Oral Presentation

The 7th TSME International Conference on Mechanical Engineering
13-16 December 2016

AMM0013

Computation of Interfacial Area and Mean Residence Time of Two-Immiscible-Liquid Mixing in a Spinning Disc Reactor

Pichaya Sompopskul[1,*], Suttichai Assabumrungrat[2], and Sompong Putivisutisak[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, 10330, Thailand
[2] Center of Excellence in Catalysis and Catalytic Reaction Engineering, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, 10330, Thailand
[*] Corresponding Author: perfectpitch.ya@gmail.com, 089-208-8536

Abstract

This work studies the mixing of two immiscible liquids in a spinning disc reactor which offers several promising advantages over conventional reactors. A commercial CFD code was used for simulation of the mixing to investigate the effect of various operating parameters. The rotating speed and liquid flow rate were varied to emulate some operational cases. The interfacial area between two immiscible liquids, 4.97×10^{-3} to 6.35×10^{-2} m^2, and the residence times of each liquid in the range of 0.5 to 3.4 seconds were obtained. Also, it was found that the rotating speed has to be maintained in the appropriate range of speed during operation. Immoderately low and high speeds can cause abnormal mixed liquid film characteristics, which are not preferred for the spinning disc reactor.

Keywords: spinning disc reactor, residence time, thin film, immiscible liquid, multiphase flow.

1. Introduction

A spinning disc reactor (SDR) is on a spotlight by its continuous mixing operation, short residence time, and maintenance simplicity [1], of which a static mixer, a microchannel and some other conventional chemical reactor do not have. By these main characters, an SDR is suited for industrial applications, especially mass production, such as food, pharmaceutical or chemical products. Many researchers confirm some advantages of an SDR above conventional chemical reactors. For example, performing the highest mixing efficiency, by a short residence time of 2-3 seconds, over a continuous flow stirring reactor and a static mixer [1]. Also, the mass transfer rates achieved from SDR are higher than packed columns and microchannels [2]. Therefore, an SDR has a potential to enhance chemical reactions which highly depends on mixing. For production of nanoparticles, an SDR can keep a particle size distribution at the target size with a small residence time [3].

In general, operation of an SDR is very simple. Two fluids fed into an SDR are mixed at the surface of disc, which rotated during an operation. A rotating disc creates a centrifugal field which drives a mixed fluid to the disc edge and exit the reactor outlet. Due to its simple structure and process, an SDR can be controlled by only changing the rotating speed or the input flow rate. The past researchers found that the rapidly rotating disc intensifies mixing and mass transfer [4], but reduces mixing liquid film height on the disc [5].

However, all the performance of SDR depends on operating conditions. It seems like the performance and operation of an SDR are not widely studied. Thus, a work which analyzes the behavior of an SDR is still needed. The information about SDR have to be collected as much as possible, to improve the reactor efficiency of providing better quality and quantity of products. To study these numerous operational cases, the numerical method or CFD is applied with simulation in details.

In this study, the performance of an SDR was analyzed numerically by a commercial CFD code. Two immiscible liquids were used and contacting area between the mixing liquids, which cannot be measured easily from experiment, was obtained from the numerical solution. Also, residence times of each liquids were calculated at different operating conditions.

2. Geometry Description

The SDR studied in this work is illustrated in Fig. 1. There are two inlets on the top which feed liquids into the reactor with a rotating disc of 410 mm diameter. The feeding holes have diameter of 10 mm each, and they are shifted from center 20 mm. Two liquids from inlets are injected above the rotating disc 3 mm and mixed together on the disc. The computation region is within the dashed line box in Fig. 1.

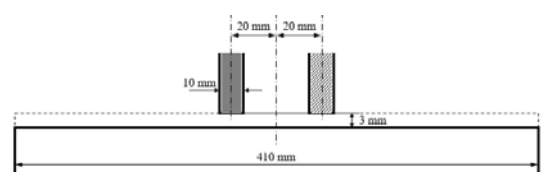

Fig. 1 Dimensions of an SDR

3. Mathematical Model

The conservation equations below are used for modelling the flow inside an SDR, mass and momentum equation. They can be expressed as follows

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla p + \nabla \cdot \left[\mu \left(\nabla \vec{u} + (\nabla \vec{u})^T \right) \right] + \rho \vec{g} + \vec{F}_{ext} \qquad (2)$$

To adapt these equations for the multiphase system, the Volume-of-Fluid (VOF) model [6] is used for modeling multiphase flow. This model can be written as

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i \vec{u}_i) = S_{\alpha_i} \qquad (3)$$

$$\sum_i \alpha_i = 1 \qquad (4)$$

4. Numerical Simulation

In this research, the numerical simulation was proceeded by commercial code, ANSYS FLUENT 15.0, which applies finite volume method for discretization of the governing equations and solve them numerically. The SIMPLE algorithm [7] and QUICK scheme [8] were used, while Compressive scheme is applied in the volume fraction equation of VOF model.

