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OBSERVATIONS ON THE SPINNING DISC MICROMIXING CHARACTERISTICS

BY

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Abstract. The spinning disc technology is one of the most versatile process intensification techniques used in different application fields. The intense micromixing is one of the strong features the spinning disc is used for. The current study includes experimental data related to the dispersion number values, obtained at different working parameters, namely the feeding liquid flow rate and the disc rotational speed. These were used to calculate the characteristic SD micromixing times, found to decrease faster with the disc rotational speed increase, especially at smaller flowrates. The shear stress is increasing fast with the rotational speed and varies with the disc radial position. Furthermore, the residence time has the smallest values at the highest rotational speeds and liquid flowrates. Thus, despite the increased micromixing obtained at large rotational speeds, the corresponding shorter residence time can be a restricting factor, since the processed liquid cannot take advantage of the enhanced turbulence.

Keywords: diffusion coefficient; indented surface; micromixing time; residence time; shear stress.

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1. Introduction

The spinning disc technology, a versatile process intensification technique used in different application fields, such as pharmaceutical and cosmetics or environmental areas (Feng *et al*., 2013; Iacob Tudose, 2014; Sana *et al*., 2019), has been investigated within this study with respect to some of the relevant micromixing characteristics of the centrifugal force driven liquid film, since it is known that the degree of mixing can control the process selectivity or the final product quality.

Previous experimental studies applied for liquid flow rates of 18, 36 and 54 L/h and disc rotational speeds of 300, 600, 900 and 1200 rpm indicated that plug flow conditions with a diminish in the radial dispersion in the spinning disc system (SDR) were generally achieved at high disc rotational speeds and high feed flowrates (Mohammadi and Boodhoo, 2012). Also, the best micromixing conditions, measured in terms of segregation index or micromixedness ratio for the well-established iodide–iodate reaction scheme (Guichardon and Falk, 2000; Boodhoo and Al-Hengari, 2012), were generally achieved in a water film at high disc rotational speeds, over 1000 rpm, and high feed flow rates of 18 L/h.

Subsequent application of SD technology for textile waste water treatment revealed that the highest solids and colour removals were obtained for liquid flow rates of 15-20 L/h and disc rotational speed of 550 rpm, somewhere in the middle of the investigated parameter intervals (Iacob Tudose and Zaharia, 2020).

Prior experimental results performed to obtain the residence time distribution using the pulse response technique, at different liquid flow rates and disc rotational speeds, (Iacob Tudose and Zaharia, 2018), endorsed the calculation, within this study, of some characteristic spinning disc parameters such as the diffusion/dispersion coefficient and the micro-mixing times, important to emphasize some of its enhanced convective features and also, point out some limitations. Additionally, a comparison between different hydrodynamics influence parameters such as the liquid flow rate, the disc rotational speed and the disc surface state can be performed in order to establish which values are more prone to improve the disc performance.

2. Materials, Method and Equations

The pulse-response technique consisting of an inert NaCl 2% solution injection into the liquid stream fed on the spinning disc of 20 cm diameter, in an experimental setup described in detail previously (Iacob Tudose, 2014; Iacob Tudose and Zaharia, 2018), was applied to obtain the residence time distributions related to the degree of mixing or dispersion within the system. The disc surface was either smooth or indented with concentric and respectively, radial grooves, as depicted in Fig. 1.

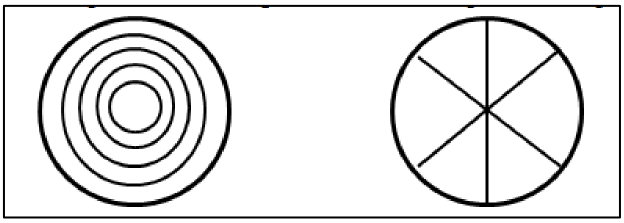


Fig. 1 – Sketch of the indented discs (*a*) concentric indentations; (*b*) radial indentations.

