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## Micromixing Characteristics in a small scale Spinning Disc Reactor

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### Abstract

Thin films formed under the high acceleration fields in the spinning disc reactor (SDR) are characterised by high shear rates and intense surface ripples which are known to play an important role in improving the selectivity, yield, and final product quality in many mixing-dependent processes. In the present investigation, we characterise the micromixing efficiency of a small scale SDR of 10 cm disc diameter for a range of hydrodynamic conditions by means of the iodide-iodate test reaction. We demonstrate herein that, under optimised conditions, the SDR gives better micromixing performance than the mechanically stirred vessel when processing water-like fluids whilst being at least as effective as other intensified mixers/reactors reported in the literature. These results highlight the potential of the SDR as an alternative intensified mixer/reactor for processes where a high degree of mixing is critically important.

**Key words:** micromixing; power dissipation; spinning disc reactor; segregation index; intensified mixer/reactor

### 1. Introduction

Mixing is used to reduce the degree of non-uniformity or gradient of a property such as temperature, viscosity or concentration in a system in order to achieve a desired degree of homogeneity at various length scales [1]. Mixing is also important in promoting both heat and mass transfer when a system is undergoing a chemical reaction. The quality of mixing of materials greatly determines the success and efficiency of many industrial processes, with ineffective mixing resulting in considerable economic and environmental implications.

Whether a chemical reaction is influenced by the mixing process is dependent on the relative time scales of the mixing and reaction. Thus, if the reagents are completely

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mixed down to the molecular scale before significant reaction takes place, mixing will have no impact on the reaction. On the other hand, if micromixing is relatively slow compared to the reaction rate, the product distribution and the quality of fast multiple reactions can be considerably affected [2]. It is therefore important to select a fast mixer which can provide the appropriate micromixing conditions when performing fast competitive reactions.

The SDR technology offers the possibility of a step change in manufacturing operations, particularly with respect to the ability to cope with very fast chemical reactions such as polymerization, crystallization and competing fast chemical reactions. It is designed to create highly sheared thin liquid films which have excellent heat/mass transfer properties. The short diffusion and conduction path length offered by the very thin films (as low as 25  $\mu\text{m}$ ) is the basis for the very transport rates within the film.

The SDR has previously been successfully used for a range of processes including free-radical and cationic polymerisation processes [3-6], precipitation of barium sulphate [7] and silver nanoparticles [8] and organic catalytic reactions [9,10] amongst others. The improved product quality observed in these processes such as high selectivity and narrow crystal size/molecular weight distributions are directly influenced by the micromixing intensity in the process liquid. However, no comprehensive study of micromixing in SDR thin films has been undertaken to date. It is our intention in this present work to confirm the hydrodynamic conditions for which the SDR film gives the best micromixing efficiency and to comparatively evaluate its micromixing performance relative to other reactor systems.

## **2. Experimental Section**

### **2.1. SDR**

A schematic representation of the small scale SDR used in this study is shown in Figure 1. The stainless steel disc of 10 cm in diameter was driven by a 125W electric motor. The rotational speed was controlled by a digital speed controller in the range of 300-2400 rpm. Cooling water was recirculated underneath the disc surface through a temperature controlled water bath to keep the disc temperature constant at 20°C. The reactants were fed onto the rotating disc through a feed distributor consisting of two pipes made of stainless steel, one for delivering the iodide-iodate-borate solution via a peristaltic pump (Watson Marlow pump 505S) and the other for delivering the sulphuric

acid via a syringe pump (Sage instruments, model 353). The feed tube diameter for each stream was 1.65 mm, except for the lowest total flowrate of 1ml/s where a 0.65mm pipe diameter was used for delivering the sulphuric acid. The feed distributor was located at the centre of the disc surface at a distance 2.0 mm above the surface.

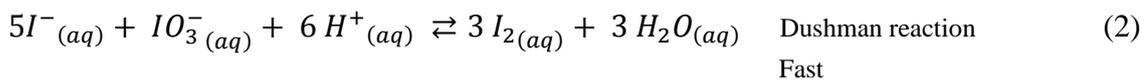
## 2.2. Stirred tank reactor (STR)

A 2 litre glass baffled stirred tank vessel (diameter T of 11.0 cm) was employed in semi-batch mode. It had provision for a water jacket through which water from a temperature controlled bath recirculated to keep the operating temperature constant at 20°C. A Rushton turbine impeller of diameter 4.4 cm positioned about 4 cm from the bottom of the vessel was used to agitate the mixture. Two acid feeding point positions were investigated: injection point < 1 > was located at a distance of 2 mm from the edge of the impeller blade in the same horizontal plane whilst the second injection point < 2 > was located directly above the first injection point, at a vertical distance of 35 mm.

## 2.3. Experimental method

### 2.3.1. The test reaction

The iodide-iodate reaction system, represented by equations 1 to 3 below, was implemented in this work. This well-established reaction scheme is widely documented in the literature as a model reaction to characterise micromixing [11-16]. The micromixing experiments were carried out using the reactant concentrations listed in Table 2 and the solution preparation method adopted from the work of Guichardon and Falk [12].



The following procedure was adopted for each of the STR and SDR:

- (1) STR: The required volume of 1.37 litres of borate-iodide-iodate solution was placed in the batch vessel. The impeller speed was set between 300 and 1200 rpm.

The acid stream of required concentration in the range 0.1 to 1.0 M was fed into this solution at the desired injection location through a stainless steel tube of 1.78 mm internal diameter using a syringe pump (Sage Instruments, model 353). An acid feed rate of 3.6 ml/min was employed which was determined to be well below the critical injection rate to ensure that only micromixing effects were measured [12, 17]. The number of moles of H<sup>+</sup> ions injected in the STR was maintained at 0.02 moles for all experiments. Samples were collected within two minutes of the required volume of acid having been injected. The concentration of iodine was measured using a UV-Vis spectrophotometer as indicated below.

