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Two regime transitions to pseudo-homogeneous and heterogeneous bubble flow for various liquid viscosities

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ABSTRACT

The gas hold-up variation and regime transition were investigated with different liquid viscosities ranging from 1.0 mPa s to 31.5 mPa s using a 0.15-m-in-diameter bubble column. In contrast to common observations, the gas hold-up graph with the superficial gas velocity could be categorized into three flow regimes: homogeneous, pseudo-homogeneous and heterogeneous flow regimes. The formation of large bubbles caused a transition from the homogeneous to the pseudo-homogenous flow regime, in which large bubbles rose vertically without oscillatory turbulence. According to the results from the dynamic gas disengagement (DGD) technique, large bubbles began to form at the transition superficial gas velocity to the pseudo-homogeneous flow regime. The transition to a heterogeneous flow regime was initiated by the turbulent movement of large bubbles. The transition superficial velocities to pseudo-homogeneous and heterogeneous flow regimes, u_{t1} and u_{t2}, decreased with increasing liquid viscosity below a critical viscosity and converged to a certain value above that viscosity. However, the correlations from the literatures could not make a reasonable estimation of the transition superficial velocities because they did not consider the possible transition to a pseudo-homogeneous flow regime. Therefore, the two transition points should be predicted separately.

1. Introduction

Bubble column reactors have a wide range of applications in industry including fermentation and coal liquefaction, owing to their intrinsic advantages, such as high heat and mass-transfer rates, low operating and maintenance costs, lack of moving parts, simple construction, operation versatility, and large interfacial area [1–3]. However, the hydrodynamics of these reactors is quite complex. Moreover, despite the extensive research in this field, elucidation of the design and scale-up of such reactors is far from complete.

One of the key hydrodynamic parameters in bubble columns is the gas hold-up (ε_G), which is defined as the volume ratio of the gas phase present in the mixture in the reactor. From this volume fraction, the residence time and interfacial area of the dispersed phase can be determined together with the mean bubble diameter. Furthermore, the total gas hold-up uniquely determines the reactant mass-transfer coefficient; for example, the ratio, k_La/ε_G, is constant and equal to approximately 0.5 at high gas throughput with turbulent liquid flow [4].

In bubble column reactors, it is commonly accepted that two main regimes can be distinguished depending on the gas flow rate, column dimensions and liquid phase properties. The homogeneous regime occurs at a low gas velocity and loses stability gradually converting into a heterogeneous (churn turbulent flow) regime at higher gas velocities. The homogeneous regime is characterized by the distribution of small and uniform-sized bubbles among which weak interactions with low breakage and coalescence frequencies occur. The bubbles ascend almost vertically or exhibit small-scale transverse and axial oscillations. On the other hand, the heterogeneous regime is defined by large and fast-rising bubbles on the column axis, liquid recirculation, and a helical bubble flow pattern. In this regime, the bubble size is governed by the dynamic equilibrium between coalescence and break up [5].

However, both small and large bubbles are observed in the homogenous regime. Therefore, Kaji et al. used the term, homogeneous regime, for the regime in which discrete bubbles are generated from a sparger and are dispersed uniformly without coalescence [6]. Many researchers including Wilkinson et al. redefined the concept of the homogeneous regime as the regime in which gas hold-up increases linearly with increasing superficial gas velocity irrespective of the uniformity of the bubble size [7,8]. Kazakis et al. defined the term, pseudo-homogeneous flow regime as the regime in which large and small bubbles coexist with laminar flow [9]. In this study, a clear distinction is made between the homogeneous

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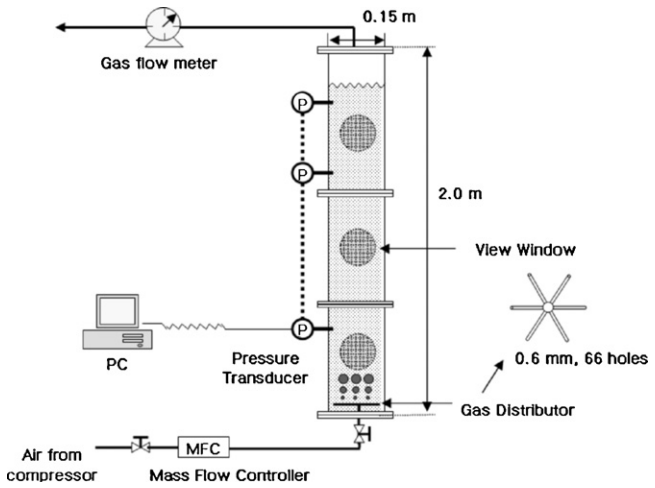

Fig. 1. Experimental setup for the gas hold-up measurements (P: pressure transducer).

and pseudo-homogeneous regimes. The term 'homogeneous flow regime' is used to denote the regime with a uniform bubble size distribution, and the term 'pseudo-homogeneous flow regime' indicates the regime in which discrete bubbles rise without turbulent flow.