In order to model the salt concentration dispersion on the disc, described by Eq. (1) and some initial and boundary conditions (2), one can use the radial dispersion model or the N-tanks-in-series model for a not very large deviation from the plug flow or the axial dispersion model. Solving the above Eq. (1), the normalized residence time distribution function E(θ) is obtained, with the normalized variance, σ_θ^2, given by Eq. (3) for the first used model, and respectively by Eq. (4) for the second mentioned model (Levenspiel, 1999):

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial r^2} - u\frac{\partial c}{\partial r} \quad (1)$$

$$t = 0,\ 0 < r < R, c = 0$$

$$t = 0, r = 0, c_0 u = cu - D\frac{\partial c}{\partial r} \quad (2)$$

$$t > 0, r = R, \frac{\partial c}{\partial r} = 0$$

$$\sigma_\theta^2 = 2\frac{D}{U_m R} + 8\left(\frac{D}{U_m R}\right)^2 \quad (3)$$

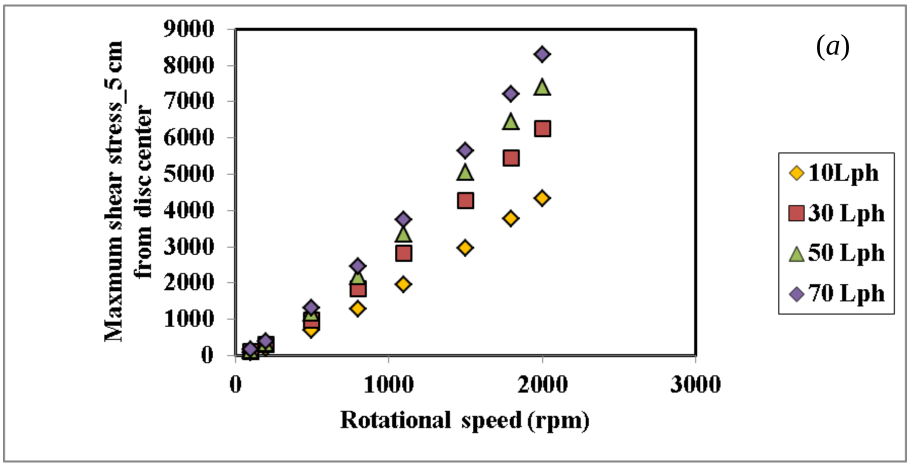
$$N = \frac{1}{\sigma_\theta^2} \quad (4)$$

where D/U_mR is the dispersion number with D the diffusion coefficient, Um the mean liquid velocity, R the disc radius and N is the equivalent number of tanks in series. Based on the experimental value σ_θ^2, using Eq. (3) and respectively, Eq. (4), one can calculate respectively, the dispersion number and the equivalent number of tanks in series, N.

3. Results and Discussions

The intense micromixing is one of the strong features the spinning disc is used for. To quantify the micromixing characteristics at different working parameter values such as flowrate and disc rotational speed, one should determine the maximum shear stress at different locations on the disc based on Eq. (6) (Boodhoo and Jachuck, 2000) and represented in Fig. 2:

$$\gamma_{max} = \left(\frac{1.5Q\omega^4 r}{\pi\vartheta^2}\right)^{1/3} \tag{6}$$



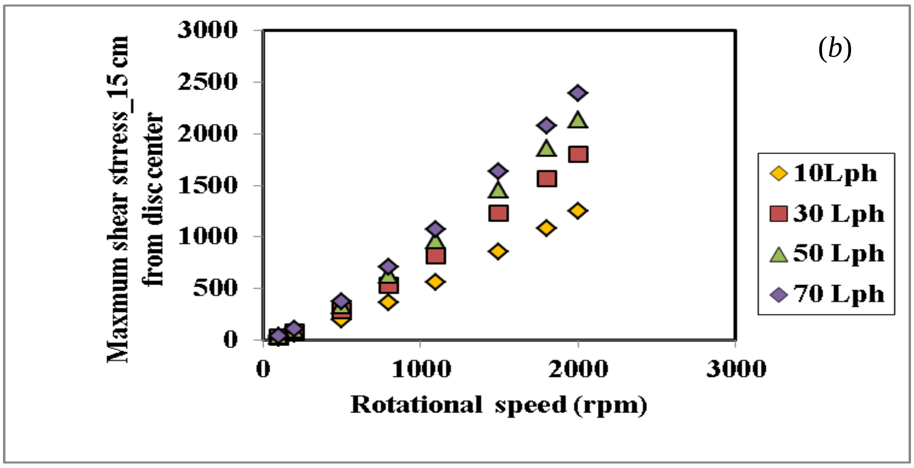


Fig. 2 – Dependence of maximum shear stress on liquid flowrate and rotational speed, at two different locations on the spinnning disc (*a*) at 5 cm; (*b*) at 15 cm.

