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Comprehensive experimental investigation of counter-current bubble column hydrodynamics: Holdup, flow regime transition, bubble size distributions and local flow properties

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HIGHLIGHTS

- We experimentally study a large-diameter counter-current bubble column.
- We compare the results obtained with different experimental methods.
- We investigate the flow regime transition.
- We analyse bubble size distributions and shapes in the developed region and near the sparger.
- We provide optical probe measurements at different axial and radial positions.

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ABSTRACT

In this paper, we apply a variety of experimental techniques to investigate the influence of the counter-current mode on bubble column hydrodynamics. We study an air–water bubble column, which is 5.3 m in height and has an inner diameter of 0.24 m, and we consider gas superficial velocities in the range of 0.004–0.20 m/s and liquid superficial velocities up to -0.09 m/s. The experimental investigation consists of holdup, gas disengagement, image analysis and optical probe measurements. The holdup measurements are compared with the literature and are used to investigate the flow regime transition. The gas disengagement measurements are used to further investigate the flow regime transition and study the structure of the holdup curve. The image analysis is used to study the bubble shapes and size distributions near the sparger and in the developed region of the column; in particular, the image analysis is applied to different gas velocities in the homogeneous regime in both the batch and counter-current modes. The optical probe is used to acquire radial profiles of the local properties (i.e., local void fraction and bubble rise velocity) to study the flow properties and further investigate the flow regime transition. Comparing the results from the different techniques, the influence of the gas superficial velocity and the liquid superficial velocity is discussed considering all main aspects of the two-phase flow, from the local flow properties to the global flow features. The counter-current mode is found to increase the holdup, reduce the bubble rise velocity, destabilize the homogeneous regime and change the local flow properties.

1. Introduction

Bubble columns are frequently used in chemical and biochemical engineering. Their main advantage is a large contact area between the liquid and gas phases and good mixing within the liquid phase. The correct design and operation of these devices rely on the proper prediction of the flow pattern and global and local flow properties—i.e., the holdup (ε_G), bubble rise velocity (u_b), local void fraction ($\varepsilon_{G,Local}$) and bubble size distributions (BSDs). The global and local flow properties are related to the prevailing flow regime: mainly, the homogeneous and heterogeneous regimes. The former is associated with small superficial gas velocities (U_G) and is characterized by the presence of small, uniformly sized bubbles with little interaction. The latter is associated with high gas superficial velocities, high coalescence and breakage phenomena and a wide variety of bubble sizes. Eventually, when a sparger with large openings is used, the quality of the gas distribution is poor,

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and a gas maldistribution regime is established at low U_G values (Nedeltchev and Schubert, 2015). The transition from the homogeneous regime to the heterogeneous regime is a gradual process in which a transition flow regime occurs. This regime is characterized by large flow macro-structures with large eddies and widened bubble size distribution owing to the onset of bubble coalescence. The global and local flow properties (and the flow regimes) are also related to the bubble column operation mode: the batch ($U_L \approx 0$ m/s), the co-current ($U_L > 0$ m/s) or the counter-current ($U_L < 0$ m/s) mode (Deckwer, 1992; Leonard et al., 2015; Rollbusch et al., 2015b). Whereas the co-current or semi-batch modes are widely studied, the counter-current mode is significantly less frequently investigated (Leonard et al., 2015).

In this paper, we apply a variety of experimental techniques to investigate the influence of the counter-current mode on holdup, regime transition, local flow properties and bubble size distributions. We study an air–water bubble column ($H_c = 5.3$ m height and $d_c = 0.24$ m inner diameter, aspect ratio $H_c/d_c > 20$) and consider gas superficial velocities in the range of 0.004–0.20 m/s and liquid superficial velocities up to -0.09 m/s. The diameter of the column and its height were chosen considering the well-known scale-up criteria for the results: $d_c > 0.15$ m and $H_c/d_c > 5$ (Kantarci et al., 2005; Leonard et al., 2015). The column diameter classifies this facility as a large-diameter pipe, considering the dimensionless diameter D_H^* proposed by Kataoka and Ishii (1987):

$$D_H^* = \frac{D_H}{\sqrt{\sigma / g(\rho_L - \rho_G)}} \tag{1}$$

where D_H is the hydraulic diameter, σ is the surface tension coefficient, g is the gravity acceleration, and $\rho_L - \rho_G$ is the density difference between the two phases. Columns with dimensionless diameters greater than the critical value $D_{H,Cr}^* = 52$ are considered to be large-diameter columns (Brooks et al., 2012), and the present bubble column has a dimensionless diameter $D_H^* = 88.13$. When the column diameter is larger than the critical value, the stabilizing effect of the channel wall on the interface of the Taylor bubbles decreases, and the slug flow can no longer be sustained because of the Rayleigh–Taylor instabilities. The hydrodynamic properties in large-diameter columns differ from the flow in small-diameter columns and the flow regime maps and flow regime transition criteria used to predict the behavior of two-phase flow in small-diameter columns may not be scaled up to understand and predict the flow in large ones (Shawkat and Ching, 2011). Therefore, ad-hoc experimental studies are needed for establishing a reliable dataset, especially for counter-current large-diameter bubble columns, owing to the lack of research. In the remainder of the introduction, we propose a literature survey about the influence of the liquid velocity over holdup, flow regime transition, local flow properties and bubble size distributions.

