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Film formation in a horizontal twin-shaft rotating disk reactor for polymer devolatilization

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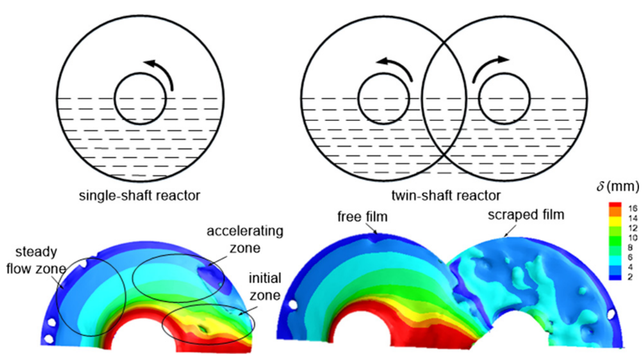
HIGHLIGHTS

- We study the film formation process in a twin-shaft rotating disk reactor.
- CFD based on VOF can predict the film thickness distribution.
- The overlapping zone affects greatly the film formation process.
- The scraped film is much thinner and more uniform than the free film.
- The disk clearance significantly influences the scraped film thickness.

GRAPHICAL ABSTRACT



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ABSTRACT

Film formation characteristics in a horizontal twin-shaft rotating disk reactor for polymer devolatilization have been investigated by means of experiment and computational fluid dynamics (CFD). Volume of fluid (VOF) model has been used to simulate the film formation process and predict the film thickness distribution on the rotating disks, validated experimentally by electrical conductance method. The mechanism for the film formation in twin-shaft rotating disk reactor is different from that in single-shaft reactor, due to the effect of overlapping zone between two adjacent disks. There are two kinds of films generated in the reactor. The free film, greatly affected by the liquid viscosity and rotating speed, shows the similar characteristics with that in the single-shaft reactor. The scraped film, generated by overlapping zone, is much thinner and more uniform than the free film for highly viscous liquid. Compared with the viscosity and the rotating speed, the disk clearance plays a more significant role in determining the thickness and the shape of the scraped film.

1. Introduction

Efficient devolatilization is an indispensable, but difficult and challenging process for the production of various kinds of polymers (Hirschfeld et al., 2015). The remaining monomers, solvents, oligomers and something alike should be removed during or after polymerization. However, the removal of volatiles becomes harder due to the increasing viscosity, ranging from 10 Pa s to 100,000 Pa s. The diffusion coefficient of volatile is extremely small and decreases with the devolatilization process. Various kinds of devices have been invented to tackle the problem (Arnaud et al., 2015; Fleury and Kunkel, 2014; Fujii et al., 2016; Hanimann and Stibal, 2013; Joseph, 1956; Wilhelm and Finkeldei, 2003).

The horizontal rotating disk reactor has been widely used as the polycondensation reactor for the production of polyester, polyamide, etc. There exists a horizontal vessel with one or two rotating shafts, on which a series of disks or cages are vertically mounted to

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Nomenclature

c	disk clearance (m)
Ca	capillary number (–)
Fr	Froude number (–)
g	gravitational acceleration (m/s^2)
$\mathbf{u}$	velocity vectors (m/s)
N	rotating speed (rpm)
p	pressure (Pa)
r	radial position (m)
R	disk radius (m)
Re	Reynolds number (–)
t	flow time (s)

Greek letters

α	volume fraction (–)
δ	film thickness (mm)
κ	curvature of the interface (–)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
θ	angular position (°)
σ	surface tension coefficient (N/m)

Subscripts

G	gas phase
L	liquid phase

strengthen the mass transfer process. Complicated flow patterns, film formation and mixing processes determine the mass and heat transfer mechanisms. It is of great significance to figure out the related physical and chemical phenomena in the reactor, particularly the film formation characteristics.