Fig. 2 indicates, as expected, a more significant increase in the maximum shear stress, especially at the largest liquid flowrates of 70 L/h and at rotational speeds larger than 800 rpm up to 2000 rpm. Also, the 5 cm location from the disc center (Fig. 2*a*), provides a more enhanced shear stress in comparison to the 15 cm location from the disc center (Fig. 2*b*). As the disc radius is increased, the fluid will benefit of larger residence times, that can be calculated using Nusselt's theory for thin laminar films, based on a force balance in the radial direction (Boodhoo and Jachuck, 2000), as indicated by Eq. (7):

$$t_{res} = \frac{3}{4}\left(\frac{12\pi^2\vartheta}{\omega^2 Q^2}\right)^{1/3}\left(R^{4/3} - r_i^{4/3}\right) \quad (7)$$

where ϑ is the liquid kinematic viscosity, ω is the rotational speed, Q is the liquid flow rate, r_i is the distance from the disc center to the liquid feed point on the disc. The residence time distribution based on Eq. (7) is represented in Fig. 3 showing that the residence time decreases with liquid flowrate increase and especially with the disc rotational speed.

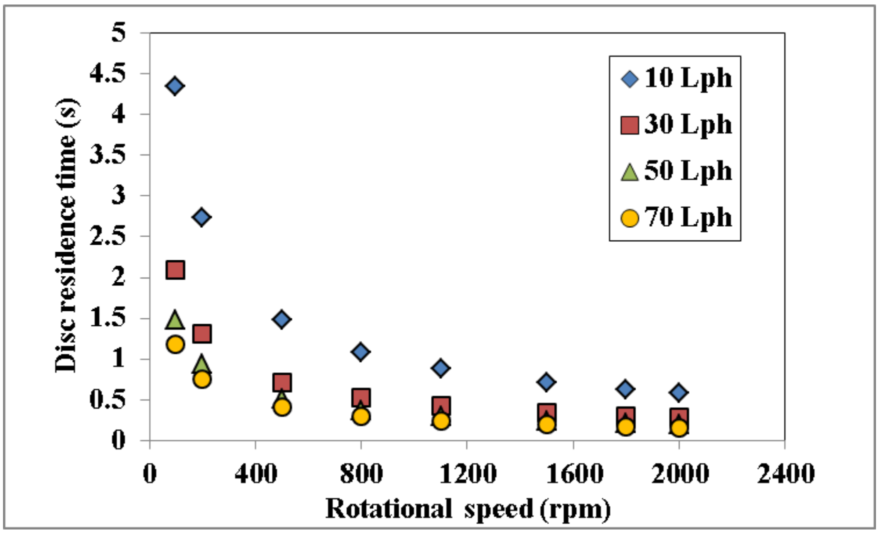


Fig. 3 – Residence time dependence on liquid flowrate and disc rotational speed.

The micromixing on the disc implies turbulent diffusion and strong deformations due to local turbulent tensions (Johnson and Prud'homme, 2003) and the characteristic micromixing time can be estimated using Eq. (4) (Baldyga and Pohorecki, 1995):

$$t_m = 2\left(\frac{\nu}{\varepsilon}\right)^2 arcsinh\left(0.05\frac{\nu}{D}\right) \quad (8)$$

where ε is the dissipation power calculated using Eq. (9) and D is the diffusion coefficient, calculated from the dispersion number.

The dissipation power is given by:

$$\varepsilon = 0.5 t_{res}\{(r^2\omega^2 + U_m^2)_o - (r^2\omega^2 + U_m^2)_i\} \tag{9}$$

The obtained diffusion coefficient values obtained from experimental data for the normalized variance, based on Eq. (3) are of 10^{-7}-10^{-8} order of magnitude, depending on liquid flowrate and disc rotational speed, similar to other reported literature values (Mohammadi and Boodhoo, 2012). Using Eqs. (8) and (9), with the calculated diffusion coefficients, the micro-mixing times were determined and plotted in Fig. 4, which clearly indicates the strong influence of the disc rotational speed rather than the liquid flowrate on micromixing time.

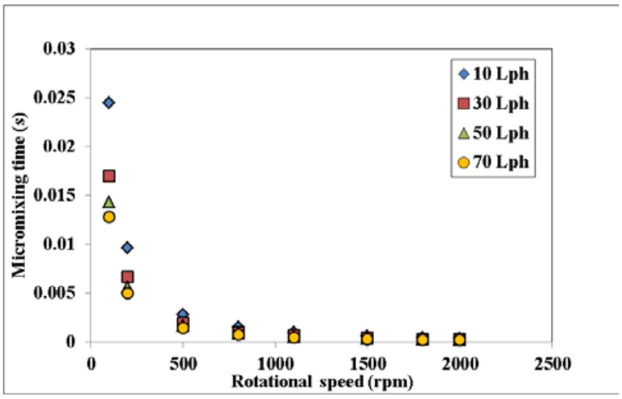


Fig. 4 – Micromixing time dependence on liquid flowrate and disc rotational speed.