- (2) SDR: Once the disc reached the desired operating temperature of 20°C, it was set to rotate at the chosen rotational speed. The borate-iodide-iodate solution and the sulphuric acid streams were fed onto the rotating disc at the desired flowrates. The disc was allowed to run for 5 minutes before three samples were collected at two minute time intervals and subjected to absorbance analysis.

### 2.3.3. Determination of the segregation index $X_S$ using a single injection method

The segregation index  $X_S$  is defined as the value representing the actual yield of the undesired product ( $Y$ ), compared with the maximum yield of undesired product ( $Y_{ST}$ ) formed under conditions where the micromixing is infinitely slow and total segregation occurs [12, 16, 18].

$$X_S = \frac{Y}{Y_{ST}} \quad (4)$$

The segregation index,  $X_S$ , is a quantitative indicator of the degree of segregation in the reaction mixture. Thus:

Perfect micromixing:  $X_S = 0$ ,

Total segregation:  $X_S = 1$ ,

Partial segregation:  $X_S = Y/Y_{ST}$

The determination of  $Y$  and  $Y_{ST}$  for the semi-batch STR and the continuous SDR follows the calculation procedure established by Fournier et al. [16].

The quantitative analysis of ( $I_3^-$ ) was carried out as suggested by Fournier et al. [16].

The product was analysed by a single beam UV/Vis Spectrophotometer (UNICAM 8700) at a wavelength of  $\lambda = 353$  nm and with an extinction molar coefficient,  $\epsilon_\lambda$ ,

determined as 2395.9 m<sup>2</sup>/mol. The concentration of tri-iodide was estimated from the Beer- Lambert law (equation (5)):

$$D_{\lambda} = [I_3^-] \cdot \epsilon_{\lambda} \cdot l \quad (5)$$

The micromixedness ratio,  $\alpha$ , is another indicator that is used to measure the micromixing quality. The higher the value of micromixedness ratio, the lower the degree of segregation in the reaction mixture and it is defined as:

$$\alpha = \frac{1 - X_S}{X_S} \quad (6)$$

### 3. Results and discussion

#### 3.1. Spinning disc reactor results

The investigated SDR variables included:

- Disc rotational speed range: 300 to 2400rpm
- Flowrate ratio R: 3 and 7
- Total flowrate: 1, 3 and 5 ml/s
- Viscosity: water system ( $\mu=1.005$  mPa.s at 20°C), 50wt% glycerol system ( $\mu = 6.0$  mPa.s at 20°C) and 75wt% glycerol system ( $\mu=35.5$  mPa.s at 20°C) [19]

The maximum relative error in all experiments was no higher than 5% for the water system and 10% for the glycerol systems indicating that the results were satisfactorily reproducible.

The total flow rate,  $Q_t$ , is the combined flow rate of the iodide – iodate – borate stream  $Q_I$  and the acid stream flow rate  $Q_{H^+}$ . The flowrate ratio R (where  $R=Q_I/Q_{H^+}$ ) is an adjustable parameter which can vary with acid concentration, as shown in Table 2, in order to keep the ratio of molar quantities of the borate and acid solutions constant in the semi-batch STR and continuous SDR reactor systems, for a valid comparison between the two reactor types. The individual flowrates of the iodide-iodate-borate ions stream, ( $Q_I$ ), and the acid ions stream, ( $Q_{H^+}$ ), corresponding to each total flowrate indicated above are given in Table 3 for two selected R values of 7 and 70.

### 3.1.1. Effects of disc rotational speed and flowrate

The effects of the disc rotational speed and total feed flowrate on the segregation index are shown in Figure 2 for the acid concentration of 1.0 M. At  $Q_t = 1$  ml/s, there is a steady decrease in the segregation index with increasing disc rotational speed. An interesting effect observed at the higher flowrates of 3 and 5 ml/s is that the disc rotational speed seems to have no strong influence on the segregation index. This would seem to suggest that the higher flowrates of 3 ml/s and 5 ml/s are sufficient to ensure a high degree of mixing intensity is achieved even when the disc speed is relatively low. Considering the effect of flowrate at a given disc speed, it is also clear from Figure 2 that higher flowrates result in lower  $X_s$  values and therefore better micromixing.

The combined effects of disc speed and feed flowrate on the micromixing intensity may be more usefully evaluated by examining the maximum shear rate generated in the thin liquid film defined by equation 7.

$$\gamma_{max} = \left( \frac{dV_r}{dz} \right)_{z=0} = \left( \frac{1.5 Q \omega^4 r}{\pi \nu^2} \right)^{1/3} \quad (7)$$

where  $V_r$  is the radial velocity given by [7]:

$$V_r = \frac{\omega^2 r}{\nu} \left( \delta z - \frac{z^2}{2} \right) \quad (8)$$

The average maximum shear rate on the disc surface was calculated on the basis of shear rate values at three radial positions of 0.01, 0.025 and 0.05 m from the centre for each set of the SDR operating conditions.

From Figure 3, the effect of disc speed combined with flowrate on shear rate is observed to be more significant at disc speeds beyond 1000 rpm. Hardly any differences can be observed in shear rate at low disc speeds within the range of flowrates used in this study. This leads us to conclude that the observed effects of higher flowrates on significant improvements in micromixing seen in Figure 2 cannot merely be explained by shear rate effects.

