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Bubble breakup in co-current upward flowing liquid using honeycomb monolith breaker

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HIGHLIGHTS

- Investigated bubble breakup process in upward liquid flow using monolith breaker.
- Observed about 60% reduction in the bubble size by the monolith breaker.
- Identified different mechanisms of bubbles coalescence at the monolith exit.
- Described a novel approach to compute breaker efficiency.
- Showed the existence of optimum liquid velocity for highest breaker efficiency.

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ABSTRACT

Bubble column reactors are used in industrial practices due to their intrinsic advantages of good mixing ability, high heat transfer and operational versatility. Generation of small bubbles in bubble column is a crucial step to improve their performance. The present investigation introduces a new approach for bubble breakup in an upward co-flowing liquid using a honeycomb monolith breaker with square cell structure. The experimental measurements were conducted using high speed imaging at different superficial liquid velocities and gas flow rates ranging between 8 to 50 cm/s and 165 to 1000 ml/min, respectively. A comparison between the bubbles generated from the monolith breaker and those generated from the nozzle shows that the monolith breaker reduces the bubble size by approximately 60% over the given range of liquid superficial velocities and gas flow rates. It is observed that at low superficial liquid velocities and low gas flow rates, the bubble size at the breaker exit follows log-normal distribution, which becomes more symmetric at higher superficial liquid velocities and gas flow rates. The main contributor of large bubbles formation at the monolith breaker exit is the bubbles' coalescence. Different mechanisms of bubbles coalescence at the breaker outlet are observed and classified into three types; multi- and successive “accumulative” coalescence, multi- and non-successive coalescence, and bubbles coalescence in the vicinity of the breaker outlet. The efficiency of the breaker is quantified in terms of the fractional conversion of bubbles' kinetic energy into the surface energy. A strong dependency of the breaker efficiency on the superficial liquid velocity is observed. The results indicate that an optimal liquid velocity exists that corresponds to the minimal bubble coalescence at which the breaker efficiency is maximum.

1. Introduction

Bubble column reactors have numerous applications in many industrial processes, such as wastewater treatment, fermentation, bio-reactions, ozonolysis, hydrogenation, chlorination, oxidation, Fischer–Tropsch synthesis, drugs and food manufacturing (Duduković, 2000; Schlüter et al., 1995; Duduković et al., 1999; Rahimpour et al., 2012). In most of these processes, the gas bubbles produced in the reactor contribute to the heat, mass, and/or momentum transfer as well as surface reaction. Hence, the efficiency of these processes is dependent on the size and number of bubbles. One effective way of achieving high efficiency of these processes is through the generation of small bubbles in larger quantity, which cumulatively have higher surface to volume ratio and in some cases, longer residence time as well. Hence, the generation of small gas bubbles and the prevention of large bubble formation are highly recommended (Behkish et al., 2002).

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In a gas–liquid two-phase flow, different bubble flow regimes may exist depending on the gas-to-liquid flow rates ratio (GLR). These regimes are identified as bubbly, slug, churn and annular regimes. In addition, the gas injection into the liquid stream could be in the same direction as the liquid flow (i.e. co-flow configuration) or perpendicular to the direction of liquid flow (i.e. cross-flow configuration). The bubble formation in both configurations has been extensively studied and reported in the literature. For example, Sada et al. (1978) reported a decrease in the bubble size in a co-flowing liquid. Oğuz and Prosperetti (1993) reported that the bubble size can be controlled in the co-flowing configuration. Bhunia et al. (1998) studied the bubble formation under constant gas flow conditions through a single nozzle in a co-flowing liquid configuration and observed that the bubble diameter decreases with an increase in the superficial liquid velocity. They concluded that an increase in the liquid density and viscosity enhances the bubble detachment process. Terasaka et al. (1999) theoretically and experimentally investigated the effect of the upward co-flowing liquid on the bubble size. They found that the bubble size decreases with an increase in the liquid flow rate and by decreasing the nozzle inner diameter. Chen and Reginald (2002) presented a non-spherical model for bubble formation in a co-flowing liquid using the interfacial element approach to describe the dynamics of bubble formation, and observed a good agreement between their simulated results and the experimental results of Terasaka et al. (1999). Fadavi et al. (2008) used a conical gas–liquid sparger in which the bubbles are sheared off the sparger holes right after their formation by the swirling liquid. They concluded that the size of the bubbles at detachment can be controlled by the flow rates of gas and liquid. Sobrino et al. (2009) compared the size of bubbles generated from a static and a rotating distributor comprised of a perforated plate that rotates about the vertical axis of the column. They observed that for the same flow conditions, smaller bubbles are generated from the rotating distributor compared to the static distributor. They argued that the centrifugal acceleration imparted by the plate rotation advances the bubble detachment and hence, reduces the bubble size. Fujikawa et al. (2003) observed a decrease in the mean bubble diameter with an increase in the rotational frequency of a porous plate distributor. The rotational frequency of the porous plate and the flow rate of the gas were used to control the diameter and number of bubbles. Ulbrecht and Ranade (1979) studied the influence of sparger angular velocity and gas flow rate on the bubble size and found that the bubbles from a rotating sparger are smaller than that from a stationary sparger due to the shear force acting across the sparger nozzle.

