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process-intensification-spinning-disc-reactor-1

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Process Intensification: A Study of Micromixing

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The extensive article under review is a doctoral thesis study conducted to systematically investigate the micro and macro mixing of thin films created by a spinning disc reactor (SDR).

PDF Version of the webpage (first pages)

https://cruisingreview.com/smx/process-intensification-spinning-disc-reactor-1.html

Process Intensification: A Study of Micromixing and Residence Time Distribution Characteristics in the Spinning Disc Reactor

1. The extensive article under review is a doctoral thesis study conducted to systematically investigate the micro and macro mixing of thin films created by a spinning disc reactor (SDR).
2. The first part of this study compares the micromixing ability of SDR technology to its primary competing processes: the semi-batch reactor (SBR) and the continuous tubular flow reactor using narrow channels (NCR).
3. Multiple operating parameters were tested for the SDR including, quote - disc rotation rates, disc size, disc surface configurations, feed flowrates, feed distribution systems, liquid feed concentrations and viscosities – unquote.
4. The second focus of this study was to determine, quote – the residence time distribution (RTD) of the liquid flow in the 30 cm SDR – unquote, under a range of different operating conditions.
5. Process intensification was primarily a strategy to reduce capital investment while maintaining the same level of production. It was quickly realized that successful intensifications also result in reduced environmental impact and better overall process efficiencies.
6. Reducing equipment size while maintaining throughput also offers the benefit of better heat transfer and mass transfer rates which helps to reduce undesirable byproducts.
7. Process intensification can be achieved through multiple possible methods: quote – the use of centrifugal forces, flow field/fluid microstructure interactions, periodic flow, high/ultra-high pressure, electric field, and diffusion/conduction path reduction – unquote.
8. The Spinning Disc Reactor (SDR) is one possible process designs which can offer significant intensification. It involves a rotating disc mounted on a horizontal or vertical shaft. Liquid reactants are fed near the center of the disc and drawn outwards due to centrifugal force.
9. Use of an SDR was successfully used, quote – at Newcastle University for industrial application: ... polystyrene production and precipitation of barium sulphate from aqueous solutions – unquote. The results were significant when compared to a conventional batch reactor.
10. The author chose to focus the study on the implementation of SDR technology vs a competing method of intensification for a number of reasons: high heat transfer rates, high mass transfer rates, ability to mix at a molecular level, ability to include parallel reactions, minimal reactant volumes, short residence times, and easy operation.
11. The liquid film produced on an SDR is typically 50-200 um thick.
12. The typical residence time of an SDR is 1-5 seconds.

Source: Al-hengari S. Process Intensification: A Study of Micromixing and Residence Time Distribution Characteristics in the Spinning Disc Reactor. October 2011. https://theses.ncl.ac.uk/dspace/bitstream/10443/1771/1/Al-Hengari (12mnth).pdf