Most of existing studies focus on the film flow in horizontal single-shaft reactors. Vijayraghvan et al. investigated the film thickness on a rotating disk (Vijayraghvan and Gupta, 1982). An expression, suitable only for low viscosity at high rotating speed, was gained to calculate the film thickness. Highly viscous molten polyethylene terephthalate (PET) was used to study the film formation characteristics in a single-shaft reactor (Cheong and Choi, 1995). Results indicated that the gravity force played an important role in determining the film thickness for highly viscous polymer. Afanasiev et al. used finite element scheme to investigate the film dynamics on a disk partially immersed in a liquid bath (Afanasiev et al., 2008). The combination of laser scan method and CFD simulation was adopted to investigate the thin film flow on a disk, where film thickness can be predicted by a correlation equation for different conditions (Miah et al., 2016).

There are limited investigations for the horizontal twin-shaft reactors. Seck et al. investigated the mixing and mass transfer characteristics in a continuous twin-shaft kneader (Seck et al., 2010). The kneader behaves like a plug flow reactor and shows great advantages for devolatilization due to the fast surface renewal of highly viscous fluids by kneading. Connelly et al. simulated the mixing behavior in a twin sigma blade mixer using finite element method (FEM) with mesh superposition technique and particle tracking (Connelly and Kokini, 2006a, 2006b). Investigations showed that the zone in the center of the mixer between the two blades had excellent distributive mixing ability. Salahudeen et al. used the thermo scientific Haake and numerical FEM simulation to study the mixing process of the internal batch mixers (Salahudeen et al., 2011). The mixing efficiency of the roller mixer is much better than that of the cam and banbury mixers. 3D FEM simulation of a Readco continuous mixer with non-Newtonian fluid was performed, where the mixer geometry and operating conditions on mixing efficiency were discussed (Rathod and Kokini, 2013). Murakami et al. studied the hold-up, power consumption, mixing time, residence time distribution and surface renewal in a horizontal twin-shaft rotating disk reactor (Murakami et al., 1972). To date, few reports are available in the literature on the film formation phenomena of high viscosity fluids in twin-shaft reactor.

The film formation mechanism is the key factor for designing and optimizing agitator configurations in a horizontal twin-shaft rotating disk reactor. There are overlapping zones between every two adjacent disks, where the film formation process is quite different from that of the single-shaft reactor. This work aims at investigating the film formation characteristics within a horizontal twin-shaft disk reactor by both CFD simulation and experiment.

2. Experimental setup

For the study of film formation phenomena, we built a bench scale horizontal twin-shaft rotating disk reactor device as shown schematically in Fig. 1. The reactor with a width of 230 mm and a length of 100 mm is made of plexiglass. The diameters of reactor, disk and shaft are 140 mm, 130 mm and 40 mm, respectively. The distance between two shafts is 90 mm. The stainless steel circular disks, which are 50% immersed in the bulk liquid phase, are alternately mounted on each shaft. There exists an overlapping zone between the two adjacent disks, which rotate in the opposite directions. Viscosity (μ), rotating speed (N), and the clearance between disks (c) can be adjusted according to the experimental and simulation requirements. The syrup of different viscosities (Newtonian fluid) is used as the experimental material, as shown in Table 1.

There are various kinds of methods to measure the liquid film thickness (δ) on the surface of disk, such as electrical conductance method (Andreussi et al., 2016), optical method (Miah et al., 2016), and ultrasound method (Dwyer-Joyce et al., 2003). The electrical conductance method is adopted for its simplicity and accuracy. As shown in Fig. 2, an electrical conductance probe and a micrometer are used to measure the film thickness. Firstly, disks rotate at a specified rotating speed within a partially filled reactor to make the film layer stable. Secondly, there exists an electric current change when the probe touches the film and the probe position ($z1$) is marked by the micrometer. Then, another electric current change occurs when the probe reaches the metal disk surface, and the probe position ($z2$) is recorded. The distance between the two marked points ($z2$–$z1$) which the probe travels corresponds to the liquid film thickness on the disk. The measurement points are located on the two vertical lines on the rotating disks when the angular coordinate is 90°, where the radial position ranges from 25 mm to 60 mm, as shown in Fig. 1a. The film thickness measurements for each point were performed three times, of which the average relative error was about 2.9% and the maximum relative error was less than 10.25%.

3. Numerical strategy

3.1. Governing equations

The flow within the horizontal twin-shaft rotating disk reactor is laminar, incompressible and isothermal. The volume of fluid (VOF) model, by which the gas-liquid interface can be accurately tracked, was chosen to describe the multiphase phase flow within