There is clearly another phenomenon, which is strongly affected by flowrate on the disc, which must come into play in the micromixing process to account for the poor mixing capability at lowest flowrate tested in this study. We suggest that this phenomenon is

related to the wetting of the disc surface which is characterised by film breakdown in the extreme case of incomplete wetting. Hartley and Murgatroyd [20] proposed a model for film breakdown expressed in terms of a critical flowrate,  $Q_c$ , below which the liquid would no longer flow as a continuous film on the disc but rather would disintegrate into rivulets as it moves away from the centre:

$$Q_c = 5.5 \left( \frac{\nu r^4}{\omega^2} \right)^{\frac{1}{5}} \left( \frac{\sigma}{\rho} \right)^{\frac{3}{5}} \quad (9)$$

Bell's experiments [21] have qualitatively proven these expectations, although this author's experimental values for  $Q_c$  in water were about 30% lower than the predicted ones. Previous studies have indicated that film breakdown can significantly limit the performance characteristics of rotating discs due to reduced available interfacial area across which mass or heat transfer occurs [21, 22]. To assess the likelihood of film breakdown in this work, plots of the critical flowrate based on the predictive model of Hartley and Murgatroyd [20] evaluated at a radial position of 0.01 m from the centre of the disc under the operating conditions used in the present investigation, for both water and high viscosity liquid (50 wt% glycerol for illustration) are shown in Figure 4. The predicted  $Q_c$  based on experimental observations in water by Bell [21] is also depicted. Because the micromixing process is most likely to occur almost immediately after the streams contact with each other on the disc, it is especially important that the critical flowrate is examined near the centre, hence the selected radial position of 0.01 m. For the water system, a critical flowrate in the region of 3 ml/s would be applicable in the 800-2400 rpm disc speed range. Flowrates well below 3 ml/s are therefore likely to result in film breakdown in the entry regions of the rotating disc. As the liquid moves away from the centre, the tendency for the film to disintegrate further leaving dry patches of the disc surface would be more pronounced due to the larger disc surface area offered at larger radii. The effect of flowrate on the micromixing profiles seen in Figure 2 fits the film breakdown argument at the lowest flowrate of 1 ml/s. At this flowrate, film breakdown would be more prominent at the lower disc speeds where the critical flowrate, according to Figure 4, would be much higher than 1 ml/s. As disc speed increases, the minimum flowrate required to suppress film breakdown is considerably lowered to a value which approaches the employed flowrate of 1 ml/s. Thus, at higher disc speeds and 1 ml/s, it is possible that film breakdown no longer has a dominant influence on the micromixing process; instead, shear rate effects become

more influential which may explain the improvement in micromixing efficiency observed at higher disc speeds at 1 ml/s.

Overall, Figure 2 serves to demonstrate that a high degree of micro-mixing can be achieved at high disc speeds and/or high feed flow rates, provided a uniform, continuous liquid film can be maintained on the disc. Under these conditions, higher shear forces are created within the liquid film which cause more lamellar stretching and therefore increased surface area under laminar flow conditions. Furthermore, numerous film surface ripples which have been shown to be more prevalent at high disc speeds and flowrates [23] are likely to induce turbulence in the upper layers of the film, thus contributing to enhance the mixing process. These combined effects contribute to the enhancement of the micromixing process.

### 3.1.2. Effect of total flowrate ratio (R) on $X_s$

Figure 5 shows that a reduction in R translates into higher  $X_s$  at any given disc speed and total flowrate studied. This effect may be better understood by considering the ratio of molar quantities of the two streams in contact with each other, expressed as:

$$\text{Molar ratio of contacting streams} = \left( \frac{q_{H_2BO_3^-} [H_2BO_3^-]_0}{q_{H^+} [H^+]_0} \right)$$

By definition,  $R = \frac{q_{H_2BO_3^-}}{q_{H^+}}$

and therefore,

$$\text{Molar ratio of contacting streams} = \left( R \frac{[H_2BO_3^-]_0}{[H^+]_0} \right)$$

When the value of total flowrate ratio (R) is decreased, for example, by increasing the flowrate rate of acid stream whilst keeping flowrate of borate stream constant, the *molar flow rate* of acid ions, given by  $q_{H^+} [H^+]_0$ , becomes larger relative to the other stream. If the flowrate of iodide-iodate-borate ions stream is kept constant, the average concentration of acid ions in the bulk of the solution will increase. Although the acid reacts in reactions 1 and 2 simultaneously, the Dushman reaction (reaction 2) would occur predominantly as its reaction order with respect to acid is higher. The enhanced rate of the Dushman reaction results in more iodine being formed and therefore an increase in the segregation index. Thus, as seen in Figure 5, a lower value of R=3 results in higher  $X_s$  due to a higher molar flow rate of  $H^+$  ions being introduced to the rotating disc. The relatively poor mixing particularly at low rotational speeds combined with the

larger quantity of H<sup>+</sup> ions in solution gives higher values of segregation index at R=3 compared with R=7.

### 3.1.3. Effect of feed viscosity on Xs

Increasing the viscosity of the liquid film causes the segregation index to rise, as expected (Figure 6). At higher viscosity and identical SDR operating conditions of disc speed and flowrate, the shear rate within the film is reduced, according to equation (7) where the maximum shear rate is seen to be inversely proportional to the square of kinematic viscosity  $\nu$  ( $=\mu/\rho$ ). This effect will slow down the micromixing rate and alter the intrinsic kinetics of the reaction [14, 24]. Interestingly, viscosity effects are gradually diminished at the higher disc rotational speeds (typically beyond 1200-1500 rpm) as observed by the curves converging to similar values of Xs. This is attributed to shear rate being greatly increased at the higher disc rotational speeds ( $\gamma_{\max} \propto \omega^4$ ), resulting in more intimate contact between the layers in the liquid film. Under these high shear rate conditions, the viscosity effects can be overcome to a large extent and the micromixing intensity is significantly improved even in the highly viscous solution. Increasing the flowrate can also compensate for an increase in viscosity in the micromixing process, as evidenced by the similar Xs values at 3 ml/s for the water system and 5 ml/s for the 50 wt% glycerol system, although this flowrate effect would not be as dramatic as with higher disc speeds.

