are listed in Tables 2 and 3, respectively. All aqueous ethanol and glycerol solutions manufactured by Duksan Reagents Co., Korea, are Newtonian fluids. All the tests were performed in semi-batch systems.

Based on the slope of the pressure drop vs. the height in the column, gas and liquid holdups were calculated. The pressure drop across the bubble column was determined using a pressure transducer (OMEGA PX771A) connected to pressure taps on the side of the column. The pressure taps were installed horizontally from the bottom of the test section at 0.05 m intervals to a height of 0.365 m and then at 0.1 m intervals to a height of 0.965 m above the gas distributor. Transducer signals of 20 Hz were saved into the computer every 30 s through an A/D converter. The axial pressure drops were measured under steady state conditions. Both phase holdups can be calculated by measuring the overall pressure gradient and solving the following two equations,

$$\varepsilon_l + \varepsilon_g = 1 \tag{1}$$

$$-\frac{dP}{dZ} = (\varepsilon_l \rho_l + \varepsilon_g \rho_g) g \tag{2}$$

Drift flux theory

In the homogeneous regime, a stable uniform bubble size leads to a linear increase in gas holdup with increasing superficial gas velocity. The point at which the gas holdup variation departs from this linear relationship is the flow regime transition point. Bennet et al. [7] identified this flow regime transition point by graphically plotting the gas holdup against the gas flow rate. However, Olivieri et al. [15] stated that a plot of ε_g vs. U_g cannot clearly distinguish the boundary of the flow regime and suggested that the drift flux theory be used to determine a more precise flow regime transition point.

Wallis [8] first proposed the drift flux theory for predicting fundamental two-phase flow kinematics. In bubble column experiments, the drift flux theory is commonly used to obtain the critical point separating the homogeneous and heterogeneous flow regimes. Wallis [8] formulated the drift flux (i.e. relative velocity or characteristic velocity) as:

$$U_W = U_g (1 - \varepsilon_g)^{n-1} \pm U_l \varepsilon_g \tag{3}$$

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