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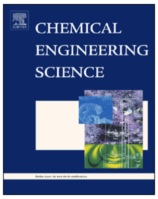

Visual study of liquid flow in a rotor-stator reactor

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HIGHLIGHTS

- Liquid flow of water and microemulsion in a rotor-stator reactor (RSR) was studied.
- A high-speed camera was used to obtain continuous and clear images of liquid flow.
- Diameter of droplets reduced with increasing layers of rotor-ring/stator-ring.
- Velocity of droplets rose with increasing layers of rotor-ring/stator-ring.
- Correlations were established to predict the diameter and velocity of droplets.

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ABSTRACT

A rotor-stator reactor (RSR) is a novel multiphase device which can greatly intensify mass transfer and micromixing processes. However, liquid flow in the reactor is still not very clear. In this work, two different liquids, water and water-in-oil (W/O) microemulsion were used to study liquid flow in the RSR. A high-speed camera was employed to obtain continuous and clear images of liquid flow, and the effects of various operating conditions such as the number of rotor-ring/stator-ring layers, the rotation speed and the liquid volumetric flow rate on the average diameter as well as the average velocity of liquid droplets and the average angle of velocity vector were investigated. Correlations were established to predict the average diameter and the average velocity of the liquid droplets, and the predicted values were found to be in agreement with the experimental values with deviations generally within 15%.

1. Introduction

The need for intensification of mass transfer and micromixing processes has led to the development of various multiphase reactors. A typical one is the rotating packed bed (RPB) (Ramshaw and Mallinson, 1979), which has been successfully applied in gas–liquid systems (Luo et al., 2012; Zhang et al., 2011), liquid–liquid systems (Zhao et al., 2007) and liquid–solid systems (Lin and Liu, 2000). On the basis of the RPB, a rotor-stator reactor (RSR), which is a novel Higee device consisting mainly of a series of concentric rotor-rings and stator-rings alternately configured in the radial direction, was proposed in 2006 (Song et al., 2006). In the RSR, high speed rotation of the rotor creates a centrifugal shear field which causes the liquid stream to split into small liquid droplets, thin liquid films and violent turbulence of the gas and liquid streams, resulting in a remarkable intensification of both micromixing and mass transfer processes. Micromixing is concerned with those features of mixing which cause the attainment of homogeneity on the molecular level (Baldyga and Pohorecki, 1995). As a matter of fact, the micromixing time in the RSR has been calculated to be about 10^{-5} s, indicating its excellent micromixing efficiency (Chu et al., 2007). Therefore, the RSR has shown good performance in the preparation of oil-in-water emulsion (Lu et al., 2008) and nano-$CaCO_3$ (Chu et al., 2005).

Studies on transport and hydrodynamic characteristics of fluid flow in reactors are highly necessary for industrial scale-up (Heindel et al., 2008). Several methods have been used to obtain visual data of liquid flow in Higee devices. For instance, Burns and Ramshaw (1996) employed a 35 mm camera to photograph liquid

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flow within the packing of RPB and to study liquid maldistribution. They also determined that the forms of liquid flowing within the packing fall into three main types: film flow, droplet flow and pore flow. Guo (1996) used a video camera fixed on the packing of the RPB to obtain continuous images of liquid flow inside the packing, and confirmed the existence of the end effect zone. Moreover, Zhang (1996) employed light impulse instead of the usual shutter to control the exposure time of photographic plate in order to obtain clear images of liquid flow in the RPB, and observed that liquid flowed in the form of films on the surface of packing, and in the form of droplets in both the end and shell zones.

However, both the photograph and camera shooting methods have the limitation of poor clarity owing to the quick movement of the liquid droplets, whereas the light impulse technique cannot give continuous images due to the limitation of the camera itself. Efforts to improve clarity and to obtain continuous images of liquid flow in multiphase reactors have been made by employing high-speed cameras (Hu et al., 2006, 2007; Mueller, 2009; Yang et al., 2000).

As a novel Higee reactor, the intensification mechanism of mass transfer and micromixing in the RSR is unclear. This knowledge is critical for the scale-up and industrial application of the RSR. Studies on the hydrodynamic characteristics of fluid flow in the RSR will lay the foundation for elucidating the mass transfer and micromixing behaviors in the RSR. To the best of our knowledge, there are no reports on the liquid flow in the RSR. Therefore, this study aimed to investigate the liquid flow inside the RSR by employing a non-invasive technique involving a high-speed camera and a specially designed RSR. The shape, size and velocity vector of the liquid droplets in the RSR were investigated for the first time. The effects of various operating conditions including the number of rotor-ring/stator-ring layers, the rotation speed and the liquid volumetric flow rate on the average diameter and average velocity of water and microemulsion droplets as well as the average angle of velocity vector were investigated.

