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A comparison of power and flow characteristics between batch and in-line rotor-stator mixers

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Abstract

Rotor-stator mixers are used in many industries to perform emulsification and de-agglomeration processes. Despite previous research, different modes of operation have not been compared in terms of flow and power characteristics. The aim of this study was to use CFD to investigate power and flow characteristics of a Silverson L5M mixer operating in batch and in-line mode. MRF was used along with the standard $k - \epsilon$ turbulence model for the simulations. Results suggest that batch mixers can be characterised in the same way as in-line mixers, and for a given mixing head design, the characterisation is independent of the mode of operation. A new way of calculating flow number is proposed, which explains some discrepant results from previous studies. Overall, this work enhances our understanding of rotor-stator mixers and allows for better design choices of mixer.

Keywords: Rotor-stator. Mixing. Power number. Flow number. CFD.

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Nomenclature

Symbols

Po_1	Power number constant	—
Po_2	Power number constant	—
Po_z	Power number constant	—
$\mathbf{U}$	Velocity vector	m s^{-1}
A_h	Total open area of stator holes	m^2
D	Rotor diameter	m
D_h	Stator hole diameter	mm
k_1	Empirical constant	—
k_2	Empirical constant	—
M	Torque	N m
N	Rotor speed	s^{-1}
P	Power	W
p	Dynamic pressure	N m^{-2}
P_L	Power losses	W
Q	Volumetric flow rate	$\text{m}^3 \text{s}^{-1}$
R_b	Base hole radius	m
R_h	Hydraulic radius	m
S	Surface area	m^2
S_{ij}	Strain rate tensor	m s^{-2}
T	Tank diameter	m
V	Volume	m^3
v_n	Normal velocity	m s^{-1}

Greek symbols

μ	Dynamic viscosity	$\text{kg m}^{-1} \text{s}^{-1}$
ρ	Density	kg m^{-3}
τ	Stress tensor	N m^{-2}

Dimensionless numbers

Eu	Euler number	$\Delta p / \rho v^2$
N_Q	Flow number	Q / ND^3
$N_{Q,i}$	Imposed flow number	Q_i / ND^3
$N_{Q,r}$	Recirculating flow number	Q_r / ND^3
$N_{Q,t}$	Total flow number	Q_t / ND^3
Po	Power number	$P / \rho N^3 D^5$

Abbreviations

CFD	Computational Fluid Dynamics
MRF	Multiple Reference Frame
PIV	Particle Image Velocimetry

1. Introduction

Rotor-stator mixers are mixing devices consisting of one or more high speed rotors, each enclosed within a stationary screen known as a stator. The high speed of the rotors combined with the close proximity of the rotors and the stators allows rotor-stator mixers to generate very high shear rates, hence they are also commonly referred to as high shear mixers. They are highly suitable for processes which require localised intense mixing such as emulsification and de-agglomeration (Atiemo-obeng et al., 2004). Although they have found widespread use in many industries, including chemical, cosmetics, agricultural, food and pharmaceutical, there is still a lack of understanding as to how these mixers truly operate. A particular case of this is in the characterisation and prediction of agitation power. Rotor-stator mixers can operate in either batch or continuous mode. Batch mode is usually preferred for laboratory and pilot scale testing, while continuous mode is usually preferred for large scale processing (Håkansson et al., 2017). Therefore, scale-up of a process involving a rotor-stator mixer typically involves not only a change in size, but also a change in mode of operation. There has been much interest recently in the development and use of a model to predict agitation power in continuous rotor-stator mixers operating in the fully turbulent regime (Kowalski, 2009; Cooke et al., 2011; Hall et al., 2011; Kowalski et al., 2011; Özcan-Taşkin et al., 2011; Jasińska et al., 2015). The model typically used for continuous rotor-stators is given by