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13. The use of mixing is a basic process involved with many industrial productions. It serves to homogenize a batch, reduce temperature and concentration gradients, and promotes mass transfer.
14. In many processes, the quality of mixing has a direct impact on overall production efficiency and the creation of undesirable byproducts.
15. The time that is required to achieve sufficient molecular level mixing can also have a significant impact on reaction performance when the time constant of the reaction is close to or less than that of the mixing time.
16. The primary goals of this study are to investigate, quote – (1) the fundamental science underlying the micromixing characteristics taking place within the thin films in the SDR and (2) the Residence Time Distribution of the film under a range of conditions – unquote.
17. Another benefit of process intensification not mentioned earlier, is the improved time to market. With an intensified process, the ability to produce product at a greater rate, and implement changes more quickly overs better market responsiveness.
18. Public and customer perception can also benefit from the implementation of process intensification. It is well understood that processes designed for overall efficiency can reduce resource requirements and offer a more sustainable business model.
19. Some of the challenges involved with process intensification include the need to replace batch processing equipment, company culture must transition from batch orientation to continuous orientation, and each reaction needs to be understood based on its intrinsic reaction time so that the proper process can be developed.
20. One process intensification design is called the multifunctional reactor which aims to combine two or more functions into a single step, for example, quote – the reverse-flow reactor which integrates reaction and heat transfer by periodic flow reversal – unquote.
21. Hybrid separation is another method which relies on the integration of membranes with at least one other separation technique to improve separation efficiency.
22. Alternative energy sources can also be used to influence the mixing, heat transfer, and mass transfer: quote – centrifugal fields, ultrasound, solar energy, microwaves, electric fields, microwaves, and plasma technology – unquote.
23. The final group of intensification methods include processes such as supercritical fluids and dynamic/periodic reactors.
24. The Spinning Disc Reactor is one design that utilizes centrifugal force to intensify the mixing of reactants producing better heat and mass transfer.
25. The thin films of liquid produced on the spinning disc can be as thin as 25 um or less. This film is very turbulent, but its turbulence is dependent on viscosity. Reactions of greater viscosity will resist distortion and turbulence but will not fully prevent it.
26. Previous works by Brauner and Maron indicated that the presence of waves in thin films was directly related to improved heat and mass transfer.
27. The centrifugal force acting on the thin film produced on the spinning disc of an SDR can induce forces 100-1000 times that of gravity.
28. NASA has done considerable research into the use of spinning discs to facilitate reactions that otherwise rely upon gravity to proceed in a reasonable timeframe.
29. Viscous thin films tend to dampen the ripples most responsible for the improved heat and mass transfer as such disc surfaces have been developed to induce greater turbulence.
30. Rotor Stator SDR's have also been developed and are comprised of two discs separated by only 1 mm. One disc spins while the other is held stationary, this creates a greater shear force and better liquid / solid and liquid / gas interaction.

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31. The first thin films studied were those produced by allowing liquid to flow down inclined or vertical walls. Much of this original work influenced the more recent move to centrifugally created thin films.
32. As with rotationally created thin films, the gravity generated thin films exhibited, quote – superior rates of heat and mass transfer which were linked to the strong mixing characteristics of the surface waves – unquote.
33. Page 55 of the study provides equations to calculate many aspects of idealized SDR thin film creation: average maximum shear rate across the disc surface, film thickness based on radial position, average film thickness, and mean residence time of the fluid on the disc.
34. The Coriolis force causes the thin film to move more slowly than the disc due to its force in the opposite direction of the rotating disc. If the centrifugal force is much greater than the Coriolis force it is understood that the Coriolis force can be described as negligible.
35. Previous work concluded that Coriolis and Inertial forces are, quote – only significant at a small distance from the distributor – unquote, the location near the axis where the reactants are being deposited onto the spinning disc.
36. In SDR's with relatively large radius, quote – the simple centrifugal model is sufficient to describe the flow – unquote.
37. The equation for determining Reynolds number for thin film on a rotating disc can be found on page 57. Reynolds number describes a ratio of the internal forces of a fluid to the viscosity of the fluid.
38. Reynolds number can help to determine the type of liquid flow present on different parts of a spinning disc: smooth laminar, wavy laminar, or turbulent.
39. Smooth laminar flow is associated with Reynolds numbers less than 16. At the other end of the spectrum, Turbulent flows are associated with Reynolds numbers in excess of 1,000.
40. Studies reviewed by the author investigated the effect of reactant flow rate and disc rotational speed. It was found that both have a significant impact on the type and location of ripples / disruptions formed in the thin film.
41. Critical flow rate is a term that has been developed to describe the minimum reactant flow rate required to allow proper thin film formation. Break down in thin film formation significantly reduces the heat and mass transfer capacity of the system.
42. One study determined that the addition of, quote – mechanically machined grooves … on the disc surface – unquote, significantly improved the heat transfer performance of the system.
43. It was also determined that disc rotational speed is the most significant factor in determining mass transfer rate.
44. In an experiment using an SDR to polymerize styrene, Boodhoo and Jachuck, demonstrated that the resulting product was produced more quickly and was of better quality in terms of a tighter particle size distribution than styrene produced by a continuously stirred reactor.
45. According a device that intends to offer throughout mixing of reactants must two crucial abilities: it must prevent areas of stagnation and it must create high shear forces. The SDR offers both characteristics.
46. Mixing occurs at three scales: macromixing, mesomixing, and micromixing.
47. Macromixing occurs, quote – on a scale greater than the minimum eddy size – unquote. It is the overall blending that increases visual homogeneity.
48. Mesomixing occurs, quote – on a scale roughly comparable with the size of the reactant feed pipe – unquote, and more finely mixes than macromixing.
49. Micromixing occurs on a molecular scale and exists at a size smaller than the minimum eddy size. This level of mixing is required for chemical reactions characterized by high rates of reaction.

