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Influence of internals on counter-current bubble column hydrodynamics: Holdup, flow regime transition and local flow properties

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HIGHLIGHTS

- Counter-current bubble column is studied in annular gap and open tube configurations.
- Holdup curves in the open tube and annular gap configurations are similar in shape.
- The presence of the internals stabilizes the homogeneous regime.
- The counter-current mode increases the holdup and decreases the bubble velocity.
- The counter-current mode destabilizes the homogeneous regime.

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ABSTRACT

Bubble columns are frequently studied without considering internals (open tube bubble columns). However, in most industrial applications, internal devices are often added to control heat transfer, to foster bubble break-up or to limit liquid phase back mixing. These elements can have significant effects on the multiphase flow inside the bubble column reactor and the prediction of these effects is still hardly possible without experimentation. In this paper, we study experimentally a counter-current gas–liquid bubble column in the open tube and annular gap configurations. In the annular gap bubble column, two vertical internal tubes are considered. The column has an inner diameter of 0.24 m, and the global and local hydrodynamic properties are studied using gas holdup measurements and a double-fiber optical probe. The gas holdup measurements are compared with the literature and used to investigate the flow regime transition. A double-fiber optical probe is used to acquire midpoint data and radial profiles of the local properties to study the flow properties and to further investigate the flow regime transition. The counter-current mode is found to increase the holdup, decrease the bubble velocity and cause regime transition at lower superficial gas velocity. The holdup curves in the annular gap and open tube configurations are similar in shape and values, suggesting that the presence of internals has a limited influence on the global hydrodynamic. In addition, it is found that the presence of the internals stabilizes the homogeneous regime in terms of transition gas velocity and holdup.

1. Introduction

Bubble columns are frequently used in the chemical, petrochemical and food production industries. Their main advantage is a very large contact area between the liquid and gas phase, a good mixing within the liquid phase throughout the column and their low price-performance ratio. The correct design and operation of these devices rely on the proper prediction of the flow pattern, the flow regime transition, and global and local flow properties (i.e., the holdup, ε_G; the bubble rise velocity, u_b; the local void fraction, $\varepsilon_{G,Local}$; and the bubble diameter, d_b). The global and local flow properties of the industrial reactors may be extrapolated from the laboratory facilities applying scale-up methods (Shaikh and Al-Dahhan, 2013). Bubble columns are frequently studied without considering internals ("*Open Tube*", *OT*, bubble columns), but, in most industrial applications, internal devices are often added to control heat transfer, to foster bubble break-up or to limit liquid phase back mixing (Youssef Ahmed et al., 2013). These elements can have significant effects on the multiphase flow inside the bubble column reactor and the prediction of these effects is still hardly possible without experimentation (Youssef

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Ahmed et al., 2013). In particular, annular gap bubble columns are reactors with vertical internal tubes. Understanding the two-phase flow inside such devices is relevant for some important practical applications. Annular gap configurations can occur in internal-loop, air-lift bubble columns and in photo-catalytic bubble column reactors containing lamps positioned on their centerline (Youssef Ahmed et al., 2013). The influx of gas, oil and water inside a wellbore casing represents a multiphase flow inside concentric or eccentric annuli (Das et al., 1999a, 199b; Hasan and Kabir, 1992, 2010; Kelessidis and Dukler, 1989; Lage and Time, 2002). In addition, annular channels have been found to replicate some of the phenomena found in these more complex geometries, such as in heat exchangers, separators, fuel bundles and steam generators. The availability of experimental data on such configuration is relatively scarce and further experimental investigations are needed for establishing a reliable dataset for model validation and scale-up purposes. Bubble columns are operated in the co-current, counter-current or semi-batch mode. While the co-current or semi-batch modes are widely studied, the counter-current mode is less investigated (Leonard et al., 2015) and – for the same reason reported above – ad-hoc experimental investigations should be performed.

Whereas the majority of studies have focused on open tubes running in co-current or semi-batch mode (Leonard et al., 2015), this study investigates a $d_c=0.24$ m inner-diameter counter-current annular gap bubble column and the influence of the internals on the two-phase flow. The diameter of the column ($d_c=0.24$ m) and its height ($H_c=5.3$ m) were chosen considering the well-known scale-up criteria for the: results obtained in a bubble column having $d_c > 0.15$ m and $H_c/d_c > 5$ may be considered representative of larger systems (Kantarci et al., 2005; Leonard et al., 2015). Moreover, the pipe considered in this study has an inner diameter of 0.24 m, which is a large diameter pipe under the ambient operating conditions, based on 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. Pipes with dimensionless diameters greater than the critical value $D_{H,cr}^*=52$ are considered to be large diameter pipes (Brooks et al., 2012). Considering air and water under atmospheric conditions, the critical hydraulic diameter is $D_{H,cr} \approx 0.13$ m. When the pipe diameter is larger than this value, the stabilizing effect of the channel wall on the interface of the Taylor bubbles becomes lower, and the slug flow can no longer be sustained due to the Rayleigh–Taylor instabilities. The hydrodynamic properties in large pipes differ from the flow in small pipes because of changes in the liquid field around the bubbles, the presence of additional turbulence and strong secondary recirculation (Shawkat and Ching, 2011). Therefore, the flow regime maps and flow regime transition criteria used to predict the behavior of two-phase flow in small pipes may not be scaled up to understand the flow in large ones. Our experimental facility has a dimensionless diameter of $D_H^*=88.13$, without considering the internal tubes, and of $D_H^*=47.37$ in the annular gap configuration. Such values are higher than the ones commonly investigated in the literature and the present experimental setup differs from the ones previously investigated, as discussed in literature survey proposed by Besagni et al. (2015). Besagni et al. (2015) reviewed the studies about the counter-current two-phase flow in vertical pipes and the two-phase flow in annulus channels. The remaining of the introduction expands the literature survey by analyzing the literature concerning bubble columns with internals and the influence of the liquid velocity on bubble column hydrodynamics.

