Mixing and Reaction in a Novel Spinning Disk Reactor

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Abstract

The spinning disc reactor concept is based on the surface rotation technique aimed at accelerating process operations, which present heat and mass transfer limitations. This paper describes the operation of a spinning disk reactor suitable for liquid phase reactions. The hydraulic performance of the reactor was evaluated using classical tracer-response techniques. The effects of flowrate and rotational speed upon mixing were determined. The performance as a reactor was also investigated using the liquid phase reaction between aqueous crystal violet and sodium hydroxide solution. Non-symmetrical single peak residence time distributions for the reactor were observed, consistent with the behaviour of two ideally mixed stirred tanks operating in series. The mean residence times increased with disk speed and this was explained by increased liquid hold up near the walls of the reactor due to the high speeds of the rotating shaft. The study showed a linear relation between the conversion of crystal violet and rotational disc speed. The rate of reaction was significantly higher than that predicted on the basis of the "two-tanks-in series" model, suggesting that enhanced mass transfer may also be present.

Introduction

Centrifugal fields, high gradient magnetic fields and electrostatics have been identified as process intensification techniques[1]. The spinning disc reactor is based on the surface rotation technique aimed at overcoming heat and mass transfer limitations. High centrifugal fields are created through the rotation of a disc causing the reacting liquids to form a thin intensely mixed film.

Potential industrial applications include: liquid-liquid extraction; gas-liquid reactions; polymerisation reactions. The SDR provide faster kinetics, for example, the phase-transfer-catalysed Darzen's reaction [2] for drug intermediates and active pharmaceuticals. Reaction times were reduced by 99.9%, the material inventory by 99% and the product impurities by 93%.

Elsewhere[3,4], the rate of polymerisation of polystyrene was found to dramatically increase in a spinning disc reactor when compared with a CSTR. Rapid increase in viscosity occurs with increasing monomer conversion which causes poor heat transfer and mixing throughout mixture.

The current work is concerned with the design and evaluation of a single stage spinning disk contactor in which a homogeneous liquid phase reaction was used to study the performance of the contactor. There were three principle aims: (i) To determine the mixing and residence time distribution behaviour of the contactor as a function of rotational speed; (ii) To study the relationship between rate of reaction and the rotational speed. (iii) To compare the performance of the spinning disc reactor with a conventional stirred tank reactor system

Experimental

The spinning disk reactor was designed to handle the reaction between two liquids fed independently to the reactor. The reactor (figure 1) comprised of a flat circular disk of diameter 150mm made from 2mm stainless steel, connected coaxially to a rotating shaft powered by a belt drive. The shaft was hollow to allow connection to a supply of reactant liquid. The second liquid was sprayed on to the top surface of the disk via a nozzle, located 30mm from the top surface of the disk, in a cylindrical vessel 200mm diameter, equipped with a single outlet port and vent.

The residence time distribution characteristics of the reactor were obtained[5] from pulse injection of crystal violet solution into one of the feed streams to the reactor followed by continuous monitoring at the outlet. The outlet was monitored continuously using a ‘spectronic 20’ colour analyser from which the residence time distributions of tracer were determined in the speed range 200-1000rpm.

The performance was evaluated using the reaction between crystal violet dye and sodium hydroxide solution.

Crystal violet + sodium hydroxide → colourless

Previous experiments [6] have shown the reaction rate to be represented thus:

$$-r = kC_{NaOH}C_{crystal\ violet} \tag{1}$$

where the rate constant k has a value of 6.9 $m^3\,kmol^{-1}min^{-1}$

If there is an excess amount of sodium hydroxide present, then the concentration of sodium hydroxide is approximately constant. The reaction rate becomes first order.

$$-r = k'C_{crystal\ violet} \tag{2}$$

where k' is a pseudo-rate constant.

$$k' = kC_{NaOH} \tag{3}$$

The conversion of a reaction is defined as:

$$\text{Conversion of A} = \frac{\text{moles of A reacted}}{\text{moles of A fed}} \qquad (4$$

Table 1.0 Operating conditions for the crystal violet reaction.

