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Rotor-Stator Mixers

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Rotor-stator mixers are commonly used in food, pharmaceutical, and cosmetics industries for processing of colloidal liquid/liquid systems and also to disperse/break solid particles and aggregates. Despite such wide industrial applications the literature information on the performance of rotor-stator mixers is rather limited. Recently, more systematic investigations of the power draw, shear rate, and emulsification been undertaken; the results of those investigations are discussed in this paper.

1. Introduction

Consumer and pharmaceutical based products are a major component of the chemical industry. Recent trends indicate an increasing demand for new products with improved performance, a shorter product life cycle, and a faster production method. This places considerable pressure on the industry to accelerate product and process development. Depending on the end use, products are delivered in various forms, a significant portion of which are creams, pastes, and emulsions.

One of the key pieces of process equipment widely used for blending, size reduction, and structuring in the manufacture of emulsions and colloidal systems is a high-shear rotor-stator mixer. These devices are popular due to their numerous industrial applications and their ability to be used in process vessels, in-line between vessels, or in a recycle loop. The advantage of the recycle loop is that for the same power duty a much smaller unit is needed compared to the equivalent batch mixer; higher viscosity fluids can be processed.

The rotor-stator assembly includes a rotor which rotates at high speed inside the stationary stator, which is interchangeable enabling different process requirements. The stators are cylindrical screens, generally with millimetres or less of clearance from the rotor, containing numerous holes or slots through which the fluid is forced. The kinetic energy generated by the rotor which is dissipated in the stator region creates very high energy dissipation rates due to the small volume.

Despite the extensive industrial applications of rotor-stator devices, little emphasis has been placed on understanding the devices on a fundamental basis. At present, process development using rotor-stator mixers occurs by trial and error at increasing

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scales, and relies on intuition more than on science. Better fundamental understanding of the flow pattern, distribution of energy dissipation and the breakage mechanism allows development of scale-up rules, which reduce the number of expensive and time consuming trials necessary to develop new products or modify existing ones.

2. Power Draw for In-Line Rotor-Stator Devices

Turbulent power for a batch rotor-stator device can be described by a single "tank" type impeller power number, equation (1).

$$\mathrm{Po} = \frac{P}{\rho N^3 D^5} \tag{1}$$

However, for an in-line rotor-stator the flow through the rotor can be controlled independently to the rotor speed. This means that the power number for an in-line device is also dependant on the flow (Cooke *et al*., 2008; Kowalski, 2009; Sparks *et al*., 1995; Bałdyga *et al*., 2007; Cooke and Kowalski, 2009; Cooke *et al*., 2010). Kowalski (2009) showed that the total rotor power can be assumed to be the sum of three terms: a power based on a stirred vessel type, a power due to the flow, and a power due to any losses in the system. This means that the total power number can be given by equation (2) (neglecting the power losses), where $\mathrm{N_Q}$ is the flow number, equation (3).

$$\mathrm{Po} = \mathrm{Po}_z + k_1 \mathrm{N_Q} \tag{2}$$

$$\mathrm{N_Q} = \frac{Q}{ND^3} \tag{3}$$

The turbulent constants in equation (2) can be calculated by multi-linear regression fitting experimental data to equation (2). Cooke *et al*. (2008) found that good estimates of the constants can be obtained using a simplified set of experiments; either with zero flow and free flow rate with varying speed; or a fixed speed and a varying flow rate. Cooke *et al*. (2008 and 2010) and Kowalski and Cooke (2010) show that there is little variation in the values predicted using any of these methods. Table 1 gives a summary of these values for the turbulent regime for a range of different systems.

The larger the holes in the screens the higher the Po_z as there is more recirculation of the fluid in the chamber. As the rotor moves, high pressure in front of the blades forces fluid through the holes while low pressure in the wake of the blades pulls the fluid back through (Utomo *et al*., 2009). This is more intensive with the larger holes.

Cooke *et al*. (2010) show that equation (2) can be modified to accommodate both laminar and turbulent flow, equation (4).

$$\mathrm{Po} = \frac{k_0}{\mathrm{Re}} + \mathrm{Po}_{z(T)} + k_1 \mathrm{N_Q} \tag{4}$$

It should be noted here that the flow number is not constant with Reynolds number as the flow rate can be manually controlled. Figure 1 is the full power curve for the standard rotor-stator screens (Cooke *et al*., 2010). The two different lines for the turbulent regime are due to different flow rates: either zero flow, or the valve fully open for free flow. The free flow number is constant in the turbulent regime and decreases as the Reynolds number decreases, Figure 2. Outside of the turbulent regime the flow number varies with the rotor speed as well as the Reynolds numbers.

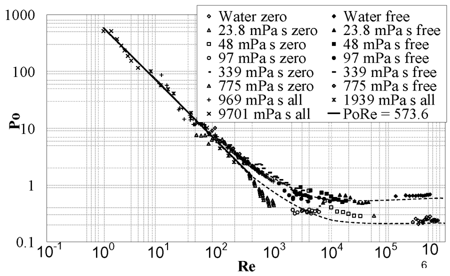

Figure 1. Full power curve for the standard double screen arrangement; the dotted lines are to guide the eye. Data taken from Cooke et al. (2010).