### 3.2. Reactor performance comparison

The comparison between different reactor configurations was based on power dissipation in the mixed liquid. Cafiero et al. [8] described the total power dissipation given to the fluid in the SDR by the action of disc rotation as:

$$\varepsilon = (0.5t_{res})\{(r^2\omega^2 + U^2)_o - (r^2\omega^2 + U^2)_i\} \quad (10)$$

where:

$$U = \left(\frac{\rho_L Q_L^2 \omega^2}{12 \pi^2 \mu_L r}\right)^{\frac{1}{3}} \quad (11)$$

$$t_{res} = \frac{3}{4} \left(\frac{12\pi^2 \nu}{\omega^2 Q^2}\right)^{1/3} (r_o^{4/3} - r_i^{4/3}) \quad (12)$$

The local power dissipation per unit mass of fluid in a stirred tank vessel can be specified as [12]:

$$\varepsilon_{local} = \emptyset \frac{N_p N^3 D_i^5}{\rho V} \quad (13)$$

where  $\emptyset$  is the relative power dissipation which is dependent on the injection position in the vessel. In this study  $\emptyset = 4$  for injection point <1> in the STR (corresponding to a location close to the impeller) and 1.6 for injection point <2> (corresponding to a location away from the impeller) [25].

Figure 7 shows the effect of power dissipation on the micromixedness ratio for the SDR and STR in water using  $[H^+] = 1.0M$ . At a flowrate of 5 ml/s, the SDR provides the optimum conditions for the best micromixing efficiency to be attained in comparison to the stirred tank vessel. Even at a relatively modest power dissipation of 5.2 W/kg, a much higher micromixedness ratio of about 15 is obtained in the SDR which is twice as much as that in the stirred tank vessel with the best possible configuration for acid injection close to the impeller at similar power input. Further increases in the power dissipation in the stirred tank to a maximum value of 21 W/kg have little impact on the micromixedness ratio. In fact, it is seen that micromixing efficiency levels off in the stirred tank reactor for injection close to the impeller beyond a power input of around 3-5 W/kg, indicating that further increases in the agitator speed in the stirred tank beyond 1200 rpm is not only impractical in terms of operational safety but it also brings no advantage whatsoever to the micromixing process. Rather, the additional power input at very high agitation speeds would tend to be dissipated in swirling vortices in the liquid which is detrimental to good mixing.

It is to be noted that that high power dissipation in the SDR at the lower flowrates of 1 ml/s and 3 ml/s are not necessarily conducive to better micromixing intensity compared to the STR. In fact, the dependence of the micromixedness ratio on power dissipation in the SDR was observed to vary considerably depending on the liquid flowrate and the liquid viscosity. Thus, the micromixedness ratio increased steadily with power dissipation at the lowest flowrate of 1 ml/s where as little change in the mixing efficiency is effected when more power is distributed into the liquid at the higher flowrates of 3 and 5 ml/s. This low flowrate effect was explained earlier in terms of the wetting of the disc surface as was discussed in relation to Figures 2 and 4. These

observations highlight the importance of appropriate flowrate selection in conjunction with optimised power dissipation in the SDR for best micromixing performance whilst minimising energy wastage.

We have extended the SDR reactor performance comparison for the water system to other intensified reactors identified in the literature, which include rotor–stator reactor (R-S-R) [26], a novel sliding-surface mixing device (S-S-M) [27] and a torus reactor (T-R) [28] (Figure 8). The SDR micromixing performance at the total flowrate of 5 ml/s is generally higher than the SSM or the RSR across the whole range of power dissipations investigated, corresponding to disc speeds of between 300 and 2400 rpm. On comparison with the torus reactor (TR), the SDR with 5 ml/s flowrate is more efficient at power dissipations less than 100 W/kg. Such a dependency on power dissipation is reflected in the correlations developed in the SDR and in the intensified reactors considered here (Table 4). Whilst the power index in the correlations for the intensified reactors varies between 0.2 and 0.498, that for the SDR under the range of flowrate conditions tested is no more than 0.17, indicating a comparatively weak dependence of the micromixing efficiency on power dissipation in the SDR. Nevertheless, the SDR's capability to give more efficient mixing at 5 ml/s is due to the particularly high coefficient in the correlation.

#### **4. Conclusions**

In this study, the micromixing efficiency in a 10cm spinning disc reactor (SDR) has been investigated by means of the iodide-iodide test reaction. The disc rotational speed, feed flowrate and viscosity and flowrate ratio have all been shown to be important hydrodynamic parameters in determining the micromixing characteristics in SDR. The best micromixing conditions in the SDR were generally achieved at high disc rotational speeds and high feed flowrates. These parameters provided the conditions for the thinnest, highly sheared continuous films, with a large number of surface ripples to be formed thereby enhancing molecular diffusion.

The highest micromixedness ratio obtained in the SDR for the water system is above 15 even at moderate power input of 5.2 W/kg. This is more than double that achieved in a semi-batch the STR under similar power dissipation even with the best possible configuration for acid injection close to the impeller.

Finally, the micromixing efficiency of the SDR was compared with that of other intensified reactors such as the sliding-surface mixing (SSM) device, the rotor–stator reactor (RSR) and torus reactor (TR). The micromixedness ratio in the SDR at the highest flowrate of 5 ml/s was consistently higher than the SSM and the RSR whilst the performance of the TR was broadly similar to the SDR at 5 ml/s, although the latter tended to be more efficient at power dissipations < 100 W/kg. These comparative results highlight the potential of the SDR as an alternative device for processes where a high degree of mixing is critically important.