The flow domain is a representative of the region inside an SDR, as shown by the dashed line box in Fig. 1. The geometry of flow domain studied here is a thin cylindrical shape with 3 mm height and 20.5 cm diameter, which was modified from the study of Leshev and Peev [9].

The flow domain is meshed with unstructured grid and composed of 132759 cells, as shown in Fig. 2. The grid was refined vertically at the bottom region, which is against the surface of rotating disc, for capturing the mixture liquid film efficiently.

The inlet flows are assumed to have uniform velocities. Properties of water and n-heptane from Table. 1 were used for the mixing simulation and assumed to be constant. The bottom boundary is set to be rotating wall with no-slip condition. The flow domain is open to the ambient and this study focuses on steady laminar flow mixing.

Table. 1 Properties of immiscible liquids

Liquid	Density (kg/m^3)	Viscosity (kg/m-s)
Water	1000	0.001
n-Heptane	684	0.000409

5. Results and Discussion

Interfacial areas between two mixing liquids and residence times of each liquid were determined on several operating conditions. The simulated SDR was run on rotating speeds of 10, 50, 100, 175, 250, 500, 1000 and 2000 rpm. Also, the volumetric flow rate for both phases was regulated equally at 5.330, 7.854, 15.708 mL/s.

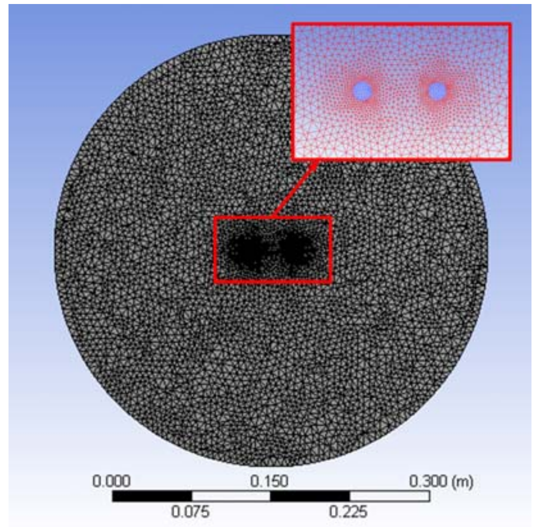

Fig. 2 Unstructured mesh of flow domain

5.1 Interfacial Area

Fig. 3 shows the computed interfacial areas for different rotating speeds and liquid flow rates. It is obvious that the rotating speed fluently reduces the interfacial area between two immiscible liquids. That means, during operation, the rotating speed have to be maintain at low speed for expanding the interfacial area. Consequently, a large area can increase mass transfer between or across two liquids.

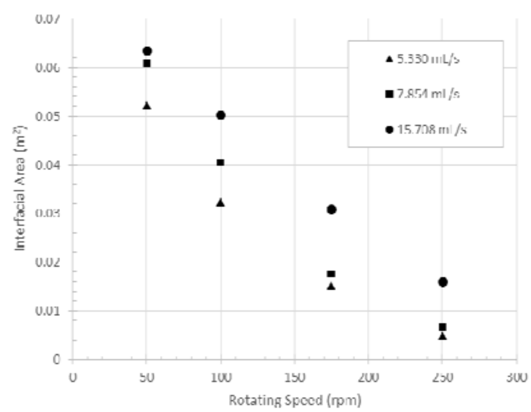

Fig. 3 Computed interfacial areas between water and n-heptane

5.2 Residence Time

An important parameter that represents the time taken in the reactor for one liquid is the mean residence time (τ), which can be calculated from the following formula

$$\tau = \frac{\text{volume occupied in the system}}{\text{inlet volumetric flow rate}} \qquad (5)$$

This was determined for each liquid. The results from Eq. (5) are shown in Figs. 4 and 5. The residence time decreases as the disc becomes faster for all inlet volumetric flow rates. Moreover, it is very sensitive to disc speeds in the low speed range, especially the lower input flow rate. At 5.33 mL/s flow rate of water and n-heptane, the residence time drops by 1.29 s for water from the speed of 50 to 100 rpm, and drops by 0.75 s for n-heptane. Whereas, the residence time drops by 0.34 s for water and 0.20 s for n-heptane in the range of high rotating speeds.