	Sodium Hydroxide	**Crystal Violet**
Liquid Phase:	Reactant A	Reactant B
Flow Rate:	1.5 ± 0.01ml/s	0.2 ± 0.02ml/s
Concentration:	0.032 ± $1x10^{-4}$mol/L	$4.94x10^{-5}$ ± $5x10^{-7}$mol/L

The conversion of crystal violet was evaluated disc speeds in the range 200-1060rpm, calculated from the average concentration in the exit over a 10 minute interval. The performance was compared with a conventional "two-tanks in series" reactor system operated under the same reaction conditions. The basis of comparison was the residence time in the conventional system to achieve the same conversion.

Results

Variation of exit tracer concentration at each disk speed is shown in Figure 2. The effect of disc speed on mixing appears to be small. As the disc speed increases the shape of the curve flattens, suggesting increase in mixing.

Figures 3 and 4 show comparisons of tracer response data with the predictions of the "two-stirred tanks in series" model. Comparisons were made at each of the disc speeds

Discussion

Figures 3 and 4 show nonsymmetrical single peak residence time distributions for the disc speeds 200-1060rpm as shown in. The experimental mean holding time increased from 78s at 200rpm to 112s at1060rpm. The 34s difference might be explained by visible liquid hold up near to the walls of the reactor generated by the high rotational speeds. Stagnant pockets of liquid near the walls retain the dye longer resulting in longer residence times.

The Tanks-In-Series Model [4] was fitted to the experimental residence time distributions. In all cases RTD were best described by a two-tank model. Figure 5 shows a strong linear relationship between disc speed and conversion of crystal violet. The main explanation is that the high rotational speeds induce high centrifugal fields within the liquid film on the disc thus promoting intense mixing and mass transfer in the film.

Comparison with the conventional "two-tanks-in-series" system showed that a conversion of 35% was achieved in the spinning disc reactor at a residence time of 90s at a disc speed of 500rpm. A residence time of 280s was required to achieve the same conversion as the conventional two-tanks-in-series system. Process intensification is also evident in figure 6, where all the experimental SDR conversions are compared with the theoretical conversions, which would be expected in a single plug flow reactor (PFR), and a single ideally stirred tank (CSTR) for residence times in the range 75-120s.

The mean residence times for the fitted tanks-in-series model shown in Table 2 were similar to those observed from the experimental results. The variance for the fitted tanks-in-series model steadily increased from 2788s^2 at 200rpm to 5672s^2 at 1060rpm. The increasing variance with disc speed is consistent with the increasing residence times discussed earlier

Table 2. Retention times of the spinning disc reactor.

Disc speed (rpm)	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**1060**
Conversion	29%	28%	30%	35%	35%	40%	44%	51%
Tanks in series model								
Mean holding time (s)	78	86	90	90	103	95	109	112
Variance (s^2)	2788	3260	3814	3809	4970	4312	5399	5672
Experimental Results								
Mean holding time (s)	79	89	91	91	105	96	111	115
Variance (s^2)	3104	4017	3250	3640	5363	5183	5987	5861

Conclusions

The results indicate a linear relation between the conversion of crystal violet and rotational disc speed over the range 300-1060rpm. The maximum rotational speed of 1060±5rpm produced the highest crystal violet conversion of 51±1%. The non-symmetrical single peak residence time distributions for the SDR accurately model the flow regime of two CSTR's in series for the disc speeds 200-1060rpm. This is most likely due to the simulated CSTR fluid characteristics in the bottom of the spinning disc reactor and in the sample pot. The mean residence times increase with disc speed due to liquid hold up near the walls of the reactor, generated by the high speeds of the rotating shaft. The SDR showed accelerated rates of mass transfer by achieving a conversion of 35% after a residence time of 90s, compared to a two CSTR system that achieved the same experimental conversion after 280s.