$$P = P_{OZ} \rho N^3 D^5 + k_1 \rho Q N^2 D^2 + P_L \quad (1)$$

which, assuming negligible power losses, can be rearranged to yield

$$Po = Po_Z + k_1 N_Q \quad (2)$$

where Po is the dimensionless power number, Po_Z can be thought of as the power number with no flow through the mixer, k_1 is an empirical constant, and N_Q is the dimensionless flow or pumping number. N_Q is given by

$$N_Q = \frac{Q}{ND^3} \quad (3)$$

The model shown in Equation (1) states that the total power draw of the mixer is the sum of two components, the first being a power required to overcome the drag force as the rotor rotates within the fluid, and the second being the power needed to pump the fluid through the mixing head. The constant k_1 , by which the second component is multiplied, varies between different designs of in-line mixers. The effect of stator or rotor design on the magnitude of this constant has not yet been systematically investigated, although it has already been stated that to do this would be highly advantageous in terms of the mechanical design of these mixers (Håkansson, 2018).

As the flow rate imposed by the external pump approaches zero in in-line rotor-stators, there is a deviation of the power number away from the model expressed in Equation (1). The power number can begin to level out or, in certain cases, it can actually increase sharply as the flow number decreases. The power number seems to level off mostly in mixers with a single screen, whereas the increase in power numbers is seen solely in mixers with a double-screen configuration. This has been recorded both using experimental measurements and CFD predictions (Jasińska et al., 2015), and a new model to replace Equation (2) has even been developed in order to account for this

phenomenon at low flow rates. This model is as follows

$$Po = Po_Z + k_1 N_Q + \frac{(Po_1 + k_2 N_Q) + |Po_1 + k_2 N_Q|}{2} \quad (4)$$

where Po_1 and k_2 are empirical constants which are used to describe the deviation at low flow numbers. There have been multiple suggestions made as to what causes this phenomenon. Recirculation in the holes has been suggested to be one of the causes, but this has not been thoroughly discussed in literature.

Despite the development and use of the model for continuous mixers, there has been relatively little effort to characterise batch rotor-stators in a similar manner. One reason for this is that it is not a simple task to change or measure the flow rate in a batch rotor-stator, as it is in a continuous one. To measure the flow, one must use either complex flow characterisation techniques, such as Particle Image Velocimetry or Laser Doppler Anemometry, or alternatively resort to simulation and use a well validated computational fluid dynamics (CFD) model. To change N_Q in a batch rotor-stator with a given screen design, one must change the geometry of the base of the stator, since the rotational speed and diameter of the rotor are both coupled to the flow rate. Previous studies have generally attempted to characterise power and flow in batch rotor-stators based on the geometry of the mixer, since the flow number is not easily known.

Utomo et al. (2009) investigated power draw and flow pattern in a Silverson L4M batch rotor-stator with various stator geometries using CFD. The geometries investigated were the slotted head, the disintegrating head, and the square hole head. For these geometries, the authors suggested that

the power number scales with the total area of the holes/slots in the stator. James et al. (2017) investigated scale-up of key power parameters for three Silverson batch rotor-stators of varying scale. These were the L5M, the AX3, and the GX10. It was found that the power number is practically constant in the fully turbulent regime. The power number in the fully turbulent regime was also found to be proportional to the total area of the holes/slots in the stator according to the following model:

$$\text{Po} = 1.60 \left(\frac{\min(R_h)}{D} \right)^2 + 1.20 \quad (5)$$

where $\min(R_h)$ is the hydraulic radius of either the holes in the screen or the base hole, depending on which is the smallest, and both 1.60 and 1.20 are empirical constants obtained from the experimental data. Note that this model takes the same form as the continuous model, Equation (2), however the flow rate is not required. One drawback of both of these studies is that the geometries investigated differ in many ways. For example, the number, size, and position of the holes/slots change in each geometry. These studies, therefore, do not provide much insight as to which geometrical parameters are actually important for characterising power and flow. It is far more beneficial to investigate stator geometries in which only one geometrical dimension is changing at any one time. Mortensen et al. (2017) conducted a study in this manner, investigating the effect of stator geometry on flow for a batch rotor-stator with a slotted head using PIV. The width of slots was varied in this study, however the number of slots was changed in order to keep the total area constant. The results suggest that the flow number, and hence also power number, actually decreased with increasing slot width, despite a

