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Liquid flow pattern transition, droplet diameter and size distribution in the cavity zone of a rotating packed bed: A visual study

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ABSTRACT

A rotating packed bed (RPB) is one of the typical process intensification equipment. Its zone between the packing and the casing (cavity zone) is an important mass transfer zone. However, the liquid flow pattern, droplet diameter and size distribution in the cavity zone of a RPB, which is essential for the mass transfer modeling and performance, are still unclear. In this work, the liquid flow in the cavity zone of a RPB was studied under different experimental conditions using photographs taken by a high-speed camera. Two typical liquid flow patterns and liquid disintegrating modes were observed. A flow pattern transition criterion for the transition of ligament flow to droplet flow was presented. Effects of rotational speed, liquid initial velocity, outer packing radius, liquid viscosity, and liquid surface tension on the average droplet diameter and droplet size distribution were investigated. Furthermore, a correlation of the average droplet diameter was proposed. The predicted values of the average droplet diameter were found to be in agreement with the experimental values with deviations generally within ± 15%.

1. Introduction

The rotating packed bed (RPB), invented by Ramshaw et al. (Ramshaw and Mallinson, 1981), is one of the typical process intensification equipment. The liquid introduced into the rotor of a RPB is sheared by the porous packing, thus generating an excellent dispersion of the liquid and leading to the enhancement of mass transfer and micromixing. RPBs have been recognized as high-efficiency contactors or reactors, which have been widely applied in polymer devolatilization (Chen et al., 2010), sulfonation (Zhang et al., 2010), absorption (Agarwal et al., 2010; Chu et al., 2014), production of nanoparticles (Chen et al., 2003), etc.

The contribution in the eye of the rotor to the total mass transfer is negligible since the lengths of liquid jets from the distributor are small (Munjal et al., 1989). The mass transfer region in a RPB can be divided into the end zone, bulk zone, and cavity zone, as shown in Fig. 1(a) (Guo, 1996). The end zone, which has a strong interaction among multiphase fluids, ranges from the inner edge of the packing to a few millimeters depth in the radial direction. The rest of the packing is called the bulk zone. The cavity zone is an annular space between the outer edge of the packing and the inner edge of the casing. However, most researches focused on mass transfer in the end zone and bulk zone (Guo et al., 1997, 2014a; Qian et al., 2009; Yi et al., 2009), and little attention was paid to the mass transfer in the cavity zone. Yang et al. (2011) reported that the mass transfer contribution of the cavity zone is about 13–25% of the total mass transfer in the RPB with the system of chemisorption of CO_2 into a NaOH solution. Guo et al. (2014b) found that the effective mass transfer area of the cavity zone takes up around 30% in the whole RPB with the same test system. The above mentioned results proved that the mass transfer in the cavity zone of the RPB cannot be ignored. Up to now, the study on the liquid flow in the cavity zone is still far from sufficient, which hence limits the profound understanding of its mass transfer modeling and performance.

Several types of visual studies have been employed to obtain fundamental data of the liquid flow in a RPB. Burns and Ramshaw (1996) used a 35 mm camera to observe the liquid flow in a RPB and reported that there were three modes of liquid behavior: droplet, film, and pore flow. Zhang (1996) observed a considerable number of liquid films flowing in the bulk zone by high-speed stroboscopic photography. Guo (1996) utilized a video camera with image resolution 542 (W)×582 (H) pixels to investigate the liquid flow in a RPB, and observed that the

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Nomenclature

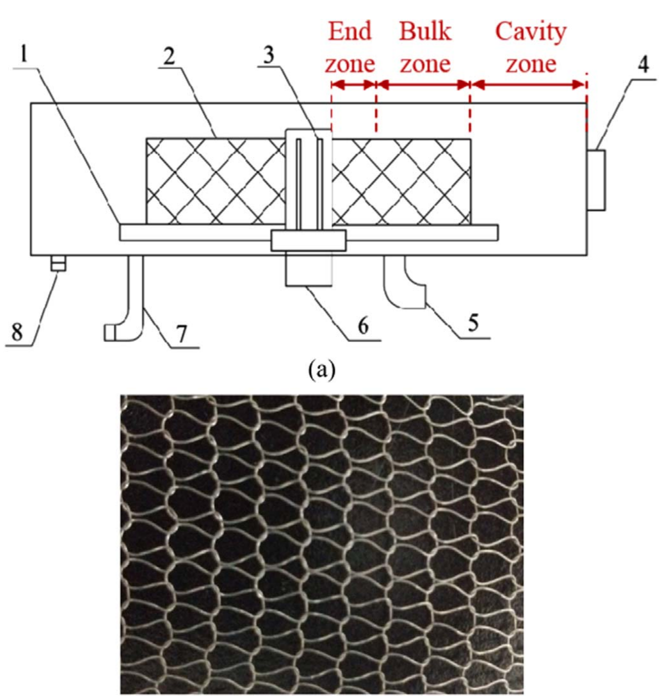
D	outer rotor radius (m)
d	droplet diameter (mm)
d_N	diameter of nozzles (mm)
N	rotational speed (r/min)
n	number of nozzles
Q	liquid flow rate (L/h)
q	liquid initial velocity number
R	outer packing radius (m)
Re	Reynolds number
u_0	liquid initial velocity ($=Q/n\frac{\pi}{4}(d_N)^2$, m/s)
u	droplet velocity (m/s)
V	cumulative volume fraction
We	Weber number

