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Residence time distributions of in-line high shear mixers with ultrafine teeth

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HIGHLIGHTS

- ▶ Backmixing behavior of pilot-scale in-line high shear mixers with ultrafine teeth.
- ▶ Large eddy simulation and combined species transport method for RTD predictions.
- ▶ The mixers behave like mixed flow reactors.
- ▶ RTDs predicted for different operational and geometric parameters.
- ▶ Channeling, short circuiting and re-entrainment defects from inefficient designs.

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ABSTRACT

The large eddy simulation and combined species transport method was validated for the residence time distribution (RTD) predictions of the pilot-scale in-line high shear mixers (HSMs) with ultrafine teeth. RTD characteristics were experimentally and numerically investigated under different rotor speeds and flowrates for the in-line HSM with double rows of inclined stator teeth. The exponential decays of the RTD curves indicate that the in-line HSM generally behaves like a mixed flow reactor, where the mixedness increases under higher rotor speeds and flowrates. It is indicated that the RTDs are greatly dependent on the HSM configurations, such as the shear gap widths, tip-to-base clearances, rows of the rotor and stator teeth, as well as patterns of the stator teeth. Defects of channeling, short circuiting and fluid re-entrainment are resulted from inefficient in-line HSM designs, such as those with large shear gap widths, large tip-to-base clearances, single rows of rotor and stator teeth, or improper angles of stator teeth. It is suggested that the in-line HSM with double rows of inclined stator teeth, narrow shear gap width and tip-to-base clearance has the advantage to provide intensified mass transport efficiency in the view of exploring novel chemical reactors.

1. Introduction

High shear mixers (HSMs), widely utilized in the dispersions due to their locally intense turbulence and shear (Atiemo-Obeng and Calabrese, 2004; Baldyga et al., 2008a, 2008b; El-Jaby et al., 2009; Hall et al., 2011), have great potential to intensify chemical reactions with fast inherent reaction rates but relatively slow mass transfer (Bourne and Garcia-Rosas, 1986; Bourne and Studer, 1992; Patterson et al., 2004; Zhang et al., 2012). Commercial HSMs can be generally categorized into batch and in-line units despite their various geometric designs. Compared with batch HSMs, the in-line teethed HSMs have the advantage of continuous operation, short residence time and high throughput. Practically, the teethed HSMs with narrow rotor and stator openings are recommended by both engineers and equipment suppliers for fine dispersions and uniform reactive mixing. And in-line HSMs with multiple rows of rotor–stator teeth are believed productive to overcome the defect of fluid bypassing in the devices with single row design (Atiemo-Obeng and Calabrese, 2004; Calabrese et al., 2002). Patented fine chemical productions using in-line HSMs have been booming recently, among which the units with multiple rows or even multiple stages of fine teeth are favored (Hassan et al., 2010a, b, c, 2011a, b, c, d; Hassan et al., 2010d). However, the practical application of this promising reactor has been impeded owing to a lack of the understanding of the backmixing behavior. Unfortunately, there are no open publications available so far to this point.

The backmixing behavior of a reactor is usually characterized through the residence time distribution (RTD), which allows comparison with ideal reactor models. To assess the RTD curve of a reactor it is often preferred to perform stimulus-response experiment by the pulse input of a nonreactive tracer to produce the E curve directly, or by the step input to generate the F curve. Theoretically the periodic and random inputs can also be used; however, their

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results are complex and hard to interpret (Levenspiel, 1999). The pulse method has the advantage of requiring smaller amount of tracer, and more importantly resolving the distinctive features of the RTD curve (Martin, 2000). As for the in-line teethed HSMs, the featured short residence time requires ultra short tracer injection duration in order to treat it as a pulse. This brings difficulty in the experimentation and the experimental data from imperfect pulse input should be properly treated in order to obtain the intrinsic RTD of the mixer.

Computational fluid dynamics (CFD) tools are becoming powerful and popular to conduct reactor design and diagnosis, since they are less restricted by the operating conditions, less time-consuming and less costly. The reported CFD simulations in HSMs are focused on single phase flow pattern analyses and power draw predictions (Calabrese et al., 2002; Özcan-Taşkin et al., 2011; Pacek et al., 2007; Utomo et al., 2008, 2009), utilizing predominantly the k–ε turbulence model. To the best of our knowledge, no publications have been reported so far on the CFD predictions of the RTDs in HSMs.