### **Nomenclature**

$C_{A,0}$  [M] initial concentration of reagent A

$D$  [ $m^2/s$ ] molecular diffusivity or diffusion coefficient

$D_i$  [m] impeller diameter

$D_\lambda$  [-] absorbance

$k$  [ $m^3/mol.s$ ] reaction rate constant

$l$  [m] optical path length

$N$  [ $s^{-1}$ ] mechanical agitator speed

$N_p$  [-] power number

$Q_c$  [ $m^3/s$ ] critical flowrate on rotating disc

$Q_t$  [ $m^3/s$ ] total volumetric flowrate

$Q_i$  [ $m^3/s$ ] volumetric flowrate of stream  $i$

$r$  [m] radial distance from centre at the point of measurement

$R$  [-] flowrate ratio

$Re$  [-] Reynolds number in SBR ( $=N D^2/\nu$ )

$Sc$  [-] Schmidt number ( $=\nu/D$ )

$T$  [m] tank diameter

$t_r$  [s] reaction time

$t_{res}$  [s] mean residence time in SDR

U [m/s] average radial velocity of SDR film

V [m<sup>3</sup> or L] liquid volume

V<sub>r</sub> [m/s] radial velocity of liquid film

X<sub>s</sub> [-] segregation index

z [m] vertical distance from disc surface

Greek symbols

α [-] micromixedness ratio

δ [m] film thickness

γ<sub>max</sub> [s<sup>-1</sup>] maximum shear rate in SDR

ε [W/kg] power dissipation

ε<sub>local</sub> [W/kg] Local power dissipation in STR

ε̄ [W/kg] average power dissipation in STR

ε<sub>λ</sub> [m<sup>2</sup>/mol] molar extinction coefficient

λ [nm] wavelength

μ [Ns/m<sup>2</sup>] liquid viscosity

ν [m<sup>2</sup>/s] kinematic viscosity

ρ [kg/m<sup>3</sup>] liquid density

σ [N/m] surface tension

Ø [-] relative power dissipation  $\left( = \frac{\varepsilon_{local}}{\bar{\varepsilon}} \right)$

ω [s<sup>-1</sup>] angular velocity

Subscripts

i inlet radial position on disc

o outer radial position on disc

Acronyms

RSR Rotor-stator reactor

SDR Spinning disc reactor  
SSM Sliding surface mixer  
STR Stirred tank reactor  
TR Torus reactor

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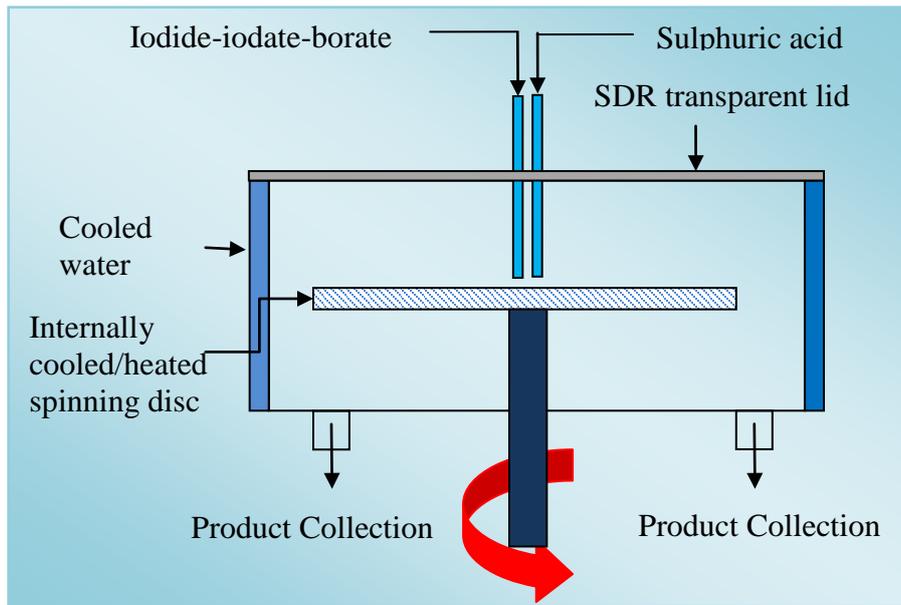