The micromixing time values are much smaller than the residence time values, at the same rotational disc speeds and liquid flowrates. One can observe from Eqs. (7) and (8) that the micromixing time decreases with the rotational speed at a faster rate than the residence time does ($\tau_m \sim \omega^{-4/3}$, $t_{res} \sim \omega^{-2/3}$) and with the liquid flow rate at a slower rate in comparison to the residence time ($\tau_m \sim Q^{-1/3}$, $t_{res} \sim Q^{-2/3}$). This suggests that it is more efficient to increase disc rotational speed in order to decrease the micromixing times, thus enhance the micromixing, intensified also by the local large shear stresses, than to increase the liquid flowrate, provided that the process taking place on the disc is characterized by a time larger than the micromixing time and also, the residence time is large enough.

Despite the fact that the largest residence times are obtained at the lowest liquid flowrate, the liquid film is prone to dryout, so this may not be feasible to use in practice. A critical liquid flow rate at which the liquid film dryout occurs was proposed (Hartley and Murgatroyd, 1964) through the Eq. (10):

$$Q_c = 5.5\left(\frac{\vartheta R^4}{\omega^2}\right)^{1/5}\left(\frac{\sigma}{\rho}\right)^{3/5} \tag{10}$$

For the current study, this means a 0.432 L/h at 100 rpm and respectively, 0.133 L/h at 200 rpm, the experimental investigated flowrate values of 10, 30, 50 and 70 L/h are much larger than the critical estimated values. However, visual observations of the 10 L/h at low disc rotational speeds of 200 rpm or larger, indicated the occurrence of liquid film dryout regions. These were not observed at higher liquid flowrates and low rotational speeds. However, at large disc rotational speeds strong atomization was registered.

The surface state influence on the hydrodynamics in the liquid film was investigated also using the pulse-response technique on two concentrically indented and respectively, radially indented discs, depicted in Fig. 1*a* and 1*b*. Three different liquid flowrates fed on the disc of 30, 50 and respectively 70 L/h and four different rotational speeds of 200, 500, 800 and respectively, 1100 rpm were investigated. Typical residence time distribution data with a symmetrical shape have been presented previously (Iacob Tudose and Zaharia, 2018). Based on Eq. (4), the normalized variance data were used to determine the equivalent number of tanks in series *N*, a low number indicating mixed flow and a high number, plug flow (Levenspiel, 1999).

Comparisons between smooth and concentric indented discs, and also, between smooth and radial indented discs, at different liquid flow rates and disc rotational speeds, using the N-tanks-in-series model, are presented in Fig. 5 and respectively, Fig. 6.

The concentric indented disc rendered for most of the investigated liquid flow rates and disc rotational speeds larger *N* values than the smoothed surface disc. Most probably, the surface grooves combined with the centrifugal force induces local liquid detachment, thus more turbulence within the liquid film is yielded. At the highest liquid flow rate of 70 L/h and disc speed of 1100 rpm, the trend is not maintained due to the intense atomization.

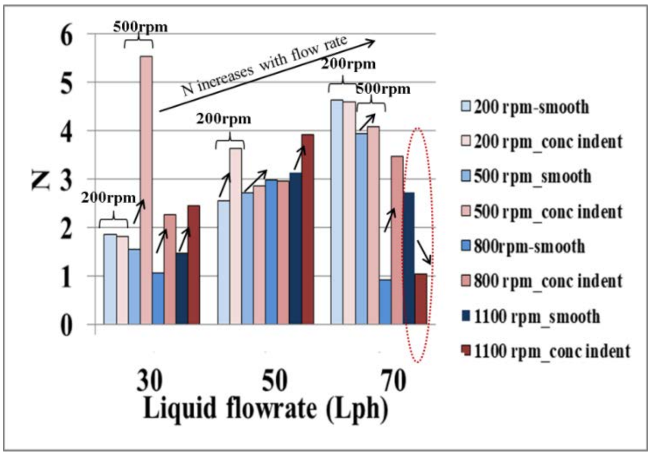


Fig. 5 – Comparison between smooth and concentric indented discs – N tanks-in-series model.

Similar trends, depicted in Fig. 6, are registered for the radially indented disc in comparison to the smoothed surfaced disc, except for the large liquid flow rates of 70 L/h and different disc rotational speeds, most probably due to the fast liquid drainage through the radial indentations.