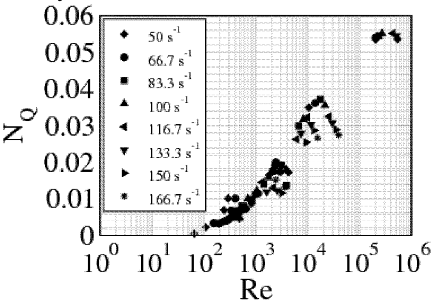

Figure 2. Variation of the flow number with the fluid Reynolds number for the standard double screen arrangement. Data taken from Cooke et al. (2010).

As the power number is inversely proportional to the Reynolds number in the laminar regime and the flow number decreases markedly, the third term in equation (4) becomes insignificant and the power number becomes nearly equal to k_0/Re for all flow rates. For high Reynolds numbers the first term in equation (4) becomes very small, so the power number becomes equal to $Po_{z(T)}$ with the modification for the flow rate.

Table 1 presents the values of k_0 for several systems; values tend to be much higher than impellers in stirred tanks as the stator and chamber provide restrictions on the flow.

3. Shear Rate

Whenever there is relative motion between liquid layers shearing forces exist that are related to the velocity gradient. Metzner and Otto (1957) showed that the average shear rate around the impeller can be calculated as a product of rotational speed and a proportionality parameter, K_S, which depends on the impeller geometry. The best approach used to determine the K_S value is that of Rieger and Novak (1973).

The values of K_S for different system configurations are given in Table 1. The increase in average shear when the standard stator is present is a factor of 6.9 over that without the stator. Cooke *et al.* (2010) attribute this to the rows of holes increasing the number of shearing points and the small gap between the rotor and stator. The rotor without screens is essentially a very small stirred vessel.

4. Drop Break-Up

At present, process development of emulsion-based products often occurs by trial and error at increasing scales to determine the optimum operating conditions to manufacture the desired product. This method results in higher development costs, start-up problems, lost time to market and considerable material waste due to the numerous trials required.

Thus, scaling rules to accurately scale-up emulsification processes are necessary to maintain the structure and characteristic properties of multiphase products.

Table 1. Values of the power constants

Equipment/Setup	$Po_{Z(T)}$	k_1	k_0	K_s
Silverson 150/250 MS in-line:				
Dual rotor dual standard screens	0.235	8.02	573.6	46.2
Dual rotor dual fine screens	0.148	9.25		
Dual rotor no screens	0.212	7.05	276.2	6.6
Silverson 088/150 UHS in-line (Hall *et al.*, 2010a)				
Dual rotor dual standard screens	0.249	7.38		
Rayneri Turbotest mixer (Doucet *et al.*, 2005):				
With stator	3	-	314	Complex behaviour
Without stator	3	-	92.7	
Silverson L4R				
Batch vessel with standard stator	1.440	-	358.6	
Flow through unit	0.187	2.39		

Break-up due to turbulent eddies, Hinze-Kolmogorov theory (Bałdyga and Bourne, 1992), utilises the concept of eddy turbulence to define a limiting drop size. It is usually assumed that drop break-up occurs due to the collisions of turbulent eddies of similar size to the drops (Liao and Lucas, 2009). If the drops are broken by turbulent eddies then the equilibrium drop sizes should scale with the energy dissipation.

Break-up due to the agitator shear rate is based on a balance between the external viscous stresses and the surface tension forces. If the break-up is due to the agitator shear rate then the equilibrium drop size is related to the shear rate generated at the agitator. This means that lower power number agitators can produce smaller drops than higher power number agitators, as shown experimentally by Zhou and Kresta (1998).

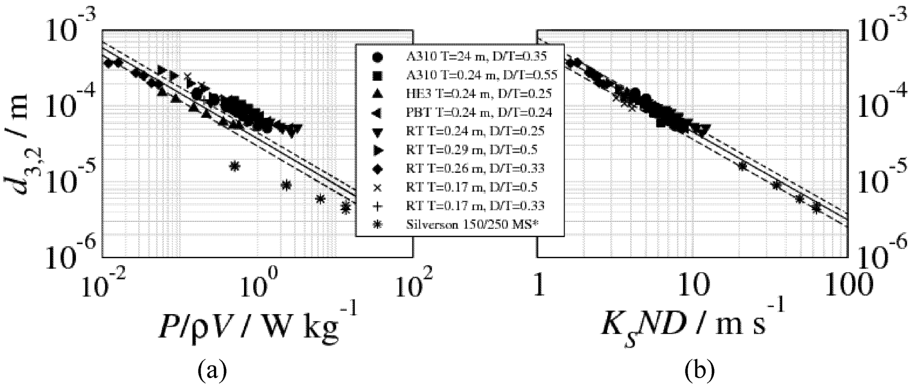

*Figure 3. Variation of the mean equilibrium drop against power per unit mass (a) and the agitator blade shear rate (b). Data for batch agitators taken from Zhou and Kresta (1998) and Musgrove and Ruszkowski (2002). Dotted lines are 20 % from the best fit. *Silverson used in recycle arrangement, data taken from Rodgers and Cooke (2010).*

Figure 3(a) presents equilibrium drop size data for silicon oil in water for stirred tanks and equilibrium drop size data for the Silverson with standard screens and no-screens. The data correlates to the shear rate much better than the power per unit volume. The drop size with and without the screen are similar, meaning that, for inviscid flows of Newtonian liquids, the rotor shear rate dominates the breakage. Future work should concentrate on development of the rotor and not just the screens. The screens do affect the break-up in a single pass arrangement, Figure 4, but this is mainly due to recirculation effects (Rodgers and Cooke, 2010).