Many studies have examined the regime transition and suggested several theoretical model equations. Several researchers including Chen et al. have reported the presence of two transition points [10,11]. Vial et al. have reported a macro-circulation of liquid phase in the transition regime that could not be attributed to turbulence [12,13]. Despite these efforts, many basic questions regarding the effects of the important operational parameters and system properties on the transition remain unanswered. Both the column characteristics and liquid media have a strong effect on these parameters. However, the effect of the liquid media appears to be more complex and thus, remains disputed.

Most studies on the effects of the liquid viscosity focused primarily on gas hold-up. It is generally reported that increasing viscosity promotes the formation of larger gas bubbles, which leads to a decrease in gas hold-up. This has been attributed to the fast ascending velocity of a large population of big bubbles, and hence their short retention times in the bed [1,14–17]. Nevertheless, there are few results reported on the effect of the liquid viscosity on the individual transitions to a pseudo-homogeneous and heterogeneous regime. Several experiments have reported that an increase in liquid viscosity also causes a decrease in the transition superficial gas velocity to the heterogeneous regime [7,14,16].

The present study focuses on identifying the homogeneous, pseudo-homogeneous and heterogeneous regimes as well as the changes in the transition superficial gas velocities with a range of liquid viscosities.

2. Materials and methods

Fig. 1 shows the experimental setup used to measure the gas hold-up and bubble size distribution. The experiments were carried out in a cylindrical Plexiglas bubble column, 0.15 m in diameter and 1.70 m in height, with the top open to the atmosphere. A perforated metallic plate containing 66 orifices with a diameter equal to 0.7 mm, arranged in a hexagonal pattern, was placed at the bottom of the column and used as a sparger with a corresponding free plate area of 0.14%. All runs were carried out at room temperature and without liquid flow. Regardless of the liquid phase tested, the ratio of the initial liquid height to the column diameter (Ho/Dc) (specific column geometry) was maintained at 7.67.

Table 1
Physical properties of the liquid phases (at $T = 25\,^{\circ}C$ and $P = 0.1$ MPa).

Liquid phase	Density (kg/m^3)	Viscosity (mPa s)	Surface tension (mN/m)
Water	981.2	1.0	71.9
0.0034% ETD	979.9	1.3	72.6
0.0060% ETD	982.0	1.8	72.7
0.0114% ETD	983.8	2.8	72.5
0.0210% ETD	984.1	8.1	72.7
0.0332% ETD	986.5	31.5	73.0

Compressed air was used as the dispersed phase and was introduced into the column from the bottom. A calibrated mass flow controller (Brooks Instrument, Hatfield, PA, USA) was used to adjust the volumetric gas flow rate. The measurements were performed by increasing the superficial gas velocity (0.00–0.14 m s^{-1}) covering both the homogeneous and heterogeneous flow regimes. Distilled water and solutions with different concentrations of a viscosity-increasing agent were used as the continuous liquid phases. In this study, acrylates/C10-30 alkyl acrylate cross-polymer (Carbopol® ETD 2020, Lubrizol, Wickliffe, OH, USA) was utilized as the viscosity-increasing agent because it efficiently increases the viscosity of the solution at small amounts with minimum changes in the other liquid properties. Table 1 lists the physical properties of the liquids used. The liquid phase viscosity was measured using a LVDV-III ultra rheometer (Brookfield, Middleboro, MA, USA), and the surface tension was measured using Krüss-K12 tensiometer (Krüss, Hamburg, Germany).

High sensitivity pressure sensors (Sensys, Ansan, Korea) were employed to provide information on the gas hold-up in the column. The distance between the pressure sensor taps was 0.70 m. The output voltage coming from the pressure sensor was linearly dependent on the differential pressure in the column and hence linearly dependent on the increase in liquid height generated by the gas present in the column. The output voltage was read and averaged for 2 min after a 2 min stabilization period and was used to calculate the corresponding gas hold-up:

$$\varepsilon_G(u_G) = \frac{H_b(u_G) - H_0}{H_b(u_G)} \quad (1)$$

where H_b and H_0 are the liquid heights before and after gas bubbling, respectively, and u_G is the superficial gas velocity.

A dynamic gas disengagement (DGD) technique was used to examine the effect of the solution viscosity on the bubble populations. The DGD technique is based on the principle that different bubble classes in dispersions can be distinguished if there are significant differences between their rise velocities [18,19]. The rate at which the instantaneous gas hold-up decreases would depend on the fraction and rise velocities of the different bubble classes. Therefore, the individual gas hold-up due to small and large bubbles can be determined by measuring the rate at which the gas hold-up decreases. Several researchers have reported various assumptions and sources of error associated with this analysis [18–20]. The main assumption is that the hold-up structure is not affected by the bubble interactions during disengagement process. However large bubbles can accelerate smaller bubbles in their wake during the disengagement. Schumpe and Grund [19] have pointed out the downward flow of liquid is especially strong during the disengagement of large bubbles, decreasing the rising velocity of the smaller bubbles. According to their results, these two effects can almost compensate for each other in a bubble column reactor.

A quick closing ball valve was installed on the inlet gas line and the sparger volume was minimized to minimize the error by the DGD technique. A pressure transducer was placed five centimeters below the clear liquid height to measure the pressure variation during bubble disengagement. The pressure transducer showed a fast