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Short communication

Micromixing efficiency of a novel rotor–stator reactor

Guang-Wen Chu [a], Yun-Hua Song [a,*], Hai-Jian Yang [a], Jian-Ming Chen [a], Han Chen [b], Jian-Feng Chen [a]

[a] *Research Center of the Ministry of Education for High Gravity Engineering & Technology, Beijing University of Chemical Technology, Beijing 100029, PR China*

[b] *College of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing 100029, PR China*

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Abstract

The importance of inlet region of rotating packed bed (RPB) was confirmed recently. This enlightened us to design another novel reactor, named rotor–stator reactor (RSR), which has multiple inlet regions along radial direction. The micromixing efficiency of RSR was studied by adopting the iodide–iodate reaction as working system. The effects of operating conditions (e.g. rotor speed and reagent concentration) on micromixing efficiency (characterized by segregation index X_S) were investigated. In addition, the effects of different rotor–stator combinations as well as the amount of rotor- and stator-ring on micromixing efficiency were also considered. Based on the incorporation model, the micromixing time of RSR was estimated to reach about 10^{-5} s, which is less than that of rotating packed bed (about 10^{-4} s).

Keywords: Rotor–stator reactor (RSR); Micromixing; Segregation index; Iodide–iodate reaction system; Incorporation model

1. Introduction

Micromixing of reactors have a large influence on the product distribution of a fast chemical reaction. For example, micromixing may influence crystal size distribution and average size of crystal. In polymerization, the molecular weight distribution was also depended on micromixing efficiency of the reactor [1]. Therefore, the development of new reactor provided with excellent micromixing efficiency is necessary and popular.

Micromixing efficiency of many reactors have been studied, including centrifugal pump [2], Tee mixers [3], tubular reactor [4], rotor–stator mixers [5,6], aerated stirred tank [7], couette flow reactor [8], static mixer [9] and so on. Twenty years ago, Ramshaw [10] highlighted rotating packed bed (RPB), a novel reactor that utilizes centrifugal acceleration to intensify mixing and mass transfer. So far, RPB has been applied to desorption [11], absorption [12], distillation [13], ozone oxidation [14] and reactive crystallization [15–17], etc. Our recent research on micromixing efficiency of RPB confirmed that inlet region of RPB plays a very important role in the mixing and reaction [18]. This result enlightened us to design another novel reactor, named rotor–stator reactor (RSR), which has multiple inlet regions arranged in series along radial direction and was expected to exhibit better micromixing efficiency.

In present work, the basic structure and characteristics of RSR was introduced first, and then the effect of operational conditions and different structures on micromixing efficiency was investigated by employing iodide–iodate reaction system. In addition, based on the incorporation model, the micromixing time of RSR was estimated according to our experimental data.

2. Experiments

2.1. Basic structure and characteristics of RSR

The basic structure of RSR was schematically described in Fig. 1. In a RSR, the rotor consists of five rings (named rotor-ring) fixed concentrically on the rotor-seat, which is driven by a motor at a speed ranging from 150 to 2400 rpm (controlled by a frequency inverter); while the stator consists of four rings (named stator-ring) mounted concentrically on the cover cap. The opened slots or holes around the circular of rotor-ring and stator-ring formed channels of fluids. Three different rotors with straight, curve slots or holes around the circular of rotor-rings were used in experiments, they were named RS,

* Corresponding author. Tel.: +86 10 64412332; fax: +86 10 64412332.
E-mail address: songhy@mail.buct.edu.cn (Y.-H. Song).

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Nomenclature

A	solution containing $H_2BO_3^-$, I^-, IO_3^-
B	H_2SO_4 solution
C_j	concentration of species j (mol L^{-1})
N	rotor speed (rpm)
n_j	molar amount of species j
X_S	segregation index
Y	selectivity of acid
Y_{ST}	selectivity at the total segregation
Greek letters	
τ_m	micromixing time (s)
τ_r	characteristic reaction time (s)

RC and RH, respectively (Fig. 2(a)). Two different stators with straight and curve slots around the circular of stator-rings were used in experiments, they were named SS and SC, respectively (Fig. 2(b)). Therefore, six rotor–stator combinations (named RS–SS, RS–SC, RC–SS, RC–SC, RH–SS, RH–SC) were used in experiments. The inner diameter of each rotor-ring and corresponding stator-ring was different, which was 52, 80, 108, 136, 164 mm for rotor-ring and 66, 94, 122 and 150 mm for stator-rings, respectively. In radial direction, the rotor-rings and stator-rings were arranged in an interval sequence. The thickness in radial direction of each ring was 6 mm, so the gap in radial direction between each rotor-ring and corresponding stator-ring was 1 mm. Aside from being specially announced, the amount of rotor- and stator-rings is respectively 5 and 4 in context, and the rotor–stator combination used is RS–SS because of its simple structure and easy to be manufactured.

