Chemical Engineering Journal 346 (2018) 329–339

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Convective mixing of miscible liquids in a rotor-stator spinning disk reactor

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HIGHLIGHTS

- Convective mixing of liquids in a rotor–stator spinning disk reactor is studied.
- Laminar flow generated by the fluid injection into a thin cavity is focused.
- Light-induced fluorescence is used to evaluate mixedness of injected liquids.
- Mixing enhancement is achieved by the densely layered structure in the cavity.
- An empirical model is proposed to correlate the observed mixing enhancement.

ARTICLE INFO

Keywords:
Rotor-stator spinning disk reactor
Convective mixing
Laminar flow
Miscible liquid
Light induced fluorescent technique
CFD simulation

ABSTRACT

Convective mixing of two miscible liquids injected into a rotor-stator spinning disk reactor (RS-SDR) has been studied using an LIF technique and CFD simulations. The fluids are ammonia water and fluorescein ammonia water solutions. The RS-SDR has a rotor 100 mm in diameter and a thin circular cavity 0.10–0.15 mm in height between the rotor and stator. Laminar flow conditions for rotation speeds up to 120 rpm and total flow rates up to 8 mL/min are considered. The fluorescein solution is injected from the second off-center hole into the cavity filled with the ammonia water supplied from the central hole. The LIF technique visualizes a spiral streak pattern formed downstream of the second injection hole. This streak pattern is analyzed to calculate the local mixedness of the two fluids. It is determined that the mixedness increases for lower flow rates, while it is less sensitive to rotation speed and cavity height. The CFD simulations indicate that the spiral streak pattern is deformed and stretched in the radial direction to form a densely layered structure of the two fluids. The development of the mixedness along the streak pattern is correlated well with Re_{inlet}/Re_{cavity}, where Re_{inlet} and Re_{cavity} are the Reynolds numbers for the injected flow and the azimuthal flow in the cavity, respectively. This Reynolds number ratio is shown to be related to the Rossby number and the position and radius of the second injection hole. The proposed correlation is based on a linear combination of injection mixing and rotation mixing. The mixedness decreases with Re_{inlet}/Re_{cavity} because the injection mixing decreases with Re_{inlet} while the rotation mixing increases with Re_{cavity}.

1. Introduction

Mixing processes depend on the time and length scales of the flows that consist of higher and lower concentration regions. As shown by Bothe et al. [1], Kockmann et al. [2] and others, mixing processes are controlled by the fluid convective motions responsible for the stretching and folding of the concentration regions and by the diffusive mixing due to molecular diffusion through the interfaces between the folded regions. The enhancement of such convective mixing is therefore crucial for improving the total efficiency of fluid mixing. Some examples of this enhancement applied to the microreactors are the convective mixing in serpentine channels reported by Plouffe et al. [3], the collision of microsegments proposed by Nagasawa et al. [4], and the enhanced engulfment in a T-shaped microchannel described by Matsunaga and Nishino [5]. Hessel et al. [6] classified the micromixing devices into passive and active types. They summarized various active micromixing methods such as the periodic flow switching method, the acoustic fluid shaking method, the electrokinetic instability method, the electrowetting-induced droplet shaking method and the ultrasound/piezoelectric membrane action method.

A stator-less rotating disk reactor is proposed as a promising active micromixing device, as studied experimentally and theoretically by Aoune and Ramshow [7]. They showed that highly effective heat and mass transfer is realized in water solution. Among various active mixing

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https://doi.org/10.1016/j.cej.2018.04.002
Received 29 December 2017; Received in revised form 3 March 2018; Accepted 2 April 2018
Available online 03 April 2018
1385-8947/

Nomenclature

General

Symbol	Description (units)
a	conversion coefficient between B and I (–)
B	16-bit brightness level of LIF image (–)
B_{ref}	reference level of B (–)
C	concentration (mol/L)
C_{ref}	reference value of C (mol/L)
$\widetilde{C}$	normalized concentration (= C/C_{ref}) (–)
$\widetilde{C}_{max}^{(k)},\widetilde{C}_{min}^{(k)}$	normalized maximum and minimum concentrations in the kth turn of the spiral streak (–)
H	cavity height (mm)
I	LIF intensity (–)
I_0	excitation light intensity for LIF (–)
I_{ref}	reference LIF intensity of I (–)
k	the number of turns
M_x, M_i, M_c	total mixedness, mixedness due to inlet mixing and cavity mixing (–)
pH	power of hydrogen (–)
Q_C	volume flow rate at the central inlet (mm^3s^{-1}ormL/min)
Q_S	volume flow rate at the second inlet (mm^3s^{-1}ormL/min)
Q_T	total volume flow rate (= $Q_C + Q_S$) (mm^3s^{-1}or mL/min)
R_D	radius of the rotor (mm)
R_I	radial coordinate of the second inlet (mm)
R_S	radius of the second inlet hole (mm)
Re_{cavity}	Reynolds number in the azimuthal flow in the cavity (= $\Omega R_I H/\nu$) (–)
Re_{inlet}	Reynolds numbers for the injected flow (= $Q_T/(\pi R_S \nu)$) (–)
$r,\widetilde{r}$	radial coordinate (mm) and its normalized value (= r/R_I) (–)
$r_{max}^{(k)}$, $r_{min}^{(k)}$	normalized radial coordinates for $\widetilde{C}_{max}^{(k)}$ and $\widetilde{C}_{min}^{(k)}$ (–)
T	temperature (°C)
$u_r,\widetilde{u}_r$	radial flow velocity (mms^{-1}) and its normalized value (= $u_r/(Q_T/(2\pi R_I H))$) (–)
$u_\theta,\widetilde{u}_\theta$	azimuthal flow velocity (mms^{-1}) and its normalized value (= $u_\theta/(\Omega R_I)$) (–)
$z,\widetilde{z}$	channel height coordinate (mm) and its normalized value (= z/H) (–)