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50. A fast reaction is described as having an equal or lessor time requirement than that of the time requirement for micromixing.
51. Page 76 offers an equation for calculating the time requirement for through macromixing using a stirred tank reactor with depth approximately equal to its diameter.
52. Page 78 shares an equation that describes the time dependency of mesomixing based on feed rate and turbulence.
53. The time requirement for micromixing can also be calculated based on another equation in page 78. Micromixing time is dependent upon the rate of molecular diffusion, shear force, and laminar interaction in the fluid.
54. According to the micromixing time formula, thin film micromixing on an SDR can be achieved in 0.1- 1.0 seconds.
55. With, quote – sufficient intensive turbulence – unquote, it is possible that, quote – time constants for micromixing are likely to fall in the range of 0.1-100 ms – unquote.
56. Using know reactions with fast characteristic reaction times allows mixing analysis. The rate and efficiency of the mixing can affect the product particle size distribution which can be used as a measure of mixing efficiency.
57. Segregation index, denoted Xs, is a measure of the portion of undesirable byproducts produced in a reaction compared to the maximum number of undesirable byproducts produced without any mixing.
58. Xs will fall between 0 and 1. Zero representing perfect micromixing; 1 indicating total segregation and no mixing.
59. The micromixedness ratio measures the portion of a reactor volume that is perfectly micromixed divided by the remaining segregated volume of reactants.
60. Residence time distribution (RTD) is the, quote – probability distribution function that describes the amount of time a fluid element could spend inside the reactor – unquote. RTD is heavily influences yield and unwanted byproduct production.
61. RTD can be measured using a tracer. A tracer is an inert compound that is added to the reactant feed stream. It is either colored or radioactive but will not react with any other materials in the system. By measuring the rate of its collection, its residence time can be calculated.
62. For the primary investigation the author implements a, quote – parallel competing reaction scheme namely the acid-base neutralization coupled with the Dushman reaction – unquote. This specific reaction was selected because much of the previous work done to quantify mixing in semi-batch reactors was performed with the same setup.
63. A labeled picture of the 10 cm spinning disc reactor used for some of the investigations is shown on page 134. A mechanical drawing of the SDR is available on page 135.
64. A labeled picture of the 30cm SDR is available on page 143 and clearly shows the grooves employed on the disc for part of the investigation.
65. Using the 10cm SDR, it was shown that, quote – the segregation index (Xs) decreases consistently with increasing rotational speed – unquote, indicating better micromixing at higher disc rpm.
66. Increasing reactant feed rates was also associated with a decrease in Xs.
67. Page 191 shows a chart of disc rotational speeds along with the calculated residence times and calculated micromixing times for each trial. The residence times, while only a fraction of a second, were orders of magnitude greater than the required micromixing times.