91 constant total area. These results contradict those of Utomo et al. (2009)
92 and James et al. (2017). It is clear from the literature that characterising
93 batch rotor-stators based on mixer geometry is no easy task and that a robust
94 model for predicting agitation power in batch rotor-stators has not yet been
95 found.

96 Håkansson et al. (2017) simulated an in-line rotor-stator under typical
97 operating conditions for the in-line mixer, ie. lower N_Q , and also conditions
98 relating to the typical operation of a batch rotor-stator, ie. higher N_Q . Dif-
99 ferences in rotor-stator hydrodynamics and the implications with regards to
100 emulsification are explained using a number known as the *fill ratio*, which
101 is essentially the ratio of the average fluid velocity through the holes in the
102 screen and the rotor tip speed, or the fraction of the holes actually occupied
103 by the high velocity jets leaving the stator. This study concluded that at
104 high values of N_Q the CFD results were very similar to PIV results for a
105 batch rotor-stator, indicating that for a given rotor and stator design, there
106 is in fact a hydrodynamic similarity between the two modes of operation.
107 This, however, has not yet been investigated further. Something similar was
108 suggested from results obtained by Carrillo De Hert and Rodgers (2017); that
109 droplet break-up in the different modes of operation could be linked using a
110 mass balance and accounting for the residence time of the droplets actually
111 in the mixing head.

112 The aims of this study were to investigate characteristics of power and
113 flow in batch rotor-stator mixers using CFD with experimental validation,
114 and to compare the characterisation with previously developed models for
115 in-line mixers. This study will make use of systematic geometry changes

116 in order to obtain the most beneficial results and conclusions. In doing so,
117 our understanding of flow dynamics in rotor-stator mixers will be enhanced,
118 benefiting both researchers in this field and also industries using these mixers
119 to carry out their processes.

120 **2. Materials and Methods**

121 *2.1. CFD model*

122 The rotor-stator mixer investigated in this study is the Silverson L5M
123 batch, laboratory scale mixer. In its standard configuration it is a batch
124 mixer, however, an in-line mixing assembly can be fitted over the mixing
125 head to switch the mode of operation. The two configurations of the mixer
126 can be seen in Figure 1. The standard emulsor screen was chosen as the stator
127 design in all cases, which consists of 6 staggered rows of 39 holes (Figure 2).
128 For the batch configuration, the mixing head was positioned in the center,
129 both vertically and horizontally, of a tank of diameter 137 mm. The height
130 of the fluid was equal to the diameter of the tank and the tank contained 4
131 baffles of length $T/10$, where T is the tank diameter. The fluid used in all
132 cases was water. For the batch mixer, the base of the stator was constricted
133 in several increments in order to change the flow rate of fluid through the
134 mixing head independently of the rotor speed, hence varying N_Q .

Figure 1: Silverson L5M configured in (a) batch mode with the TorqueSense torque meter, and (b) continuous or in-line mode using the in-line mixing assembly.

135 A hybrid mesh containing 14 million elements was used for the batch
 136 simulations. Preliminary mesh independent tests have shown independence
 137 of the results with meshes of this level of refinement. The mesh was refined
 138 in the proximity of the mixing head so that at least 10 elements were present
 139 between the rotor and the stator. Proximity and curvature functions were
 140 used to refine the mesh around the shaft.

Figure 2: CFD geometry for Silverson L5M configured in (a) batch mode and (b) continuous or in-line mode.