2. Experimental section

2.1. Structure and characteristics of the RSR

Fig. 1(a) shows a schematic diagram of an RSR, which mainly consists of a series of concentric rotor-rings and stator-rings alternately configured in the radial direction. The rotor comprises six rotor-rings fixed concentrically on the motor-driven rotor seat, while the stator consists of five stator-rings formed by pins mounted concentrically on the cover cap. The open space and holes on the stator-rings and rotor-rings (as shown in Fig. 1(b)) form the radial channels for the liquid stream.

2.2. Experimental setup and procedure

Fig. 2 shows a schematic diagram of the experimental setup used for visualization of liquid flow in the RSR. The RSR employed in this study was specially designed for visual observation, and its specifications are shown in Table 1. Liquid was pumped into the RSR through the liquid inlet and sprayed uniformly to the innermost layer of the rotor-ring via a nozzle. It then flowed radially outwards through the rotor-rings and stator-rings under the action of centrifugal force generated by the rotation of the rotor, and finally left the RSR via the liquid outlet. In order to observe the liquid flow, the full metallic cover cap of the RSR was replaced with a partial version, which could hold stator-rings of different layers.

A high-speed camera (FASTCAM SA4, Photron Limited, Japan) with a prime lens (AF 50 mm f/1.4D, Nikon Co., Japan) was placed vertically above the cover cap, and the specifications of the camera and the lens are shown in Table 2. Two spot lights (ZF-1300, Shanghai Photographic Equipment Factory, China) were employed as supplementary lights.

Water and water-in-oil (W/O) microemulsion were used as the liquid streams, respectively. The W/O microemulsion was obtained by directly mixing surfactant (S) of octyl phenoxy poly ethoxy (Triton X-100, Chemically Pure, Tianjin Guangfu Fine Chemical Research Institute, China), cosurfactant (C) of 1-pentanol (Analytically Pure, Tianjin Guangfu Chemical Reagent Factory, China), oil phase (O) of cyclohexane (Analytically Pure, Beijing Chemical Works, China) and water phase of deionized water under vigorous stirring. Its composition was maintained at a fixed ratio of S/C/O=3/3/4 (w/w) with a water content of 10 wt%. The properties of the W/O microemulsion are shown in Table 3.

The obtained images were processed by Image J software through human–computer conversational mode. The process involved demarcating the boundary of the liquid droplets in order

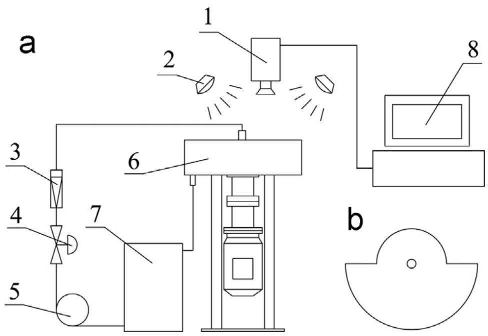

Fig. 2. Experimental setup for the visualization of liquid flow in the RSR. (1) High-speed camera; (2) spot light; (3) flowmeter; (4) valve; (5) pump; (6) RSR; (7) tank; (8) computer; and (9) top view of the cover cap.

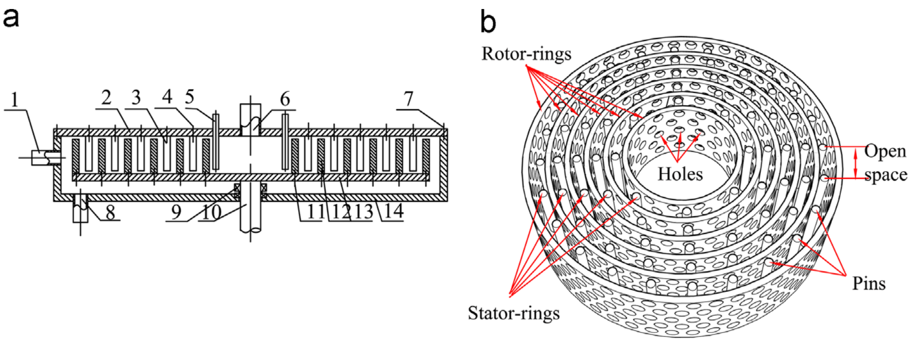

Fig. 1. Schematic diagram of RSR. (a) Structure of RSR; (b) 3D diagram of rotor-rings and stator-rings (1) gas inlet; (2) cover cap; (3) stator; (4, 7, 11) bolts; (5) nozzle; (6) gas outlet; (8) liquid outlet; (9) seal; (10) shaft; (12) rotor; (13) rotor seat; and (14) casing.