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The effect of mesh-type bubble breaker on two-phase vertical co-flow

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ABSTRACT

The influence of a mesh-type bubble breaker in a two-phase vertical co-flow is experimentally investigated using high-speed imaging. A range of liquid and gas flow rates were considered that correspond to the gas-to-liquid flow rates ratios (GLRs) from 0.05 to 39.6 covering bubbly, slug and churn flow regimes. The mesh-type bubble breaker was found to be effective in reducing the size of nozzle-generated bubbles in two-phase co-current vertical flow. The bubble size reduction by 50%-70% is observed in the presence of the mesh-type bubble breaker compared to that without a bubble breaker. The results also show that at a given GLR, the mesh-type bubble breaker delayed the flow regime transition compared to that without a bubble breaker. A Froude number correlation was proposed to predict the mean bubble size downstream of the bubble breaker for the bubbly flow regime, which accurately predicted the bubble size over a range of bubble breaker parameters. It is observed that the geometry of the bubble breaker influence the two-phase flow regime transition. At low liquid flow rates, small pore size of the breaker was found to be effective. This effect diminishes at higher liquid flow rate due to the elongation of the bubbles by the liquid inertia. The results also show that a longer bubble breaker located closer to the bubble generating nozzle is the most effective in producing bubbly flow over a longer range of gas-liquid flowrates ratios.

1. Introduction

Bubble column reactors are essential components in many chemical and mechanical processes involving two-phase flows in which the mixing of gas and liquid phases is required (Kantarci et al., 2005; Jakobsen et al., 2005; Leonard et al., 2015). They are widely used due to their capability to allow high rates of heat and mass exchange between gas and liquid phases. The basic structure of a bubble column reactor is a vertical cylinder containing flowing or stationary liquid with gas injected at the bottom of the vessel in the form of bubbles that rise and mix with the liquid phase and facilitate the heat and/or mass exchange. In the biochemical industry, bubble column reactors are used as bioreactors for the production of proteins, enzymes and antibiotics as well as other industrial products (Arcuri et al., 1986; Bordonaro and Curtis, 2000; Son et al., 2000; Chang et al., 2001; Shiao et al., 2002; Nanou et al., 2012). Other chemical processes such as wastewater treatment also utilize bubble column reactors (Matheswaran and Moon, 2009; Lucas et al., 2010). For mechanical applications, bubble column reactors are used as absorbers units for heat absorption refrigeration systems (Fernandez-Seara et al., 2005, 2007; Castro et al., 2009).

In bubble column reactors, the size of the bubble entering the liquid domain is an important design parameter, since it has a direct influence on the two-phase exchange process. A large single bubble will have relatively small surface area to volume ratio compared to numerous small bubbles with the same cumulative volume as the large bubble. The smaller surface area to volume ratio reduces the interfacial area between the two phases, which results in the lower heat and mass exchange rates between the two phases. The growth and detachment of bubbles formed in a two-phase gas liquid vertical co-current flow from a conventional single vertical gas nozzle has been well documented in the scientific literature. Sada et al. (1978) performed an experimental study to measure the size of single and coalesced bubbles that detached from a single nozzle in an unbounded vertical liquid flow. Their results show that the bubble size for liquid-inertia dominated flow can be predicted by a modified Froude number correlation that relates the gas inertial forces, bubble buoyancy forces and the liquid drag on the generated bubble, to the bubble size and nozzle diameter. They observed that the bubble size increases with increasing gas flow rate and decreases with increasing liquid flow rate. Terasaka et al. (1999) also investigated the bubble formation in upward flowing liquid in a column. Through observation of bubble growth at the nozzle tip, they proposed a non-spherical bubble growth model considering the balance of internal and external pressure forces as well as the inertial forces from both gas and liquid flows exerted

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onto the bubble interface. The model predicted the growth of the bubble volume at the nozzle and the volume of the bubble after detachment. The bubble size predictions from their model were in good agreement with experimental results over a range of gas-liquid flow rates ratio (GLR). However, the model was not able to accurately capture the shape of the formed bubbles. Chen and Tan (2002) proposed an interfacial element model to predict the shape and growth of non-spherical bubbles. They compared the bubble size predicted from their model with the experimental results from Terasaka et al. (1999) and found the model predictions to be in good agreement with the experimental data. The model also effectively predicted the shape of a single bubble forming at a nozzle in an upward liquid flow.

In some applications of bubble column reactors, the ratio of gas-liquid flow rates (GLR) exceeds the condition at which a single vertical nozzle can produce bubbly flow (Fernandez-Seara et al., 2005, 2007). The two-phase flow regimes at higher GLRs have been studied in the past. Hewitt (1978) and Hewitt and Roberts (1969) studied two-phase flow regimes in both vertical and horizontal pipes. Through experimental observation of two-phase vertical co-flow, they identified four regimes: Bubbly, Slug, Churn and Annular. Generally, as the GLR increases, the flow regime transitions from a bubbly flow to slug, to churn and finally to annular flow. It has been found that the flow conditions at which the transition from bubbly to slug flow regime occurs is not very sensitive of the pipe geometry (Coleman and Garimella, 1999). Flow transition maps were created to predict the flow regime based on the fluid properties and flowrates of both phases (Hewitt, 1978; Hewitt and Roberts, 1969). However, these maps are valid for the fully developed region of the flow, downstream of the entrance.