142 ANSYS Fluent version 18.1 was used to run each simulation. Simulations
 143 were run on 12 cores. All simulations were steady-state, with the MRF
 144 technique employed to model rotor rotation. The cylindrical MRF interface
 145 was positioned exactly in the middle of the rotor-stator gap. A previous
 146 study suggested that CFD simulation of rotor-stators should only be carried
 147 out using the transient Sliding Mesh technique due to the periodicity of the
 148 power and the flow as the rotor moves past the holes/slots (Mortensen et al.,
 149 2018). However, the holes of the standard emulsor screen are small, closely
 150 spaced, and staggered in between rows. This means that the periodicity of
 151 power and flow will be much smaller than in other stators, and therefore the
 152 MRF technique is adequate. As is good practice in any CFD investigation
 153 using MRF, multiple rotor positions were tested in order to validate this.
 154 The standard $k - \epsilon$ turbulence model was used along with the standard wall
 155 function to model the near-wall, viscosity affected region. This model is

156 well-known to under predict turbulent dissipation, however in this particular
 157 study, turbulent dissipation is of relevantly little concern due to the fact that
 158 turbulent transport of species or other phenomena such as droplet break-up is
 159 not being modelled. The $k - \epsilon$ turbulence models have been widely used with
 160 success to predict mean flow properties in both batch and in-line rotor-stator
 161 mixers (Håkansson et al., 2017; Jasińska et al., 2015; Minnick et al., 2018;
 162 Mortensen et al., 2018; Özcan-Taşkin et al., 2011; Utomo et al., 2008, 2009).
 163 Spatial discretisation of momentum and turbulence was achieved using the
 164 third order MUSCL scheme, the gradient using least squares cell based, and
 165 the pressure using PRESTO!. Under-relaxation factors were kept as their
 166 default values. The no-slip condition was specified at all solid walls, ie. tank
 167 walls, shaft, rotor and stator, so that $\mathbf{U} = \mathbf{0}$ at the wall. The water-air
 168 interface at the top of the tank was modelled by specifying a shear of zero at
 169 the interface, so that $\boldsymbol{\tau} = \mathbf{0}$ at the wall. For in-line simulations, the inlet was
 170 specified as a velocity inlet and the outlet was specified as a pressure outlet.

Figure 3: CFD mesh for (a) and (b) batch rotor-stator, and (c) and (d) in-line rotor-stator.

171 The criteria for solution convergence were that the residuals for all solved flow
 172 and turbulence equations were stabilised and the total bending moments on
 173 the rotor were constant with respect to the iteration number.

Figure 4: Cross section of Silverson L5M mixing head. Red lines show surface used to calculate radial flow through the holes of the stator. Blue line shows surface used to calculate axial flow through the base of the stator.

174 For the batch rotor-stator, the flow rate was calculated across two surfaces.
 175 The first was at the inside entrance to the holes of the stator, ie. the inner
 176 radius of the stator screen. The second position is at the top of the base of
 177 the stator. These surfaces are shown in Figure 4. Since there is flow in both
 178 directions on both of the surfaces, the positive and negative flows, for both
 179 the radial flow through the holes and the axial flow through the base, were
 180 calculated respectively as follows

$$Q_{+ve} = \frac{\iint_S |v_n| \, dS + \iint_S v_n \, dS}{2} \quad (6)$$

$$Q_{-ve} = \frac{\iint_S |v_n| \, dS - \iint_S v_n \, dS}{2} \quad (7)$$

181 where Q_{+ve} and Q_{-ve} are the positive and negative volumetric flow rates
 182 respectively in $\text{m}^3 \text{s}^{-1}$ with respect to the direction of the cylindrical axis,
 183 and v_n is the velocity component normal to the surface, S , across which the

184 flow is calculated, ie. radial velocity for flow through the holes and axial
 185 velocity for flow through the base. The flow for the in-line rotor-stator was
 186 calculated in exactly the same manner, except axial flow was measured across
 187 the inlet boundary instead of the base of the stator.