A simple and prevailing method to simulate the RTD is to model the tracer experiment by solving the species transport equation (Deshmukh et al., 2009; Singh et al., 2007; Vedantam et al., 2006; Zhang et al., 2007), where the accurately predicted velocity field is needed. Therefore, the accuracy of the CFD simulations using the k–ε turbulence model still need to be improved owing to its inherent weakness, e.g., the unsatisfactory performance in the near-wall region, insensitivity to streamline curvature and rotation as well as an excessive damping of turbulence (Fluent, 2006; Singh et al., 2011). The large eddy simulation (LES), which has been successfully utilized to simulate complex flows in the stirred vessels (Alcamo et al., 2005; Derksen and Van den Akker, 1999; Hartmann et al., 2004a, 2004b; Murthy and Joshi, 2008; Yeoh et al., 2004, 2005), turbomachineries (Byskov et al., 2003; Kato et al., 2003; Sinha et al., 2000; Tokyay and Constantinescu, 2006) and cyclones (Brennan, 2006; Delgadillo and Rajamani, 2005; Narasimha et al., 2006; Slack et al., 2000), is a promising route to disclose more accurately the flow characteristics in the practical HSMs (Zhang et al., 2012).

In this article, we investigated the RTD characteristics of pilot-scale in-line HSMs with ultrafine teeth in order to disclose the backmixing behavior of HSMs with the aid of the commercially available CFD package. First, the stimulus-response experiments were carried out under different operating conditions in a model in-line HSM using an imperfect pulse injection of the tracer. The intrinsic RTDs obtained via deconvolution were utilized to evaluate the feasibility of CFD assisted diagnosis of in-line HSMs, where a more idealized virtual pulse injection of the tracer was adopted. Then the effects of several important geometric parameters on the RTDs were studied using the validated CFD model. The results obtained here are fundamental to explore potential applications of in-line teethed HSM in chemical reaction processes.

2. Experimental procedure

Fig. 1a shows the schematic experimental setup used for the RTD analysis. The in-line teeth HSM used for RTD measurement was a custom-built, pilot-scale unit (FLUKO®, FDX1/60), of which the front and circumference of the volute as well as the stator head were all made from transparent Plexiglas. The rotor consisted of two rows of 52 teeth with 1 mm gaps. The stator had two rows of 30 teeth (15° backward inclined) with 2 mm gaps. The geometric details of the rotor and stator heads are shown in Fig. 1b and c. Important dimensions of the experimental mixer are listed in Table 1.

Table 1
Important dimensions of the experimental in-line high shear mixer.

Items	Dimensions (mm)
Outer rotor diameter	59.5
Inner rotor diameter	47
Number of rotor teeth	52
Outer stator diameter	66
Inner stator diameter	53.5
Number of stator teeth	30
Gap between rotor and stator teeth	0.5
Teeth tip-to-base clearance[a]	1
Diameter of the mixing chamber	90
Inlet tube diameter	25
Outlet tube diameter	20

[a] The clearance from the rotor teeth tip to the stator teeth base, and that from the stator teeth tip to the rotor teeth base.

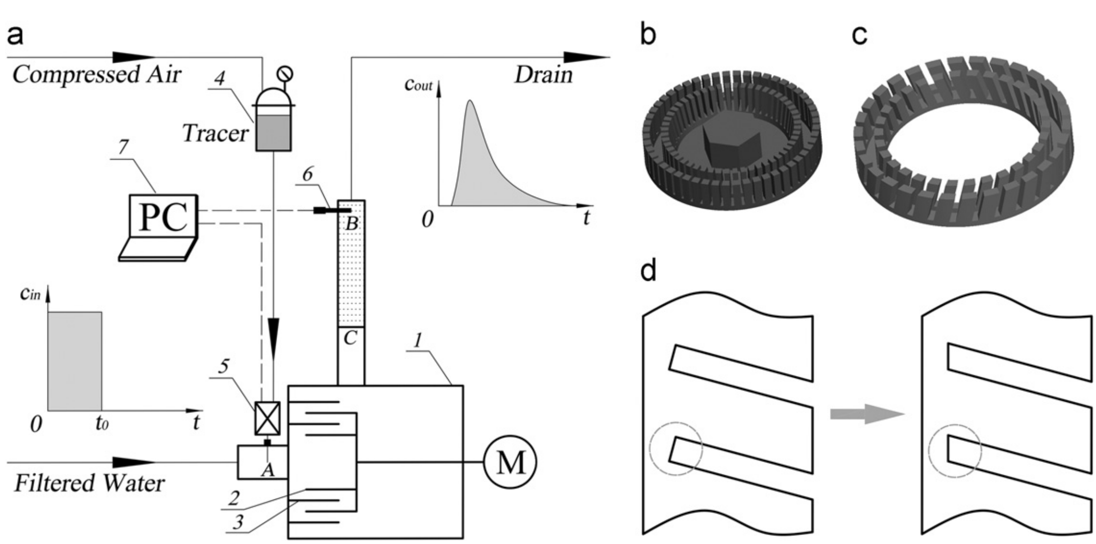

Fig. 1. Experimental geometry of the in-line high shear mixer. (a) Schematic setup for RTD analysis: 1-In-line high shear mixer; 2-Rotor head; 3-Stator head; 4-Tracer storage tank; 5-Solenoid valve; 6-Conductivity probe; 7-Personal computer. Geometric details of (b) the rotor head and (c) the backward inclined stator teeth. (d) Approximation of the stator teeth in CFD simulations.