Low liquid velocities do not affect the holdup—as found by several investigators (Akita and Yoshida, 1973; de Bruijn et al., 1988; Lau et al., 2004; Rollbusch et al., 2015a; Sangnimnuan et al., 1984; Shah et al., 1982; Shawaqfeh, 2003; Voigt and Schügerl, 1979; Yang and Fan, 2003)—because, if U_L is low compared with the bubble rise velocities, the acceleration of the bubbles is negligible (Hills, 1976). For example, Akita and Yoshida (1973) ($d_c = 0.152$ m, $H_c = 2.5$ m) observed a negligible effect of U_L (up to 0.04 m/s) in both co-current and counter-current operations. At higher liquid velocities, the column operation influences the holdup: the co-current mode reduces the holdup (Biń et al., 2001; Chaumat et al., 2005b; Jin et al., 2007; Kumar et al., 2012; Otake et al., 1981; Pjontek et al., 2014; Shah et al., 2012; Simonnet et al., 2007), and the counter-current mode increases the holdup (Besagni and Inzoli, 2016a; Besagni et al., 2014, 2015; Biń et al., 2001; Jin et al., 2010; Otake et al., 1981) as bubbles are either accelerated or decelerated by liquid motion (Leonard et al., 2015; Rollbusch et al., 2015a). Baawain et al. (2007) showed that the counter-current or co-current operation modes influenced the holdup by approximately 5% in weight, and less than 1% in bubble size, showing that the effect observed is mainly caused by the bubble rise velocity and not only the bubble size. Biń et al. (2001) showed that the holdup increases with increasing U_L in counter-current mode and decreases (or remains constant) in co-current mode. The effect is more pronounced at high gas velocities, and the difference in the holdup between co-current and counter-current mode is approximately 10%. The same trends were observed by Jin et al. (2010) ($d_c = 0.160$ m, $H_c = 2.5$ m), who reported a maximum difference of 2% between counter-counter and co-current modes. Similar trends were found by Otake et al. (1981) ($d_c = 0.05$ m, $H_c = 1.5$ m). Besagni et al. (2014, 2015) ($d_c = 0.24$ m, $H_c = 5.3$ m), (Besagni and Inzoli, 2016a) found that the counter-current mode influences the column hydrodynamics affecting both the holdup and the local flow properties in annular gap and open tube (with a "*pipe-sparger*") bubble columns. Their analysis covered gas superficial velocities up to 0.26 m/s and liquid superficial velocities up to -0.11 m/s. It appears that the influence of the operation mode is lower at high holdup (Besagni and Inzoli, 2016a; Besagni et al., 2014, 2015; Jin et al., 2010). With regard to the regime transition, Jin et al. (2010) reported that the transition point is the same among the three working modes if U_L is lower than 0.04 m/s, whereas for higher U_L (in co-current and counter-current modes), the transition velocity decreases with increasing superficial liquid velocity. Otake et al. (1981) observed an earlier regime transition increasing the liquid flowrate in the counter-current mode (U_L up to -0.15 m/s). Similar conclusions were drawn by Yamaguchi and Yamazaki (1982a) ($d_c = 0.04$ m and 0.08 m), Besagni et al. (2014, 2015) and Besagni and Inzoli (2016a). It is worth noting that the hydrodynamic properties of bubble columns are determined by the momentum exchange between the liquid and gas phases. Therefore, the flow in a bubble column is governed by the same mechanisms as in other pipe flows. In this respect, Besagni et al. (2015) proposed a survey on counter-current flow in vertical pipes; as a result, most of the studies focused on small-diameter pipes, and our experimental setup ($D_H^* = 88.13$) covers a range in which there is a lack of studies.

The holdup is also a function of the axial and radial position in the column. The spatial variation of the holdup gives rise to pressure variation, which results in liquid recirculation in the bubble column (which governs the rate of mixing, heat transfer and mass transfer). Knowledge of the local void fraction profiles would help in determining the flow regimes, liquid mixing, and heat and mass transfer, and knowledge of the local flow properties would help in the Computational Fluid Dynamics (CFD) model validation. Local void fraction holdup profiles may be center peaked, wall peaked or flat, depending on U_G, U_L, the column design, the sparger design, the nature of the gas–liquid system and the operating conditions. During recent decades, many experimental measurements of holdup profiles have been reported by using a variety of techniques, as reviewed by Joshi et al. (1998). Among the different techniques, we employed needle probes. In general, two types of needle probes have been previously used for measurement in bubble columns: optical fiber and impedance/conductive probes (Boyer et al., 2002). Optical and impedance probes operate based on the differences in the refractive index or conductivity, respectively, of the liquid and gas phases. In this study, dual-tipped optical probes have been used: these devices are capable of simultaneously measuring local holdups, bubble chord lengths and rise velocities (Chabot et al., 1998; Chaumat et al., 2007; Magaud et al., 2001; Moujaes, 1990; Shiea et al., 2013).

In addition to the holdup, another important parameter of bubble column hydrodynamics is the Bubble Size Distribution (BSD). The BSD generated at the sparger gradually changes along the column owing to coalescence and break-up phenomena until reaching an equilibrium/developed BSD. Along with the holdup, the BSD provides an evaluation of the interfacial area (Kantarci