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Experimental investigation on the influence of ethanol on bubble column hydrodynamics

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ABSTRACT

We experimentally investigate the effect of ethanol (0.05% in mass) on the hydrodynamics of a large-diameter and large-scale bubble column. The bubble column is 5.3 m in height, has an inner diameter of 0.24 m, and we consider gas superficial velocities in the range of 0.004–0.20 m/s. The experimental investigation consists of gas holdup measurements and image analysis. The gas holdup measurements are used to investigate the flow regime transition and the global bubble column hydrodynamics. The image analysis is used to investigate the bubble shapes and size distributions near the sparger and in the developed region of the column. The presence of ethanol increases the gas holdup, stabilizes the homogeneous regime and modifies the bubble shapes and size distributions. In particular, the addition of ethanol increases the mean bubble aspect ratio and decreases the bubble diameters. The results suggest that the addition of ethanol changes the bubble properties, which modifies the bubble size distribution and shapes, thus, stabilizing the homogeneous flow regime and, finally, increasing the gas holdup.

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 gas holdup (ε_G) and bubble size distribution (BSD). The global and local flow properties are related to the prevailing flow regime: mainly, the homogeneous and heterogeneous regimes (Nedeltchev, 2015; Nedeltchev and Schubert, 2015; Nedeltchev and Shaikh, 2013). 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. 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. Despite the classification reported above is widely used and accepted, it is too simplified: the interactions between the phases inside the bubble column are extremely complex making the classification of the flow regimes not straightforward. In the practical cases, both small and large bubbles may appear at low U_G values (Besagni and Inzoli, 2016a; Besagni and Inzoli, 2016b): for example, when a sparger with large openings is used, the quality of the gas distribution is poor, a “*gas*

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Nomenclature

Acronyms

BSD	bubble size distribution
EtOH	ethanol

Symbols

a	major axis of the bubble [m]
b	minor axis of the bubble [m]
c	coefficient in the ellipse equation [–]
d_o	gas sparger holes diameter [mm]
d_c	diameter of the column [m]
d_{eq}	bubble equivalent diameter [mm]
D_H	hydraulic diameter [m]
D^*_H	non-dimensional diameter [–]
$D^*_{H,Cr}$	critical non-dimensional diameter [–]
h	height along the column [m]
H_c	height of the column [m]
H_D	height of the free-surface after aeration [m]
H_0	height of the free-surface before aeration [m]
J	drift-flux [m/s]
g	acceleration due to gravity [m/s^2]
n	parameter in Eqs. (10)–(11) [–]
S	parameter in the swarm velocity method [–]
U_b	parameter in the drift-flux method [m/s]
u_∞	terminal bubble velocity [m/s]
U	superficial velocity [m/s]
x	variable in Eq. (12) [–]
y	variable in Eq. (12) [–]
θ	bubble orientation [°]
φ	aspect ratio [-]
σ	surface tension [N/m]
ρ	density [kg/m^3]
ε	gas holdup [–]

Subscripts

L	liquid phase
G	gas phase
T, E	subscripts in the drift-flux formulation
trans	transition point
swarm	swarm velocity

maldistribution regime” (as defined by Nedeltchev and Schubert, 2015), is established at low U_G values. Kaji et al. (2001) defined as homogeneous regime, the regime in which discrete bubbles are generated from a sparger and are dispersed uniformly without coalescence. Wilkinson et al. (1992) defined the homogeneous regime as the regime in which gas holdup increases linearly with increasing U_G, regardless of the uniformity of the BSD. Kazakis et al. (2007) defined as “*pseudo-homogeneous regime*” the regime in which large and small bubbles coexist with laminar flow. Yang et al. (2010) distinguished between the homogeneous and pseudo-homogeneous regimes: the former denotes the regime with a uniform BSD, whereas the latter indicates the regime in which discrete bubbles are generated from the sparger and the gas holdup increases almost linearly with increasing U_G, but no uniformity in the radial bubble distribution near the sparger region exists. For the sake of clarity, an accurate definition of homogeneous regime within this research is needed. Taking into account the previous literature and our experimental research (Besagni, 2016; Besagni and Inzoli, 2016b), we classify the flow regimes (in large-diameter bubble columns) as follows:

(i) homogeneous regime;
(ii) transition regime;
(iii) heterogeneous regime.

