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Characterization of liquid flow in the spinning cloth disc reactor: Residence time distribution, visual study and modeling

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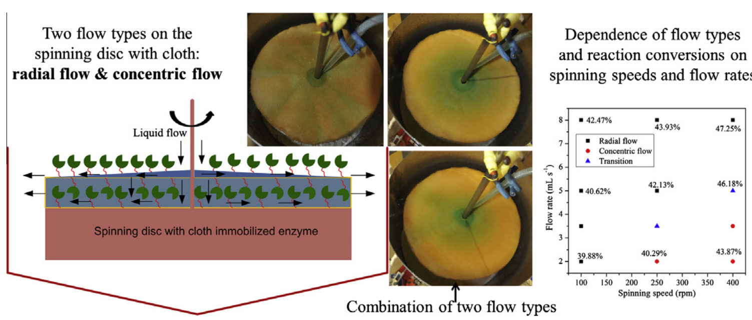
HIGHLIGHTS

- Residence time distribution and flow imaging done on spinning cloth disc reactor.
- Flow within cloth is well mixed – opposite to conventional spinning disc reactors.
- Flow becomes more plug flow with increasing flow rate and spinning speed.
- Two types of bulk flow in spinning cloth: radial finger-like and concentric flow.
- Well-mixed reactor and Ping Pong Bi Bi kinetic models fitted the obtained data well.

GRAPHICAL ABSTRACT



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ABSTRACT

The spinning cloth disc reactor (SCDR) is an innovative enzymatic reaction intensification technology. The SCDR uses centrifugal forces to allow the spread of thin film across the spinning disc which has a cloth with immobilized enzyme. Research has shown this geometry promotes accelerated reactions due to high mass transfer rates and rapid mixing. In this study, the flow regimes in the SCDR were characterized by means of residence time distribution (RTD) analysis and visual study tracking dye staining.

RTD analysis showed that the flow pattern on the spinning disc with/without cloth became closer to plug flow with an increase of spinning speed and flow rate. With the cloth, the equivalent number of tanks-in-series was at least 2 times lower than that without cloth at different spinning speeds and flow rates, indicating the flow is better mixed, in contrast to the typical plug flow found for conventional spinning disc reactor. Two flow regimes were observed in the visual study with the dye spreading within the spinning cloth: radial finger-like flow and concentric flow. At low spinning speeds and high flow rates, the flow was in the form of a few random and uneven radial streams, with the zone between these streams free of dye. At higher spinning speeds and lower flow rates, this uneven radial flow was replaced by an even concentric flow. Using tributyrin hydrolysis as a model reaction, a SCDR reactor mathematical model based on perfectly mixed model was developed to simulate the variation in SCDR conversion with spinning speed and flow rate, and the model fitted well with the experimental data. The overall results indicate the SCDR is neither a conventional spinning disc reactor nor a rotating packed bed, but a separate class of spinning disc-type reactor for process intensification, called 'spinning mesh disc reactors' (SMDRs).

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Nomenclature

C	substrate concentration in the bulk solution ($mol\ m^{-3}$)
V_r	liquid volume in the reactor (m^3)
V_t	total liquid volume in the system (m^3)
r'	global reaction rate ($mol\ m^{-3}\ s^{-1}$)
Q	volumetric flow rate ($m^3\ s^{-1}$)
υ	kinematic viscosity ($m^2\ s^{-1}$)
ω	spinning speed ($rad\ s^{-1}$)
h	film thickness (m)
r	distance between any point on the disc to the center (m)
R	constant, the radius of the disc (0.125 m)
C_i	substrate concentration at the interface ($mol\ m^{-3}$)
C_0	initial concentration of the glyceride ($mol\ m^{-3}$)
k_L	mass transfer coefficient ($m\ s^{-1}$)
a	effective interfacial area per unit volume (m^{-1})
k_La	global mass transfer coefficient (s^{-1})
ν'_{max}	apparent maximum reaction rate ($mol\ m^{-3}\ s^{-1}$)
K'_m	apparent Michaelis–Menten constant for the glyceride ($mol\ m^{-3}$)
K'_i	apparent inhibition constant for the fatty acid ($mol\ m^{-3}$)