Figure 1. Schematic representation of the spinning disc reactor

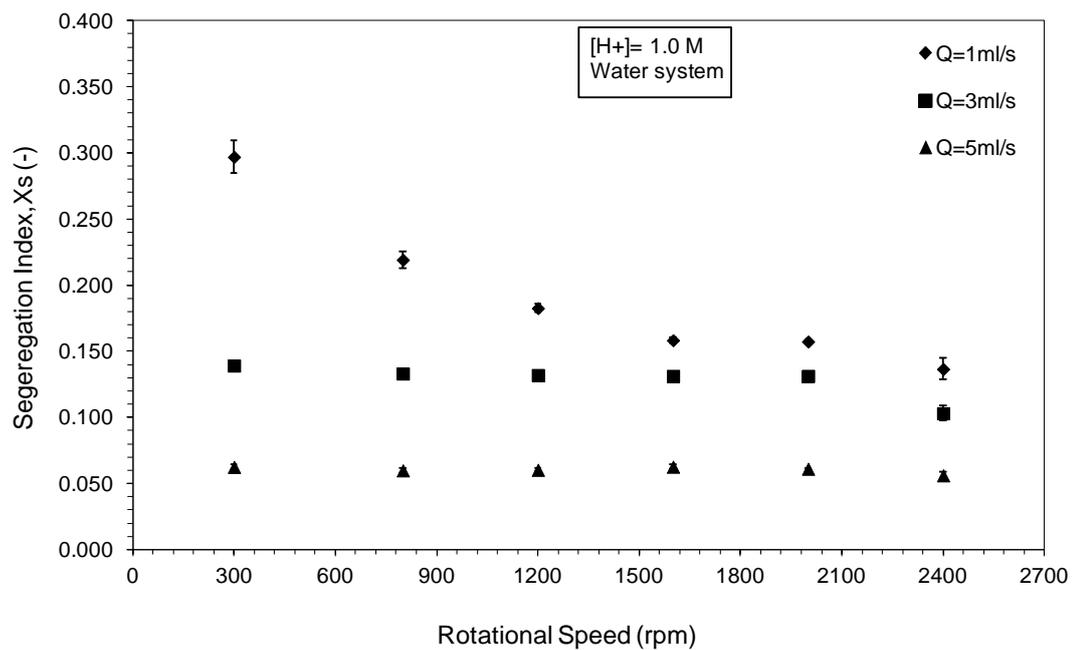


Figure 2. Effect of rotational speed and total flowrate on the segregation index

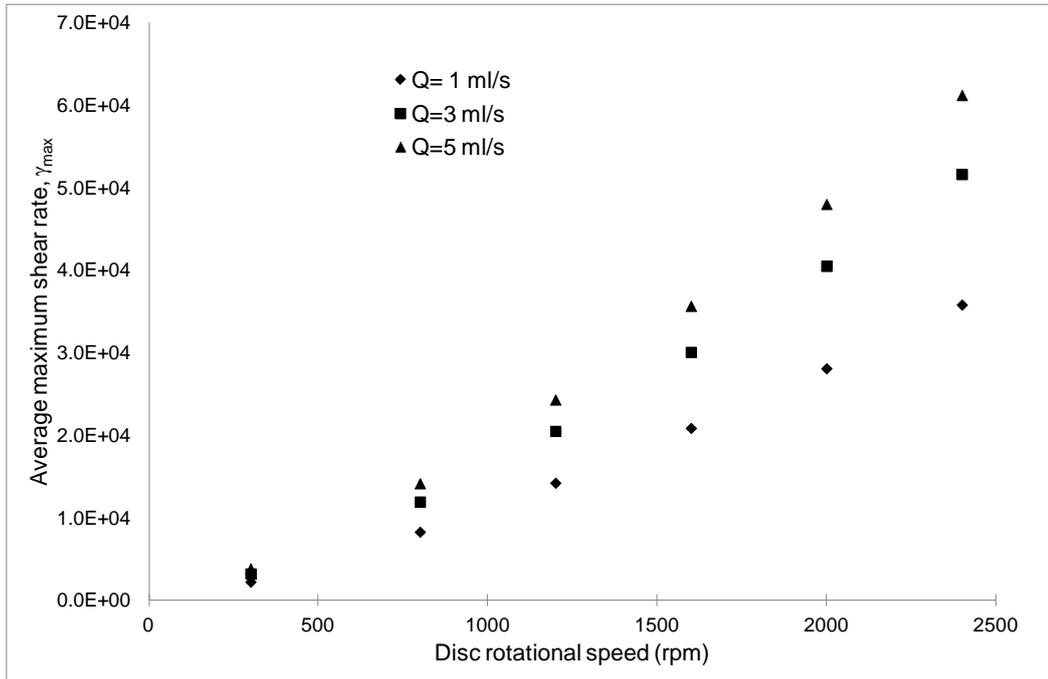


Figure 3. Combined effects of disc speed and feed flowrate on average maximum shear rate in thin film on rotating disc surface (water system)

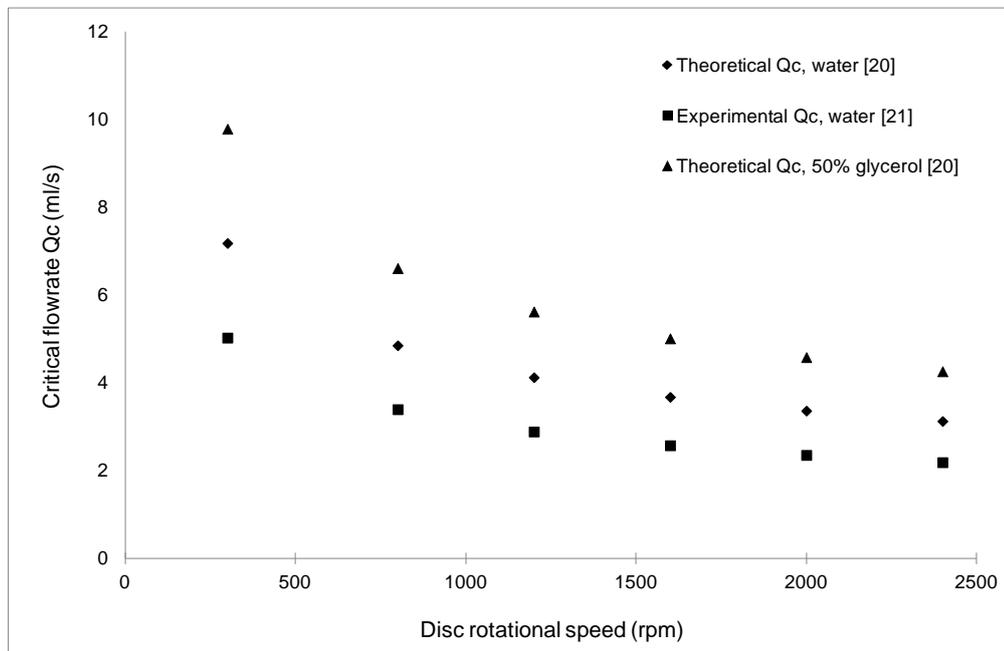


Figure 4. Critical flowrate for determination of film breakdown on rotating disc (estimated at  $r=0.01$  m from the centre)

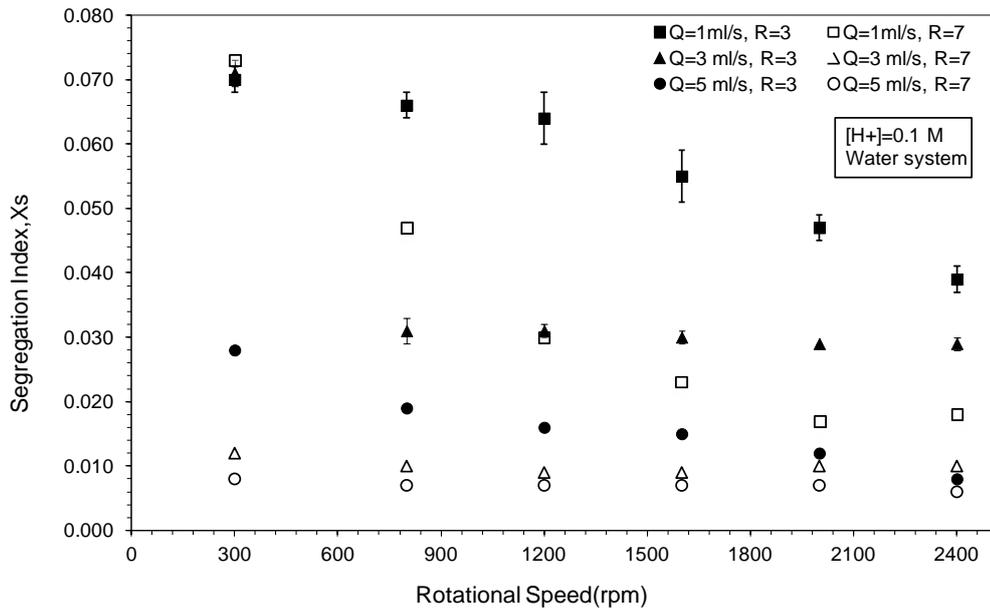


Figure 5. Effect of liquid feed ratios (R) on segregation index at various total flow rates