Figure 4 shows the variation of the single pass drop size against the liquid flow rate with the standard double screens for a variety of oil viscosities. It can be seen that when the oil viscosity is lower there is a greater impact of the flow rate on the single pass drop size. This is most likely due to the drop breakage time increasing with increasing viscosity ratio, therefore, the higher viscosities would need a much lower flow rates to significantly increase the probability of drops breaking to a smaller size.

Depending on the produce being produced, the viscosity of the dispersed phase may vary; however, the same drop size may need to be produced. Hall *et al.* (2010b) showed that the viscosity ratio is the important factor, not the dispersed phase viscosity. Figure 5 shows the variation of the viscosity ratio with the drop size; this is a good correlator.

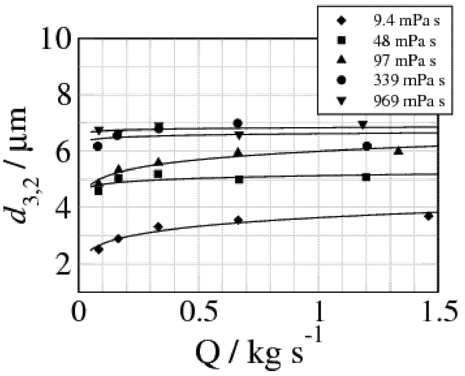

Figure 4. Variation of the drop size with flow rate The lines are power law fits. Data is taken from Hall et al. (2010b).

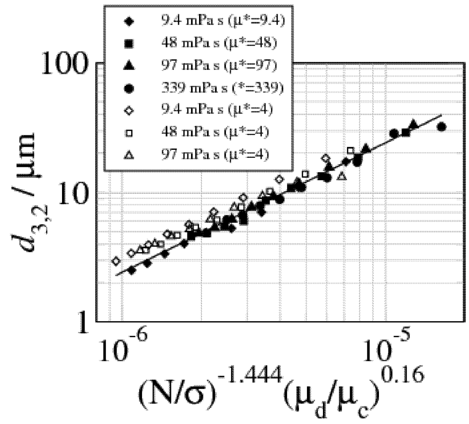

Figure 5. Variation of the single pass drop size, $d_{3,2} = 2.4\times10^{6}\left(N/\sigma\right)^{-1.444}\left(\mu_d/\mu_c\right)^{0.16}$*. Data is taken from Hall et al. (2010b).*

One of the main advantages of in-line rotor-stator mixers is the fact that they can be used either in a recycle arrangement or as a continuous single-pass system. The drops produced in a recycle system depends on the time of the process whereas the drops produced in a single pass is more heavily dependant on the flow rate and screens. Figure 6 shows the variation of the drop size with the residance time for two different viscosity oils. The lower the oil viscosity the larger the difference between the long time drop size and the single pass drop size. The difference in start to end drop sizes is not that different between different recycle flow rates; however, the speed of approach to the final equilibrium size is faster with faster recycle rates (Hall *et al*., 2010b and 2010c). This is because when the residence time for the systems is the same, the one with the faster recycle rate has had the drops pass through the rotor-stator device more times.

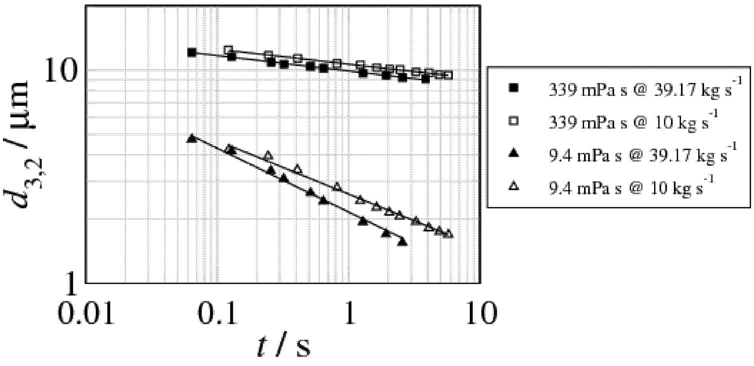

Figure 6. Variation of the drop size with residance time for oils of difference viscosity at different flow rates at 11000 rpm, data taken from Hall et al. (2010b).

5. Conclusions and Recommendations

The power consumption of rotor-stator devices can be calculated from equation (4); the Metzner-Otto constant increases dramatically with the stator. The stator also performs very little drop break-up, but it does increase local recirculation. The recycle flow rate has little effect on the drop size, and the viscosity ratio is a good drop size correlator.

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