Greek letters

ν	kinematic viscosity (mm^{2}/s)
Φ	quantum efficiency of fluorescence (–)
θ	azimuthal angle measured from the center of the second inlet (rad)
$\theta^{(k)}$	azimuthal angle in the kth turn of the spiral streak (rad)
Ω	angular velocity ($rads^{-1}$) or rotation speed (rpm)

techniques, the use of a thin fluid layer formed between a rotating disk and a stationary disk is another promising approach as demonstrated by Meeuwse et al. [8,9], Visscher et al. [10] and de Beer et al. [11]. The presence of the strong shear and the three-dimensional fluid motion in the layer can remarkably enhance the convective mixing of the fluids. Meeuwse et al. [8,9] studied gas-liquid and liquid-solid mass transfers in a rotor-stator spinning disk reactor (RS-SDR, hereafter) with a 132 mm disk diameter and a 1 mm rotor-stator cavity height. The maximum rotation speed was 180 rad/s (1710 rpm) and they demonstrated a noteworthy mass transfer augmentation in the layer between the disks. Visscher et al. [10] used the same RS-SDR and obtained up to 15 times higher mass transfer rates than those obtained in the state-of-the-art microchannels available at the time. Such attractive features of an RS-SDR were studied in more detail by de Beer et al. [11], who proposed a flow-pattern map for single-phase flows in a RS-SDR. Martinez et al. [12] measured the micromixing time in the RS-SDR proposed by Meeuwse et al. [8,9] by using the Villermaux–Dushman reaction. The micromixing times measured range from 0.113×10^{-3} s to 8.76×10^{-3} s, thus demonstrating remarkable rapid micromixing.

The flow structures and related characteristics in the RS-SDR cavity have been studied extensively. Experimental work by Daily & Nece [13] considered enclosed flow configurations where the disk Reynolds number, $\Omega R_D^2/\nu$, varied in a wide range from 10^3 to 10^7 and the axial clearance parameter, H/R_D, varied in the range of 0.0127–0.217. They reported four flow regimes classified by the conditions if the flow is laminar or turbulent and if there are merged boundary layers or separated boundary layers. The flow transition in the enclosed-cavity configuration drew much attention previously as reported by Schouveiler et al. [14] and reviewed by Launder et al. [15]. The effect of the throughflow in the cavity was studied by Poncet et al. [16,17] who reported the transition between a Batchelor flow with two boundary layers separated by a central rotating core and a Stewartson flow with only one boundary layer on the rotating disk.

Unlike previous studies on the flow transition, this work focuses on the convective mixing due to fluid injection into the outward throughflow in the cavity of an RS-SDR. The outward throughflow is generated by a continuous supply of the first fluid through the central hole and the second fluid is injected through an off-center hole in the stator. The potential for convective mixing enhancement in RS-SDR demonstrated by the previous studies mentioned above is further pursued in this study. Much smaller cavity heights (i.e., 0.10–0.15 mm) than those studied previously are used in the present reactor with a 100 mm disk diameter. The resultant disk clearance ratio is less than 0.003. Rotation speeds as high as 120 rpm (and corresponding disk Reynolds numbers up to 31,300) are given to the rotor and the flows in the fluid layer between the rotor and the stator remain laminar throughout the present conditions. The convective mixing of the two miscible liquids, i.e., ammonia water and fluorescein ammonia water solutions, both injected into the cavity, is visualized. A light-induced fluorescence (LIF) technique is used to evaluate the degree of convective mixing. This LIF technique confirms that the flow in the cavity is laminar throughout the present experimental conditions. This observation is consistent with the presence of the laminar flow with the merged boundary layer reported by Poncet et al. [16,17] and also with the presence of the laminar torsional Couette flow reported by de Beer et al. [11]. The effects of the total injection flow rate, rotation speeds and cavity heights on mixedness are examined in detail. CFD simulations are also carried out to clarify the three-dimensional characteristics of the flow responsible for the enhancement of convective mixing in the cavity. A simple empirical model is proposed to describe the convective mixing enhancement in the RS-SDR.

2. Method

2.1. Rotor-stator spinning disk reactor

The RS-SDR studied here has a rotor driven by a DC servo-motor and a cylindrical chamber filled with liquid as shown in Fig. 1. The reaction space of the RS-SDR consists of three cavities: the mixing cavity, the reaction cavity and the connection cavity. The mixing cavity is a thin gap between the rotor and stator. The stator is made of polished synthetic quartz glass 15 mm thick for optical observation and has a central hole and 9 off-center holes. The central hole and the off-center holes are 0.8 mm and 0.38 mm in diameter, respectively and they are perpendicular to the stator surface. Only one of the 9 off-center holes, located 27 mm from the central hole, is used with the central hole in the present