As mentioned above, the main characteristics of RSR were as follows: (a) the rotor- and stator-rings were arranged in an interval sequence in radial direction, which consists of multiple inlet regions along radius direction. The fluid was redistributed when passing through every stator-ring; (b) fluid was fully dispersed when passing through the slots or holes opened on rotor-rings and stator-rings, so high surface renewing ratio of fluid elements can be obtained; (c) the channel of fluid can not be fouled because fluid stands high shear force when passing through the gaps between the rotor-ring and corresponding stator-ring. It is suitable for high viscous or crystal system; (d) RSR has excellent flexibility because the rings were fixed on cover cap and rotor-seat by bolts, which is easy to dismantle and assemble or replace according to specific demands.

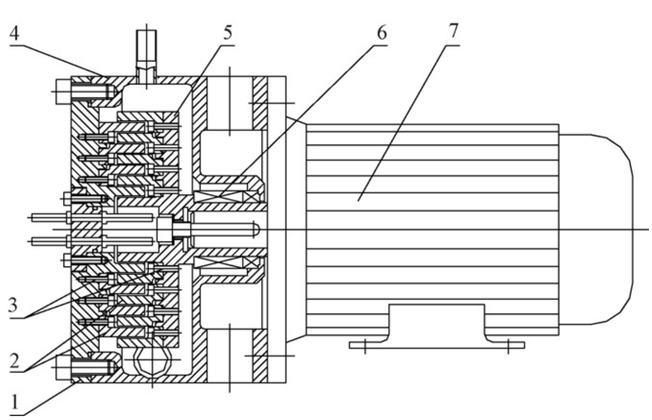

Fig. 1. Schematic description of RSR. (1) Cover cap; (2) rings; (3) bolts; (4) casing; (5) rotor-seat; (6) seal; (7) motor.

2.2. Parallel competing reaction system

Physical methods, such as optical and conductometric methods have been limited because of their poor distinguishability and instrumental limitations. Hence, chemical methods (i.e. chemical reactions as molecular probes) were widely used to test the micromixing efficiency. Fournier et al. developed a novel parallel competing reaction scheme used as working system to characterize micromixing [19]. Its experimental procedure and reactions kinetics were also presented [20,21]. This reaction scheme consists of the following three chemical reactions:

$$H_2BO_3^- + H^+ \Leftrightarrow H_3BO_3 \tag{1}$$

$$5I^- + IO_3^- + 6H^+ \Leftrightarrow 3I_2 + 3H_2O \tag{2}$$

$$I^- + I_2 \Leftrightarrow I_3^- \tag{3}$$

The neutralization reaction (1) is quasi-instantaneous, and redox reaction (2) is fast but much slower than the reaction (1). In perfect mixing conditions, the injected H^+ was consumed by reaction (1), and reactions (2) and (3) may not occur. In partial or total segregation conditions, the injected H^+ was consumed competitively by reactions (1) and (2), and the formed I_2 can further react with I^- to yield I_3^- according to reaction (3). The amount of I_3^- produced depends on the micromixing efficiency. The selectivity Y of H^+ and the segregation index X_S were defined respectively:

$$Y = \frac{2(n_{I_2} + n_{I_3^-})}{n_{H_0^+}} \tag{4}$$

$$X_S = \frac{Y}{Y_{ST}} \tag{5}$$

where $Y_{ST} = 6C_{IO_{3,0}^-}/(6C_{IO_{3,0}^-} + C_{H_2BO_{3,0}^-})$ is the value of Y in total segregation case. The value of X_S is within the range of $0 < X_S < 1$ for partial segregation, and $X_S = 0$ and $X_S = 1$ indicate perfect micromixing and total segregation, respectively.

In our experiments, solutions A and B were prepared first. The procedure for preparation of solution A was as follows: (1) powders H_3BO_3 (281.017 g) and NaOH (90.909 g) were dissolved in 15 and 5 L water, respectively. And then the as-prepared solutions were mixed to obtain the buffer solution; (2) powders KI (48.42 g) and KIO_3 (12.483 g) were dissolved in 0.5 and 2.5 L water, respectively. And then these two solutions were added to the said buffer solution; (3) the rest water was added into the as-prepared solution to prepare 25 L of solution A, which was a mixture of iodate (0.01167 mol L^{-1}), iodide (0.00233 mol L^{-1}) and borate ions (0.0909 mol L^{-1}). The solution B was H_2SO_4 solution (0.05–0.08 mol L^{-1}, corresponding concentration of H^+ was 0.10–0.16 mol L^{-1}).