It is worth noting that the slug flow regime may not be detected because of the well-known instabilities (further details are provided in the following paragraphs). The homogeneous regime is defined as the regime where only “*non-coalescence-induced*” bubbles exist (as detected by the gas disengagement technique and discussed by Besagni and Inzoli (2016b)). Then, the homogeneous regime is divided into “*pure-homogeneous*” (or “*mono-dispersed homogeneous*”) regime and “*pseudo-homogeneous*” (or “*poly-dispersed homogeneous*” or “*gas maldistribution*”) regime: the former is characterized by a mono-dispersed BSD, whereas the latter is characterized by a poly-dispersed BSD. We define the mono-dispersed and poly-dispersed BSDs accordingly with the change of sign of the lift force coefficient, as described by several authors (Besagni et al., 2016; Besagni and Inzoli, 2016b; Lucas et al., 2016; Zahradnik et al., 1997; Ziegenhein et al., 2015). The transition regime is identified by the appearance of the “*coalescence-induced*” bubbles (Besagni and Inzoli, 2016b) and, at high gas velocities, a fully heterogeneous regime is reached (Sharaf et al., 2015). The transitions between the different flow regimes depend on the operation mode, design parameters and working fluids of the bubble column. For example, when using a “*fine*” sparger, the homogeneous regime is stabilized (Mudde et al., 2009), using a “*coarse sparger*” (large openings), the mono-dispersed homogeneous may not exist and, using a “*very coarse sparger*” (very large openings), the homogeneous regime may not exist and a “*pure heterogeneous regime*” takes place (Ruzicka et al., 2001). In the previous papers we studied the influence of the column and sparger design (Besagni and Inzoli, 2016b,c), operation modes (Besagni et al., 2014, 2016; Besagni and Inzoli, 2016b,c) and electrolyte concentration (Besagni and Inzoli, 2015) over the bubble column fluid dynamics. This paper focuses on the effect of ethanol on gas holdup, flow regime transition and BSD; in the following, we offer a brief literature survey on these aspects.

In air–water bubble columns—operating at ambient temperature and pressure—the homogeneous regime ends approximately at $U_{trans} \approx 0.04$ m/s (Deckwer and Field, 1992). Depending on the many variables of the system U_{trans} either reduces (“*homogeneous regime destabilization*”) or increases (“*homogeneous regime stabilization*”). Alcoholic solutions are well-known to stabilize the homogeneous regime owing to the suppression of the coalescence (Hikita et al., 1980; Jamialahmadi and Müller-Steinhagen, 1992): the alcohol molecules are composed of hydrophilic and hydrophobic parts that are adsorbed at the interface when dissolved in water, causing the coalescence suppression (Albijanić et al., 2007). The stabilization of the homogeneous regime by the addition of ethanol was verified by Krishna et al. (1999, 2000a,b) ($d_c = 0.1$, 0.15 and 0.38 m, $H_c = 4$ m, EtOH up to 1%$_{vol}$), Al-Oufi et al. (Al-Oufi et al., 2011) ($d_c = 0.102$ m, $H_c = 2.25$ m, EtOH up to 300 ppm$_{wt}$) and Dargar and Macchi (2006) ($d_c = 0.127$ m, $H_c = 2.75$ m, EtOH up to 5%$_{wt}$). A consequence of the homogeneous regime stabilization is the increase in gas holdup (Al-Oufi et al., 2011; Dargar and Macchi, 2006; Kelkar et al., 1983; Krishna et al., 1999, 2000a,b; Pjontek et al., 2014;