Greek symbols

μ	viscosity (mPa s)
ρ	liquid density (kg/m^3)
σ	surface tension (mN/m)
ω	angular velocity (1/s)
λ	calibrated spatial resolution of the droplet photograph (mm/pixel)

Subscripts

g	gas phase
l	liquid phase
b	breakup



(b)

Fig. 1. (a) Schematic of RPB and (b) photograph of stainless steel wire mesh packing (1) rotor; (2) packing; (3) liquid distributor; (4) gas inlet; (5) gas outlet; (6) shaft; (7) liquid inlet; (8) liquid outlet.

liquid flow pattern was complex in the end zone. Also, liquid film flow was observed on the packing's surface when the rotational speed ranged from 300 to 1100 r/min and pore flow was observed in the gap of packing layers when the rotational speed ranged from 300 to 600 r/min. Yan et al. (2012) investigated the liquid flow with capturing colored liquid trajectories on the plates in a RPB. The flow of liquid in the bulk zone as film, droplet, and ligament was observed. Recently, Li et al. (2015) used a high-speed camera to study the liquid flow in a rotor-stator reactor without packing. Effects of the number of rotor-ring/stator-ring layers on the liquid flow pattern were investigated and demonstrated that the droplet flow was the main pattern.

Aforementioned visual studies were mainly conducted for the end zone and bulk zone of the RPB. However, information about the liquid flow, such as liquid flow patterns and liquid disintegrating modes, produced by the packing in the cavity zone of a RPB was scarce. The present work investigated the effects of rotational speed, liquid initial velocity, outer packing radius as well as liquid viscosity and surface tension on liquid flow pattern, droplets diameter, and droplets size distribution using photographs taken by a high-speed camera. Based on the analysis of the consecutive frames of photographs, liquid disintegrating modes on the outermost packing layer were presented. Additionally, a correlation of the average droplet diameter was proposed.

2. Experimental section

2.1. Structure of RPB

Fig. 1(a) is a schematic of the RPB used in this study. Its dimensions and operating conditions are listed in Table 1. The stainless steel wire mesh packing is shown in Fig. 1(b). It has a specific surface area of 500 m^2/m^3, porosity of 0.97, and fiber diameter of 0.22 mm. The first packing layer fixed at the inner support of the rotor and the outer packing radius can be varied by changing the number of packing layers.

2.2. Experimental setup and materials

The experimental setup as illustrated in Fig. 2(a) consisted of a RPB system and an image acquisition system. For the RPB system, the liquid was fed into the rotor through a stationary distributor. It moved radially outwards through the rotor driven by the centrifugal force generated by the rotating shaft. The liquid distributor consisted of two tubes configured in parallel to the axis, and each tube has one 3 mm nozzle. The liquid phase was subsequently collected at the bottom of the casing and discharged through the liquid outlet.

The image acquisition system comprised a high speed camera (FASTCAM SA4, Photron Limited, Japan) in combination with two lenses (AF 60 mm f/2.8D, Nikkor; AF 200 mm f/4D, Nikon Co., Japan), 1300 W lamp (ZF-1300, Shanghai Photographic Equipment

Table 1
Specifications of the RPB and operating conditions.

Items	Values
Geometrical Parameters of RPB	
Outer radial of casing (m)	0.317
Outer radial of rotor (m)	0.2225
Inner radial of rotor (m)	0.088
Height of rotor (m)	0.054
Operating Conditions	
Rotational speed (r/min)	300, 500, 700, 900, 1100
Liquid initial velocity (m/s)	1.179, 1.965, 2.751
Outer packing radius (m)	0.1025, 0.1225, 0.1425, 0.1825, 0.2025, 0.2225