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Interaction between partitioning porous plate and rising bubbles in a trayed bubble column

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ABSTRACT

In a trayed bubble column, the structure of the partitioning plate plays an important role on the bubble behavior. This study examined the effect of the opening ratio and pore size of the plate on the bubble break-up frequency and bubble size distribution. The sieve tray was used as the partitioning plate. The opening ratio was closely related to gas cap development. The stagnation of bubble flow and a gas cap were observed with an opening ratio less than 48.5%. The gas cap increased with decreasing opening ratio and increasing superficial gas velocity. The main effect of the sieve tray could be categorized into the additional drag force and bubble break-up depending on the sieve pore size. When the sieve pore size was smaller than the Sauter diameter of the bubble swarm, the movement of rising bubbles was interrupted by the drag force applied by the surrounding mesh lines. On the other hand, when the sieve pore size was larger than the Sauter diameter, the bubbles were affected by the additional bubble break-up. After the bubbles penetrated the sieve tray, the bubble size distribution shifted to a smaller one and the Sauter diameter decreased.

Keywords: Bubble columns; Sieve tray; Opening ratio; Bubble break-up frequency; Bubble size distribution; Sauter diameter

1. Introduction

Bubble column reactors are used widely in industrial practices, such as adsorption, fermentation, bio-reactions and coal liquefaction, given the intrinsic advantages of the good mixing ability, high heat transfer efficiency and operation versatility (Kantarci et al., 2005; Ribeiro and Mewes, 2007). In particular, in industrial applications introducing the reactants as a gas phase, the bubble induced mixing improves the mass transfer between reactants and catalysts as well as the reaction efficiency. Therefore, the mass transfer rate and gas hold-up (ε_G) are representatively used to evaluate the efficiency of bubble columns. The gas hold-up is defined as the volume ratio of the gas phase present in the mixture in the reactor.

The gas hold-up is strongly affected by the flow regime, bubble size distribution and liquid circulation velocity. In bubble column reactors, the flow pattern can be categorized into three distinguished flow regimes depending on the superficial gas velocity, which is the volumetric gas flow rate divided by the column cross-sectional area. At a low gas velocity, the homogeneous flow regime is formed and characterized by the small and narrow bubble size distribution with small scale transverse oscillations. In this flow regime, there are weak interactions among the bubbles causing low breakage and coalescence frequencies. As the bubble packing density increases at higher gas velocities, bubble flow loses its stability exhibiting a helical flow pattern and liquid circulation. This heterogeneous flow regime is characterized by large and fast-rising bubbles of which the size distribution is strongly

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Nomenclature

d_B	bubble diameter (m)
D_C	column diameter (m)
d_{SP}	sieve pore size (m)
F_B	bubble break-up frequency
$f_{b,n}$	number of cases in which a single bubble is broken-up into n bubbles
$f_{c,k}$	number of cases in which k bubbles coalesce into a single bubble
f_0	number of cases in which the bubbles experience no bubble break-up and coalescence
g	gravitational acceleration (m s^{-2})
h	column height (m)
ΔP_0	pressure difference for constant column height before gas bubbling
ΔP_b	pressure difference for constant column height after gas bubbling
u_G	gas superficial velocity (m s^{-1})

Greek letters

ε_G	gas hold-up
ρ_l	liquid phase density (kg/m^3)
ρ_g	gas phase density (kg/m^3)

influenced by dynamic equilibrium between bubble coalescence and break-up (Chaumat et al., 2007). The transition flow regime is positioned between the homogeneous and heterogeneous flow regimes.

The bubble behavior in a bubble column is also dependent on the reactor design parameters as well as the operating conditions such as liquid properties (Ribeiro and Mewes, 2007; Chaumat et al., 2007; Li and Prakash, 2000; Ruzicka et al., 2003; Yang et al., 2010), reactor temperature and pressure (Wilkinson and Dierendonck, 1990; Behkish et al., 2007; Krishna et al., 2000) and superficial gas velocity. Many researchers have examined different reactor designs to improve the overall gas hold-up (Davis, 2002; Michael, 1956; Kölbel and Ackermann, 1958; Chang, 1994; Jiang et al., 2006). Michael (1956) reported the effect of an internal central tube on the liquid circulation within the reactors. Kölbel and Ackermann (1958) introduced a reactor with long shafts to minimize the liquid circulation. Chang (1994) incorporated a peripheral downcomer into a slurry bubble column reactor to enhance the gas separation. Jiang et al. (2006) examined the effect of the arrangement of internal structures, such as cooling tubes in the bubble column.