In the view of liquid flow rate variation, residence times at any rotating speed becomes lower as the liquid flow rate increases. However, the effect of low rotating speed still takes a significant role on the residence time sensitivity. At 50 rpm, the residence time drops by 1.67 s for water and 1.04 s for n-heptane. But at a higher rotating speed, 250 rpm, the residence time drops by 0.39 and 0.42 s for water and n-heptane, respectively.

Apart from that, n-heptane has shorter residence times than water in all cases, even though both liquids were injected at same flow rates.

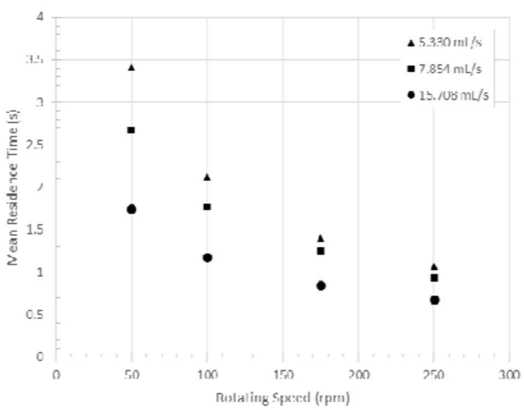

Fig. 4 Mean residence times of water

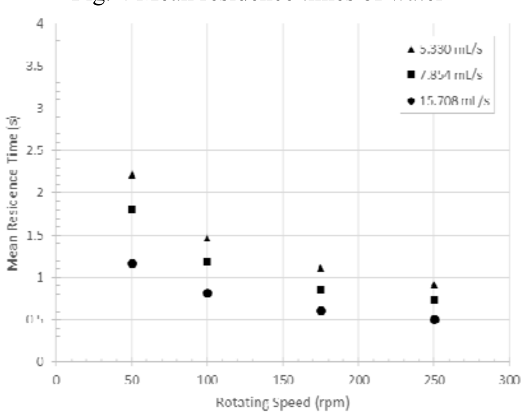

Fig. 5 Mean residence times of n-heptane

5.3 Undetermined Numerical Solutions

All the cases notified early were computed. Nevertheless, some cases did not give a desired solution. For 10 rpm rotating speed, the computations face diverged solutions. This occurrence could be ascribed that the outer radial region of mixed liquid film has hydraulic jump, a sudden increment of the liquid film thickness which followed by an immediate fall, as the past study of film flow on a rotating disc found by Leshev and Peev [9]. Hydraulic jump can be formed if the liquid film is fed on a disc with low rotating speed or at rest. However, the existence of hydraulic jump implies inconsistency of the mixed liquid film which is already out of consideration.

On the other side, at the rotating speed of 500 and 1000 rpm, the numerical solutions converge but defects of the film are found. The mixed liquid does not completely cover the rotating disc. The pits that occur on the liquid film make the performance of SDR difficult to predict. Actually, in practical, an SDR should not be operated in these conditions. So, the computed interfacial areas and residence times from these cases are ignored. Although, at 2500 rpm rotating speed, the solutions also diverge, including 15.708 mL/s at 1000 rpm case, but its divergence is not beyond the expectancy.

6. Conclusion

In this study, mixing of two immiscible fluids in a spinning disc reactor was numerically investigated. The reactor has two liquid feeding holes on the top and the mixed immiscible liquids exit at the edge of rotating disc. From the results, the interfacial area between the liquids is fluently decreased when the rotating speed is increased. Also, the mean residence time of each phase is short when the reactor operating at high speed. However, the change of residence time is sensitive to the rotating speed only in the range of low speed. Moreover, operating the reactor at extremely low speed can cause hydraulic jump, which is not preferred during operation. In addition, when the speed of the disc is too high, defects are occurred on the mixed liquid film.

7. Acknowledgement

The authors would like to acknowledge the support from Ratchadapiseksomphot Endowment under Outstanding Research Performance Program and the Thailand Research Fund (DPG5880003).

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