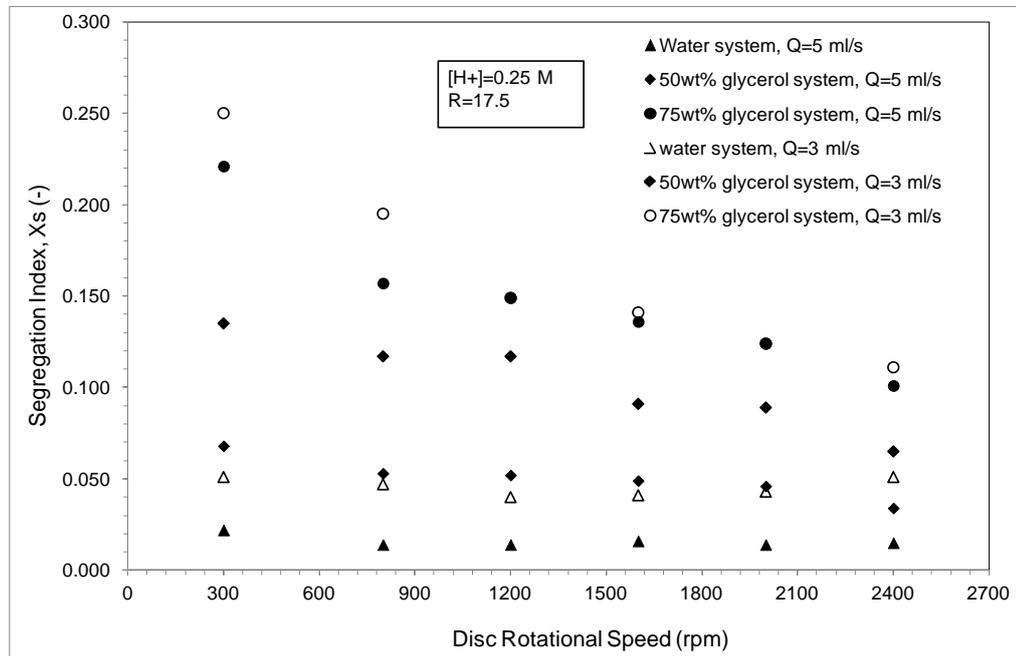


Figure 6. Effect of feed viscosity on segregation index in SDR

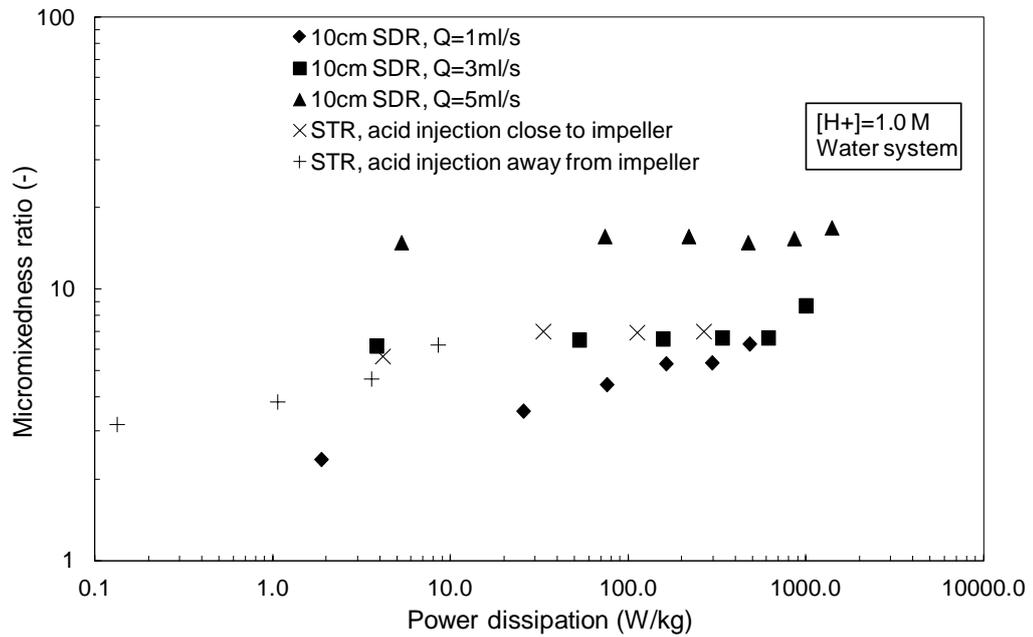


Figure 7. Effect of power dissipation on the micromixedness ratio in 10 cm SDR and STR