References

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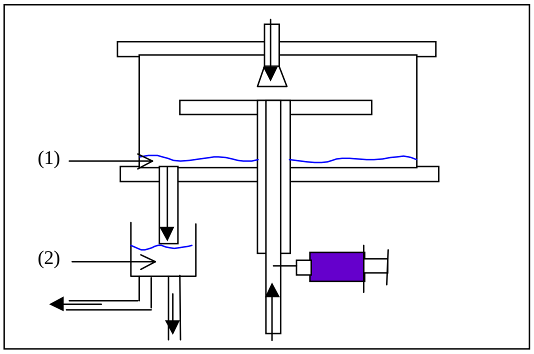


Fig 1 Spinning disk reactor arrangement

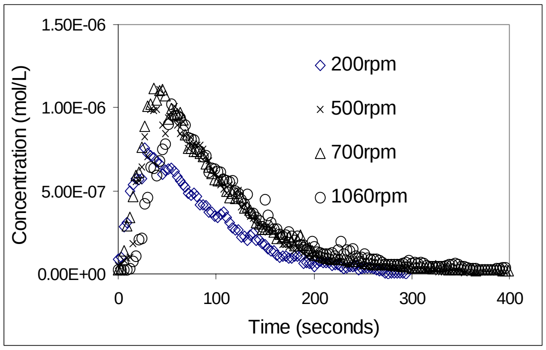


Fig2 Tracer response - effect of disc speed

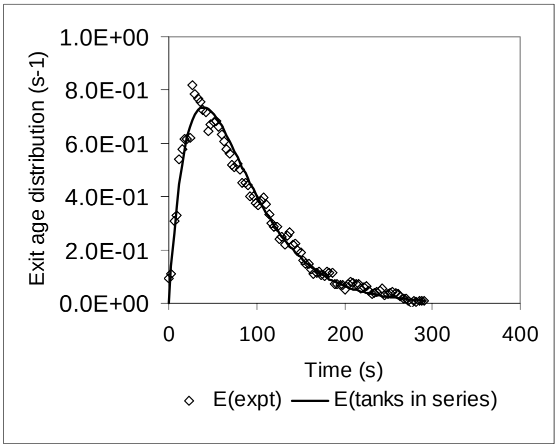


Fig3 Residence time distribution at 200rpm

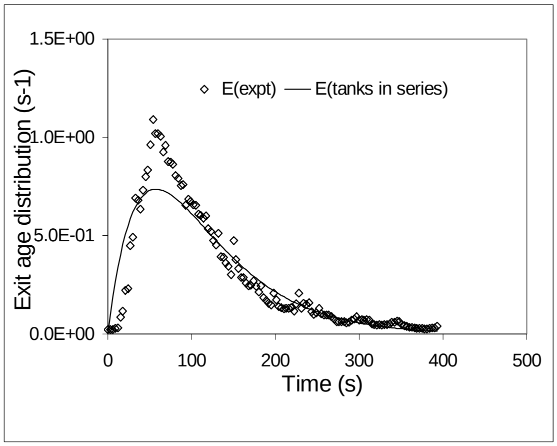
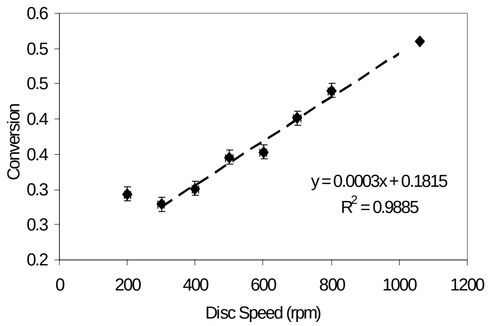


Fig 4 Residence time distribution at 1060rpm



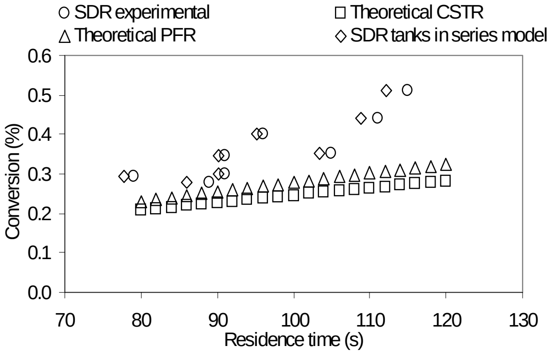


Fig 5 Conversion of crystal violet vs disc speed

Fig 6 Performance comparison with reactor models