In addition, there has been considerable research on the trayed bubble column reactor (Thaker and Rao, 2007; Alvaré and Al-Dahhan, 2006a,b; Kemoun et al., 2001; Doshi and Pandit, 2005; Dreher and Krishna, 2001). For example, Thaker and Rao (2007) reported that the staging of the column caused an increase of the mass-transfer coefficient and gas hold-up. Alvaré and Al-Dahhan (2006a), in their review on axial mixing in trayed bubble columns, examined the effect of tray structure and operating conditions using a co-current up-flow bubble column. They concluded that the tray open area and superficial liquid velocity had the strongest effects on liquid backmixing. In an additional study, they reported that the tray hole diameter and superficial gas velocity were the most important factors to consider for increasing the overall gas hold-up (Alvaré and Al-Dahhan, 2006b). On the other hand, Kemoun et al. (2001) observed the local and overall gas hold-up in a trayed bubble column using γ-ray computed tomography and suggested that the trays have no effect on improving the overall gas hold-up, which contradicted previous research results. This opposing result might be because the Kemoun group used their own design for trays that contain a downcomer zone.

According to Doshi and Pandit (2005), the gas cap accumulated by bubbles was formed below the partitioning plate in a trayed bubble column. The gas cap is dispersed in the form of gas layer, not gas bubbles, therefore causing the decrease of the interfacial area between the gas and liquid phases. This gas cap increased in height with increasing superficial gas velocity and made a large contribution towards the increase in apparent gas hold-up. Dreher and Krishna (2001) also reported an increase in gas cap with increasing superficial gas velocity.

This undesirable gas cap for mass transfer may be because of the relatively low opening area of partition plates. The opening ratio is defined as the ratio of the area open by pores to the total plate area. The high gas flow rate will be blocked by a narrow opening area of the partitioning plates and the pressure will increase to form gas cap below the plates. Table 1 lists the opening ratio of the partitioning plates used in previous studies. Therefore, to examine the effect of the partitioning sieve on the gas hold-up variation more reasonably, it is important to choose the experimental conditions without generating a gas cap. The present study employed sieve trays with high opening ratios above 60% to observe the effect of their geometry on the bubble behavior. Although there have been many previous studies on a trayed bubble column, little attention has been given to the interaction between the rising bubbles and trays. This study is concerned with the changes in gas hold-up, bubble break-up frequency and bubble size distributions with a range of sieve tray pore sizes.

2. Materials and methods

Fig. 1 shows a schematic diagram of the experimental setup used to observe the bubble behavior variation in a trayed bubble column. The experiments were carried out in a 0.15 m diameter and 1.70 m tall cylindrical bubble column with a top open to the atmosphere.

The bubble column was sectionalized into four stages by three partitioning plates that were placed at a constant interval of 0.4 m. The partitioning plate assumes the sieve tray in the form of a mesh with a fixed pore size that ranges from 1.01 mm to 16.9 mm. To investigate the effect of the sieve pore size, the thickness of the sieve tray was less than 1.6 mm. We identified no effect of the tray thickness below 3.2 mm on the gas hold-up and bubble behavior (the experimental result is not shown here). The opening ratio of each sieve tray remained above 60% to minimize the effect of the gas cap.

To examine the effect of the opening ratio on gas cap development, the sieve tray with a pore size of 4.4 mm was combined with the screening plates. The screening plate had the form of a concentric circle which consisted of the open inner part and closed outer part. The gas flow penetrated through the open inner space. The opening ratio was controlled by changing the open area of the screening plate. Table 2 lists the characteristics of the sieve trays used in this study.

A perforated metallic tube was employed as a sparger at the bottom of the bubble column. It contained 66 orifices