It is not clear if (and how) the presence of internal tubes in a large-diameter bubble column may affect the hydrodynamics in terms of flow regime transition and holdup. Indeed, few studies concerning the hydrodynamic of bubble columns with internals can be found in the literature. Carleton et al. (1967) studied different column diameter (0.076 m, 0.153 m and 0.305 m) with different internal tubes (with size ranging from 0.025 to 0.076 m). The authors reported an increase of the holdup in the annular gap configuration. Yamashita (1987) studied three different columns (0.08, 0.16 and 0.31 m inner diameter) and the influence of inner tubes on gas holdup. They reported an increase of the holdup if compared with the case without inner tubes. Yamashita also found that gas holdup does not depend on the arrangement of vertical tubes; however, it increased with both their number as well as with their outer diameter. O'Dowd et al. (1987) studied a slurry bubble column (0.108 m inner diameter) with and without internal baffles (five tubes with outer diameter of 0.019 m diameter). The gas holdup increases in the baffled column as compared to the un-baffled one, and bubble size increases in the baffled column at high gas velocities. Jhawar et al. (Jhawar and Prakash, 2014) studied a 0.15 m column and compared the gas holdup, local liquid velocity and bubble fractions holdups obtained with and without internals (0.0127 m outer diameter). The holdup may increase or decrease depending on the configuration and disposition of the internal tubed. Maurer et al. (2015) studied the influence of inner tubes (with outer diameter ranging from 0.01 to 0.02 m) in a 0.14 m column by using x ray tomography. The authors reported a reduction in bubble size for the case with vertical internals. Al-Oufi et al. (2010, 2011) investigated an annular gap bubble column, using different inner tube diameters (0.025, 0.038, 0.051 and 0.070 m) placed concentrically inside the outer column of 0.102 m. The authors found higher holdup in the open tube column design

Considering the influence of the inner tubes over the two-phase flow, it is relevant to refer to the studies concerning the effect of column diameter in a bubble column. The data of Fair et al. (1962) and Yoshida and Akita (1965) show that the effect of the column diameter on the gas hold-up is negligible for columns larger than 0.15 m. Hughmark (1967) has found an effect of column size on gas hold-up up to a diameter of 0.10 m. Kato et al. (1972) conducted measurements in 0.066-, 0.122 and 0.214 m columns and found that the gas hold-up increases with decreasing column size. Koide et al. (1979) measured the gas hold-up in a 0.55 m column and found no significant difference from the literature values reported for columns less than 0.60 m in diameter. Deckwer et al. (1980) found a difference in hold-up between a 0.041 m column and a 0.10 m column. Hikita et al. (1980) measured hold-up in a 0.10 m column and compared their results with the ones reported in the literature for columns larger than 0.10 m, finding no appreciable effect of the column diameter on the holdup. Gopal and Sharma (1983) measured the gas hold-up in 0.2, 0.6 and 1.0 m columns and concluded that the column diameter and sparger do not significantly influence the gas hold-up values. Nottenkamper et al. (1983) measured the gas hold-up in 0.19, 0.45 and 1.0 m columns and obtained comparable results for the 0.19 and 0.45 m columns but lower hold-up values for the 1 m column at high gas rates, which they attributed to the larger diameter. Koide et al. (1984) observed smaller gas hold-up values in columns smaller than 0.2 m. Despite some contradictory results in the literature, it appears that most investigators consider a column size of 0.10–0.30 m large enough to obtain gas hold-up values that can be reliably used to predict hold-up values in larger columns.

There is no general agreement on the role of liquid velocity on the hydrodynamics of the bubble columns, and studies focused on counter-current bubble columns are still limited. Akita and Yoshida (1973) have studied the effect of the liquid flow rate on the gas hold-up in a column 0.152 m in diameter. They have concluded that the effect of the liquid flow rate is negligible for superficial liquid velocities up to 0.04 m/s, either in gas–liquid counter-