1. Introduction

Process intensification is considered as a promising development path for the chemical process industry, aiming to improve production efficiency, lower cost, enhance safety and reduce environmental pollution [1]. The spinning disc reactor (SDR) is one such process intensification technology, which consists of a rotating disc with a jet of liquid impinging onto the center of top surface of the disc. The centrifugal force of the spinning disc forces this liquid to form a thin and highly sheared film on top of the rotating surface, leading to rapid mixing and short residence times. Research has shown that the heat and mass transfer in such devices can be significantly enhanced by the fluid dynamics within these films [2–4]. The SDR has been applied in a wide range of chemical reactions such as polymerization [5], nanoparticle preparation [6–9], photocatalysis [10,11], and transesterification in biodiesel synthesis [12]. The rotating packed bed (RPB) reactor, as a novel multi-phase contactor, is another reactor type which also uses centrifugal acceleration as driving forces to intensify mass transfer rate [13,14]. In the RPB, the liquid sprays on the inside of the packed bed and spreads outwards by the centrifugal force. The gas is introduced from the outside and flows inward (counter-currently) to the liquid. The RPB has been reported to use in distillation [15], nanofiber and nanosphere preparation [16,17], photocatalyst preparation [18], adsorption [19–21] and catalytic reactions [22].

Recently, the SDR concept has for the first time been introduced to immobilized enzymatic reactions as a novel rotating reactor system: the spinning cloth disc reactor (SCDR). Previous work has proven the feasibility of the SCDR in tributyrin emulsion hydrolysis, and its high efficiency in terms of reaction rates, conversion and stability was highlighted in comparison to the conventional batch stirred tank reactor (BSTR) [23]. Based on the principles of the SDR, the SCDR also uses centrifugal forces to allow the spread of a thin film across a spinning horizontal disc; however this disc has a cloth (with thickness of 1.5 mm) with immobilized enzyme resting on top of it. The SCDR therefore produces a flow of thin film both on top of as well as through the cloth, thus providing more effective surfaces for reaction. The cloth is critical to increasing the potential of immobilized enzymes in a variety of reactions, since it should produce accelerated reaction rates due to high mass transfer rates and rapid mixing on top of and within the cloth, with the cloth potentially helping protect the attached enzymes from excessive hydrodynamic forces, as well as providing an additional structure that can promote mixing and turbulence at the appropriate spinning speeds and flow rates. Therefore, the SCDR has characteristics of both the SDR and RPB: the cloth spins on the disc and is fed liquid like an SDR, but the liquid flow is interrupted by the cloth mesh, giving the flow on the disc characteristics that may be more like that in a RPB. Consequently both systems will be used in the analysis of the SCDR in this work.

The most popular techniques adopted in characterizing the flow regimes in the SDR and the RPB are visual quantification studies (through taking images with a conventional camera or a high speed camera) and residence time distribution (RTD) techniques.

For the SDR, it has been reported that several flow regimes can form on the spinning disc: smooth waves, concentric waves, spiral, irregular waves and film break up, which change with the spinning speeds, flow rates and physical property of liquid [24,25]. Boiarkina et al. [4,10] observed the boundaries of different water waves with a high speed camera at spinning speeds of 50–400 rpm and flow rates of 5–35 $mL\ s^{-1}$. Mohammadi and Boodhoo [26] found that the RTD in SDR became narrower as the increase of spinning speeds and flow rates, implying the flow behavior became closer to ideal plug flow.

For the RPB, liquid is usually assumed to flow as thin films on the packing surface for simplicity when modeling the system. However, visual observations have indicated that liquid is traveling through the packing in uneven rivulets and droplets rather than in uniform film flow, which causes a maldistribution of liquid and hence decreases the overall efficiency of the reactor [27,28].

The flow properties on a spinning disc have been studied with both RTD and visual techniques [10,26], however, the introduction of the cloth will affect the flow properties, and the reported results of flow regimes in the SDR therefore may not be applicable to the SCDR. Consequently, the flow regimes in the SCDR need to be characterized to get a more in-depth understanding of flow characteristics and patterns to allow for better process control as well as reactor modeling and design. As such, the aim of this research is to characterize the flow regimes in the SCDR by means of RTD analysis and visual studies with dye, for a range of spinning speeds and flow rates. These results will be compared to the SDR and the RPB, and used to further model the reaction rate and conversion in the SCDR with respect to spinning speeds and flow rates, using tributyrin hydrolysis as a model reaction and immobilized lipase on woolen cloth as the biocatalyst.

2. Materials and methods

2.1. Materials

Unbleached organic woolen cloth (color: natural cream, thickness: 1.5 mm) was purchased from Treliske (Otago, New Zealand). Amano lipase derived from *Pseudomonas fluorescens*, polyethyleneimine (PEI), tributyrin (98%), tritonX-100, coomassie brilliant blue G 250, sodium bicarbonate and sodium carbonate were obtained from Sigma–Aldrich (New Zealand). Glutaraldehyde