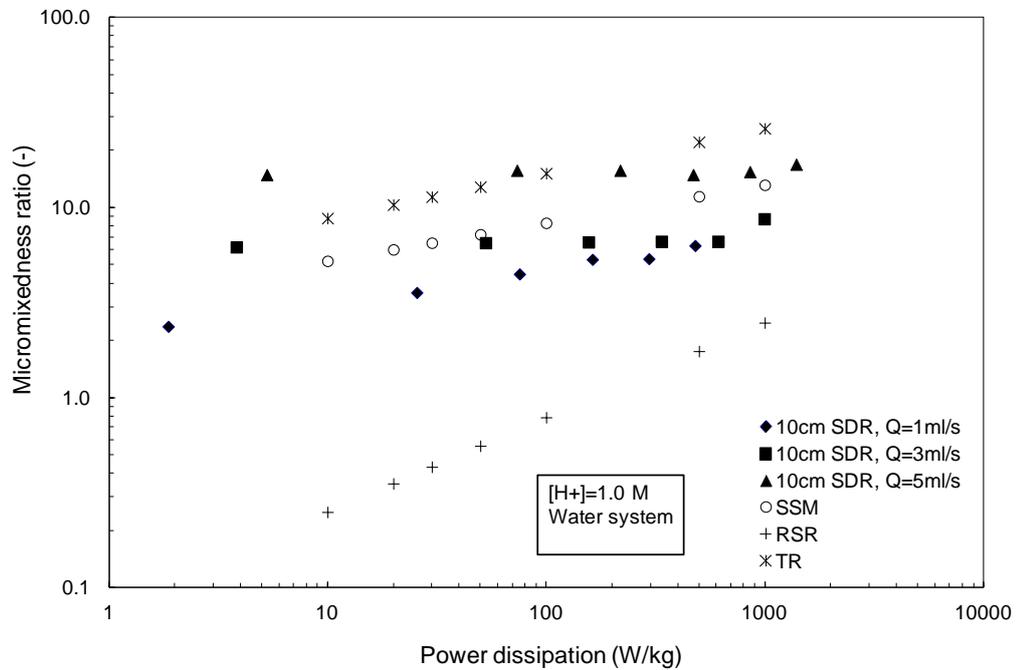


Figure 8. Micromixing efficiency comparison between 10 cm SDR and various intensified reactor configurations

Table 1: Initial concentration of the reactants

Reactants	Concentration used (M)
[H <sub>3</sub> BO <sub>3</sub> ]	0.1818 for water system and 0.0909 for 50 wt% and 75wt% glycerol systems
[NaOH]	0.0909
[KI]	0.01167
[KIO <sub>3</sub> ]	0.00233
[H <sup>+</sup> ]	0.1, 0.25, 0.5, 1.0

Table 2: Initial concentrations for solutions I and H and their flow rate ratios used in SDR (at constant molar ratio of reactant streams)

Solution I			Solution H	R=Q <sub>I</sub> /Q <sub>H</sub>	$\left(\frac{q_{H_2BO_3^-}[H_2BO_3]_0}{q_{H_0^+}[H^+]_0}\right)_{SDR}$
C <sub>IO<sub>3</sub><sup>-</sup>,0</sub> (mol/l)	C <sub>I<sup>-</sup>,0</sub> (mol/l)	C <sub>H<sub>2</sub>BO<sub>3</sub><sup>-</sup>,0</sub> (mol/l)	C <sub>H<sup>+</sup>,0</sub> (mol/l)		
2.3X10 <sup>-3</sup>	1.16X10 <sup>-2</sup>	0.0909	0.1	7	6.363
2.3X10 <sup>-3</sup>	1.16X10 <sup>-2</sup>	0.0909	0.25	17.5	6.363
2.3X10 <sup>-3</sup>	1.16X10 <sup>-2</sup>	0.0909	0.5	35	6.363
2.3X10 <sup>-3</sup>	1.16X10 <sup>-2</sup>	0.0909	1.0	70	6.363

Table 3: Individual flowrates of (Q<sub>I</sub>) and (Q<sub>H+</sub>) corresponding to each total flowrate at different values of flowrate ratio R (= Q<sub>I</sub> / Q<sub>H+</sub>)

R	Q <sub>t</sub> ,(ml/s)	Q <sub>I</sub> ,(ml/s)	Q <sub>H+</sub> ,(ml/s)
7	1.0	0.875	0.125
	3.0	2.625	0.375
	5.0	4.375	0.625
70	1.0	0.986	0.014
	3.0	2.958	0.042
	5.0	4.929	0.070

Table 4: Comparison of micromixing correlations developed for 10 cm SDR (present work), the rotor–stator reactor (R-S-R) [26], the sliding-surface mixing device (S-S-M) [27], and the torus reactor (T-R) [28]

Reactor type	Operating conditions	Micromixing correlation
10 cm SDR	Disc speeds 300-2400 rpm	
	Q <sub>t</sub> = 1ml/s	$\alpha = 2.096\varepsilon^{0.1743}$
	Q <sub>t</sub> = 3 ml/s	$\alpha = 5.649\varepsilon^{0.0387}$
	Q <sub>t</sub> = 5 ml/s	$\alpha = 14.56\varepsilon^{0.0124}$
Sliding-surface mixing device (S-S-M)	Rotating disk speed up to 3000 rpm; recirculation flow rate up to 500 ml/min	$\alpha = 3.3\varepsilon^{0.2}$
Rotor–stator reactor (R-S-R)	Rotating speed: 300-2400rpm; total flowrate of 340 l/h	$\alpha = 0.0794\varepsilon^{0.498}$

*This is the submitted , pre-peer-reviewed manuscript version of the published paper:*  
*Boodhoo, K.V.K., Al-Hengari, S., Micromixing characteristics in a small scale spinning disc reactor, Chem. Eng. Technol. , 35(7), 1229–1237 (2012) DOI: 10.1002/ceat.201100695*

Torus reactor (T-R)	Stirring speed: 100 -1300rpm	$\alpha = 5.1\epsilon^{0.236}$
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The micromixing efficiency in a 10cm spinning disc reactor (SDR) has been investigated by means of the iodide-iodide test reaction. The best micromixing conditions were generally achieved in a water film at high disc rotational speeds and high feed flowrates. The SDR gives improved micromixing performance, particularly at the highest flowrate of 5 ml/s, compared with other reactor configurations. These results highlight the potential of the SDR as an alternative intensified mixer/reactor for processes where a high degree of mixing is critically important.