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68. In another test, it was shown that acid concentration had a significant impact on the segregation index (Xs). As such, the initial concentration of reactants clearly has an impact on mixing as well.
69. By adding glycerol to the aqueous reactions, the author was able to control the viscosity of the reactants and investigate its effect on Xs. It was shown, quote – clearly that the segregation index is affected by the viscosity of the feed – unquote.
70. It was also observed that increasing the speed of the disc was able to partially overcome the negative impact of increased viscosity on micromixing.
71. Power dissipation is a measure of how much physical energy is transmitted to the fluid by the spinning disc. Higher power dissipation is typically associated with better micromixing and a lower segregation index. Testing indicated that increased disc speed, higher flow rate, and lower reactant viscosity were all associated with greater power dissipation.
72. Studies with the 30 cm SDR and differing flow rates brought up the realization that an optimal flow rate often exists based on process parameters. For the given test, Xs decreased as flow rate was increased from 3 ml/s to 9 ml/s, regardless of disc speed. At flow rates above 9 ml/s, Xs began increasing, indicating a decrease in micromixing efficiency.
73. The study author offers the explanation that at a certain flow rate, the fluid is not able to fully couple with the spinning disc at which point the Coriolis effect becomes a significant influence in the fluid movement. When this happens, less energy is imparted to the fluid and less micromixing occurs.
74. In an investigation of power dissipation using the 30cm SDR and varying flow rates and disc speeds it was also shown that while increasing flow rate will increase powder dissipation, it will at some flow rate also increase the segregation index (Xs) indicating less micromixing.
75. Experiments using a grooved 30cm disc showed the opposite results regarding flow rate and segregation index. Low flow rates displayed a higher segregation index on the grooved disc when compared to the smooth disc. At higher flow rates, the Xs was less with the grooved disc than the smooth disc.
76. The author explains this phenomenon with the idea that at a sufficiently low flow rate, the entire disc is not fully wetted. As such, the thin film forms rivulets at the bottom of the grooves rather than a uniform thinness across the whole surface. At higher flow rates the liquid is able to fully wet the grooved disc allowing for more surface area for mass and thermal transfer.
77. The author also undertakes several comparable investigations involving Narrow Channel Reactors (NCRs) to compare their efficacy with the SDR.
78. Results from the multiple tests, quote – confirm that the micromixing efficiency in SDRs at a given power dissipation is better than in SBR (Stirred Batch Reactor) and NCRs – unquote.
79. Comparison of results between the 10 cm and 30 cm SDRs, controlling for other variables, showed that, quote – the 30cm SDR performs better than the 10cm SDR as a result of a larger disc surface area available – unquote.
80. This larger surface area translates into greater residence times and therefore more opportunity for micromixing to occur.
81. Investigations of the residence time on SDR indicated that higher disc rpm led to shorter residence times, but more importantly a decrease in residence time variance. Lower residence time variance is associated with a more idealized plug-like flow with less back mixing. This likely indicates a more uniform thin film layer over the surface of the disc and more uniform micromixing.
82. Similarly, it was shown that increased flow rate also yielded a decrease in RTD variance and more uniform flow/mixing. This only appears to hold true until a certain flow rate is reached at which the benefit of additional flow rate is not seen.
83. RTD was also increased because of increasing the viscosity of the reactants, but this effect is somewhat overcome by increasing disc rpm and increasing flowrate.

84. Positive initial results of testing the 30 cm grooved disc vs the 30 cm smooth disc led to additional testing to determine whether or not back mixing was occurring.
85. In comparing multiple disc rotation speeds using both the smooth and grooved discs at the same reactant flow rate (3 ml/s), it was found that the grooved disc produced less variance in RTD, indicating a more plug like flow.
86. When the reactant flow rate was increased above 9 ml/s the benefit of higher disc speed and grooved vs smooth has less impact. At, and above, 9 ml/s the RTD is very uniform for all disc speeds and disc surfaces. This reduced variance at higher volume indicates that at a certain reactant flow rate, the liquid movement across the disc will become more uniform and plug-like.
87. The author suggests that, quote – higher flow rates will allow better use of available surface area of grooved discs ... and also result in better mixing– unquote.
88. Additional testing with 30 cm smooth and grooved discs indicated that increased reactant viscosity creates increased RTD as well as increased RTD variance.
89. Similar to the disc rotation speed testing, at a certain flow rate 9 ml/s and greater the effect of the increased viscosity is negligible.
90. After performing all investigations involved with this study, the author concludes that, quote – the best micromixing conditions in the SDRs were generally achieved at high disc rotational speeds, high feed flowrates and on the large rotating discs – unquote.
91. These ideal parameters created the most uniform, thinnest films on the spinning disc surface with the greatest shear forces all of which contribute positively to micromixing.
92. In comparing experimental data with previous works by Baldyga and Pohorecki, the author demonstrates that SDRs, quote – have excellent micromixing efficiency – unquote.
93. Comparisons with other intensified mixing processes showed that, quote – SDRs give significantly better micromixing performance than the SBR and NCRs – unquote.
94. The author suggests that further investigation is needed in visualization and mathematical characterization of the fluid movements on the surface of the disc so that better predictive models can be built for future SDRs.
95. Results from this investigation highlight the importance of disc surface area on the micromixing efficiency of the system. One recommendation for future development was to employ multiple discs that flow from one to the next.
96. Overall, the author clearly recognizes the benefits and micromixing efficiencies offered by the SDR as opposed to other intensified mixing processes. With better understanding of the relevant forces at work and design features influencing them, there is much potential for SDR use in multiple industries.

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