Morgenstern and Mersmann (1982) observed that the rotation of the nozzle leads to an early detachment of bubbles in a viscous liquid. Ghosh and Ulbrecht (1989) investigated the bubble formation in viscous liquids at different rotational speeds of the tank and observed smaller bubble formation during tank rotation compared to that in the stagnant liquid. Manabu et al. (1998) investigated the bubble formation from a single-hole nozzle placed vertically upward in a rotating water bath. They concluded that smaller bubbles can be generated from a single-hole nozzle by rotating the lance in a molten metal bath at a gas flow rate lower than a critical value. Miyahara et al. (1999a, 1999b) observed bubble splitting in the shear layer formed around a liquid jet that was discharging in a large volume of the same liquid. They concluded that the maximum stable diameter of splitting bubbles due to a turbulent jet from a nozzle is slightly smaller than the turbulent jet from an orifice.

Martínez-Bazán et al. (1999) studied the breakup of air bubbles that were injected into a fully developed turbulent water jet. They computed the bubble breakup frequency in nearly homogeneous and isotropic turbulent conditions and found that the probability of breakup depends on the bubble diameters and on the value of the dissipation rate of turbulent kinetic energy of the surrounding water. Mashelkar and Sharma (1970) found that a bubble column filled with packing in an upward co-flow configuration increases the interfacial area between bubble and liquid phases due to the enhanced bubble break-up, resulting in a higher gas holdup. Pandit and Doshi (2005) discussed the effect of sectionalizing bubble columns and argued that the bubble size in the sectionalized column is governed by the plate-hole diameter as well as the percentage of the free area of the plate. They concluded that the sectionalizing plates are responsible for the re-breakage of the bubbles, which reduces the average bubble size. Lee and Sherrad (1974) observed extensive bubble breakup in the presence of large particles in the gas–liquid system. Chen and Fan (1989) studied the collision between a single particle and a single bubble in a liquid medium and observed that the particle penetration is only a necessary, but not a sufficient condition for the bubble disintegration in the case of single-particle single-bubble collision. They concluded that the penetrated bubble is deformed into a doughnut shape and the bubble disintegration occurs only if the penetrating particle has a diameter greater than the height of the doughnut-shape bubble.

Kim et al. (1988) investigated the heat transfer characteristics in three-phase fluidized beds with floating bubble breakers using an axially mounted cylindrical heater. They observed that the floating bubble breakers increased the heat transfer coefficient compared to a fluidized bed without floating bubble breakers. Kim and Kim (1990a, 1990b) studied individual phase holdups and mass transfer characteristics in three-phase fluidized beds with floating bubble breakers of different sizes, densities and shapes (cubic, cylindrical and hexagonal). Their results show that the volumetric mass transfer coefficient in three-phase fluidized beds with hexagonal-shaped breakers is up to 40% greater than that in a bed without floating bubble breakers. They also concluded that, in general, the volumetric mass transfer coefficient increases with an increase in the breaker density, projected area and contact angle between the floating bubble breakers and the liquid.

Yang et al. (2012) used sieve tray as the partitioning plate to examine the effect of the opening ratio and pore size on the bubble break-up frequency and bubble size distribution in a tray-type bubble column. They observed that the increase in the gas holdup in the bubble column is contributed by an increase in the gas residence time, smaller average bubble size diameter, and lower rate of bubble coalescence. Alvare and Al-Dahhan (2006a, 2006b) examined the effect of tray structure and operating conditions in a co-current up-flow bubble column. They concluded that the tray open area and superficial liquid velocity had the strongest effect on the liquid back mixing. Krichnavaruk and Pavasant (2002) studied the influence of a perforated plate on the gas–liquid mass transfer in an airlift reactor, and found that the perforated plate helped in breaking large bubbles. Zhang et al. (2005) studied the influence of a specially designed internal, called a bubble scraper, in an external-loop airlift reactor. The results showed that this internal had a profound effect on the bubble breakup resulting in a more uniform radial distribution of the gas holdup and liquid velocity. Prasser et al. (1998, 2001) presented a method to measure bubble size in a tube using wire-mesh sensor having an array of 16×16 measuring points. They observed slicing of bubbles as they penetrate through the wire-mesh, which caused significant bubble fragmentation. They also reported that the process of bubble fragmentation was independent of bubble size and liquid velocity, which was varied from 0 to 0.8 m/s. Jain et al. (2013) used the Discrete Bubble model (DBM) to study the effect of introducing a static mesh of thin wires inside the bubble column on the liquid and bubble dynamics. Their results indicated that the mesh opening has a very strong and direct influence on the cutting of larger bubbles into smaller ones.