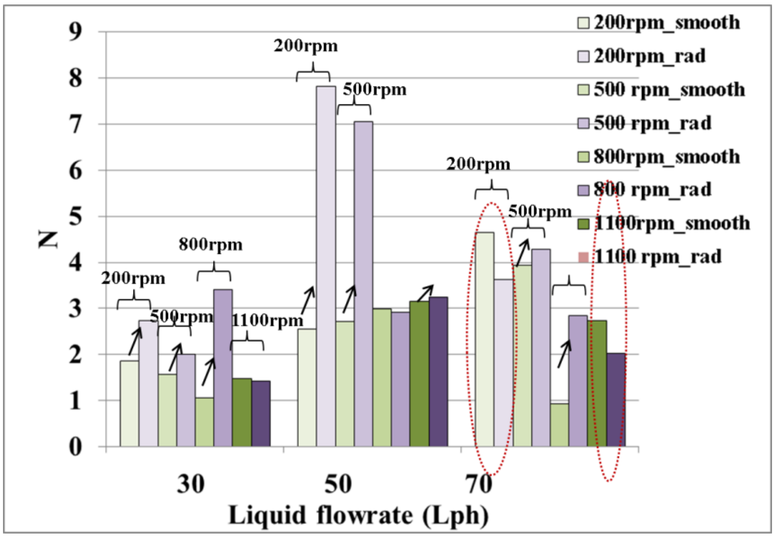


Fig. 6 – Comparison between smooth and radial indented discs, – N tanks-in-series model.

All the above observations related to micromixing and residence times and the working depending parameters are sustained by experimental results obtained previously for textile waste water treatment using the SD technology when the highest suspended solids and color removals were not obtained at the highest liquid flowrates or disc rotational speeds with very small micromixing times but also, with small residence time, but rather at relatively low liquid flow rate of 15 L/h and a rotational speed of 550 rpm (Iacob-Tudose and Zaharia, 2020). Knowledge related to the process kinetics taking place in the textile WW film on the disc would be useful to further support the previous statements.

In conclusion, a picture of the parameters influencing the hydrodynamics on the spinning disc can be depicted as follows:

– at low constant rotational speed values, an increase in the liquid flow rate fed on the disc is characterized by shorter micromixing time values but also, by shorter residence time values, thus the process taking place on the disc will benefit less from the micromixing;

– at higher rotational speeds, when the ripples formation on the free liquid film surface, characteristic to a turbulent flow, is registered, higher shear stresses are created and the micromixing time decrease is more significant, thus the micromixing is extremelly efficient with respect to the process taking place in the liquid film, as long as the residence time is long enough and the atomization does not occur.

These improved flow characteristics indicate that the spinning disc should be operated at specific parameter values. However, the advantage of intense micromixing lies within a specific range of the studied liquid flow rates and disc rotational speeds, not necessarily the largest, when the turbulent rippled liquid film surface occurs, the shear stress increases and the micromixing intensity is enhanced, while the residence time is large enough and the SD technology is efficiently used.

4. Conclusions

The presented data demonstrate that a high degree of micromixing can be achieved mostly at high disc speeds and/or relatively high liquid feed flow rates, however this is not necessarily beneficial to the process kinetics taking place on the disc. Additionally, the high shear forces acting within the liquid film rather at shorter distances from the disc center enhance the micromixing. Despite the intense turbulence within the liquid film, its benefit can be not well exploited if the residence times are relatively short. One can conclude, that the optimum of a process taking place on a spinning disc, either a physical or chemical process, may be attained only at specific values of the operating parameters.

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OBSERVAŢII PRIVIND CARACTERISTICILE MICROAMESTECĂRII PE DISCUL ROTITOR

(Rezumat)

Tehnologia discului rotitor este una dintre cele mai versatile tehnici de intensificare a proceselor utilizate în diferite domenii de aplicație. Microamestecarea intensă este una dintre caracteristicile deosebite ale discului rotitor. Studiul actual include date experimentale legate de valorile numărului de dispersie, obținute la diferiți parametri de lucru, și anume debitul lichidului de alimentare pe disc și viteza de rotație a discului. Acestea au fost utilizate pentru a calcula timpii caracteristici de microamestecare care scad rapid odată cu creșterea vitezei de rotație a discului, în special la debite de alimentare mai mici. Tensiunile de forfecare cresc rapid cu viteza de rotație a discului și variază cu poziția radială pe disc. În plus, timpul de staționare are cele mai mici valori la cele mai mari viteze de rotație și debite de lichid. Astfel, în ciuda microamestecării intensificate, obținute la viteze de rotație mari ale discului, timpul de staționare mai scurt corespunzător poate fi un factor restrictiv, deoarece lichidul procesat nu poate beneficia de turbulența crescută de pe suprafața în mișcare.