Ujang et al. (2006) and Waltrich et al. (2013) studied the evolution of two-phase flow from the entrance region to the fully developed region. These studies show that the flow regime is not only dependent on the GLR but also that the flow regime changes along the length of the pipe as the gas regions coalesce. When the gas is injected into the liquid flow, the initial flow regime may not be the same as the predicted regime from the flow transition maps proposed by Hewitt (1978) and Hewitt and Roberts (1969). A two-phase flow with gas and liquid flowrates corresponding with a slug flow regime can begin as a bubbly flow regime at the pipe entrance immediately downstream of the gas nozzle. As the two-phase flow continues through the pipe, the initial nozzle generated bubbles begin to coalesce forming plug and slug bubbles eventually reaching its fully developed flow regime as predicted by Hewitt (1978), and Hewitt and Roberts (1969).

For bubble column reactors that operate at high GLRs, the regime is not expected to be of the bubbly flow, which constitutes the highest surface area to volume ratio for the gas phase. Hence, to achieve higher mass exchange in the column reactors at high GLRs, a mechanism needs to be used to break large (slug or churn) gas regions and transition the regime back to bubbly flow which otherwise would be in slug or churn flow mode. Several techniques have been reported in literature to generate smaller bubbles or to break large bubbles. Fadavi et al. (2008) investigated the use of a sparger and found a reduction in the bubble size by adding a rotational flow with a passive swirl device to the liquid before the gas was released through the sparger. This swirl increased the shearing force from the rotational liquid and caused early bubble detachment that resulted in smaller bubble generation. The effect of rotational flow was also investigated by Sobrino et al. (2009). They used a perforated plate, rotating at a set speed, to release gas into a fluidized bed. It was found that an increase in the rotational speed of the bed decreased the bubble size at detachment due to the increase in shearing forces. Manabu et al. (1998) investigated the use of a porous nozzle in a stationary water bath. At low gas flow rates, the porous nozzle was found to reduce the size of the injected bubbles. As the gas flow rate increased, the pores' effectiveness reduced and the gas region similar to the slug regime was formed in the pipe. They concluded that the pore has no effect at the higher gas flow rates and the size of the gas region was only dependent on the nozzle diameter.

The turbulent liquid flow has also been shown to control bubble and droplet size in two-phase flows. The study of turbulence in two-phase flow is dated back to the pioneering work of Tikhomirov (1991) and Hinze (1955). Their studies showed that the size of a stable liquid droplet in a turbulent liquid flow is dependent on the integral length scale of the turbulent flow and the turbulent intensity. They proposed a critical Weber number to predict the stable droplet size in a two-phase flow that relates the shear stress of a turbulent eddie to the surface tension of the dispersed phase. If the Weber number of the droplet is greater than the critical Weber number, the turbulent shear stress would cause the droplet to split until the stable droplet size has reached. The same relation can be used in gas-liquid flows to predict the stable bubble size when the liquid flow is turbulent. In recent years, studies have been performed to estimate the critical Weber number and stable bubble or droplet size for a range of specific flows including gas-liquid flow in tubes (Hsiao et al., 1988; Duan et al., 2003; Galinata et al., 2005; Hasketh et al., 1987). By increasing the turbulent intensity in a gas-liquid flow, the probability and frequency of bubble break-up can be increased allowing smaller and more dispersed bubbles to be generated.

Passive devices placed downstream of a single nozzle or bubble dispersion system have also been studied as mechanisms to break up bubbles into smaller daughter bubbles. These devices can be used to add a shearing force to the flow similar to that of a turbulent eddie. Miyahara et al. (1999a, b) investigated bubble breakup in a two-phase vertical co-flow by using an orifice plate and a converging-diverging nozzle. Bubbles were formed from a single nozzle in an upward flowing liquid. The two-phase flow continued through an orifice plate or converging-diverging nozzle forcing a turbulent jet to form. The increased turbulence broke the initial bubble into multiple smaller daughter bubbles. A critical Weber number correlation was developed as a function of the Reynolds number of the flow through the orifice (Miyahara et al., 1999b). The use of multiple sieve trays has been shown to increase mixing of liquid and gas phases for a variety of flow regimes (Alvare and Al-Dahhan, 2006; Yang et al., 2012; Kemoun et al., 2001). The positioning of the trays, the pore size and the opening ratio of the sieves can affect the bubble size distribution, liquid mixing and gas holdup in a vertical tube. Wire-mesh sensors were studied by Prasser et al. (2001) as a non-intrusive method for bubble size measurement in two-phase flows. It was observed that the wire-mesh caused a bubble fragmentation and a cloud of dispersed small bubbles when a relatively small bubble passed through the mesh grid. As the bubble size increased, the occurrence of coalescence increased and the initial bubble was able to reform. For slug and churn flow regimes, a wire mesh would be ineffectively for the breakup and dispersion of the gas phase.

A honeycomb monolith breaker with elongated pores of uniform size was studied by Gadallah and Siddiqui (2015). Their bubble breaker was able to reduce the size of nozzle-generated bubbles by 60%. They also proposed the existence of an optimal liquid velocity that allows for minimal bubble coalescence downstream of the bubble breaker. Mesh-type bubble breakers are an interesting solution as they combine both a shearing force of wire mesh and the two-phase flow dynamics in microchannels. The study of two-phase flow regimes in microchannels has recently been an active topic of research (Serizawa et al., 2002; Triplett et al., 1999; Yue et al., 2008). The flow regime maps for microchannels differ from those of previously mentioned studies that investigated the bubble dynamics and two-phase flow in larger diameter pipes.