188 The power draw from the rotor can be calculated using several methods.
 189 One commonly used method is to calculate the power using the total energy
 190 dissipation:

$$P = \rho \iiint_V \epsilon \, dV + 2\mu \iiint_V \bar{S}_{ij} \bar{S}_{ji} \, dV \quad (8)$$

191 where V is the total volume of fluid, ϵ is the turbulent dissipation rate, μ is
 192 the dynamic viscosity, and S_{ij} is the strain rate tensor. The first term on
 193 the right hand side of the equation represents the energy dissipated due to
 194 turbulent fluctuations whilst the second term represents the energy dissipated
 195 due to the mean flow.

196 The second method is to evaluate the bending moments on the rotor by
 197 integrating the pressure across all of the solid surfaces of the rotor. It is
 198 generally accepted that the latter method is more accurate when a RANS
 199 turbulence model is used, since all RANS turbulence models under-predict
 200 turbulent dissipation (Rielly and Gimbun, 2009). It is for this reason that
 201 the power in this study is solely calculated using the bending moment on the
 202 rotor:

$$P = 2\pi NM \quad (9)$$

203 where M is torque or bending moment.

204 2.3. Experimental validation

205 Experimental validation of the CFD power predictions was carried out
206 using a Silverson L5M custom fitted with a 1 N m TorqueSense torque me-
207 ter. The torque was measured at rotor speeds between 2000 min^{-1} and
208 7500 min^{-1} in 500 min^{-1} increments. To reduce error, the torque losses due
209 to the bearings were measured before and after each run by measuring the
210 torque of the mixer in air as opposed to water at the same speeds as the ac-
211 tual experimental runs. These values were then subtracted from the values
212 obtained in the experimental runs in water.

213 3. Results and discussion

214 In the following section, the results from this study will be presented and
215 discussed. Results regarding the validation of the CFD model can be found
216 in the supporting information for this paper.

217 3.1. Varying base diameter in batch mode of operation

218 Figure 5 shows the effect of varying the base diameter of the stator with
219 various screen hole sizes on the power number of the mixer. Note that when
220 $R_b = 0$, the base is fully closed so there is no flow through the base. For
221 each screen hole size, the power number generally follows the same trend
222 as the base diameter is varied. At low base diameters, the power number
223 increases exponentially with the base diameter. This can be expected due
224 to the fact that the hydraulic radius of the base hole is much smaller than
225 the hydraulic radius of the holes in the screen, so the power is controlled by
226 the flow into the base. Therefore, the power is expected to be proportional
227 to the area of the base hole, $Po \propto R_b^2$. As the base hole is opened, the

228 flow becomes restricted by the holes in the screen and so the power number
 229 reaches a plateau, whose magnitude depends on the size or area of the holes.
 230 Once the base is opened even further, flow begins to exit through the base
 231 of the stator as well as through the holes. The point at which this base flow
 232 begins is dependent on the size or area of the holes in the screen.

Figure 5: Power number as a function of base hole radius for various screen hole sizes.

233 3.2. Effect of varying flow number on power number in batch rotor-stators

Figure 6: Power number as a function of flow number in batch mode for various screen hole sizes.

234 As discussed in Section 1, the effect of varying flow number on power
 235 number for a given stator design or geometry has not been previously studied
 236 for batch rotor-stators. Figure 6 shows the power number as a function of
 237 the flow number for the batch simulations. In this case, the flow rate used in
 238 the calculation for N_Q was the total flow rate exiting the mixing head. For
 239 this part of the study, the only data considered is that in which there is no
 240 negative axial flow through the base of the stator, therefore the total flow out
 241 of the stator is equal to the positive radial flow through the inside surface
 242 of the holes. The effect of N_Q on Po is shown for three different hole sizes
 243 in the screen. For each hole size, the results suggest there is a strong linear
 244 relationship between the two variables, and that ultimately, batch rotor-
 245 stators with no flow exiting the base of the stator can be characterised in a

Table 1: Values of k_1 and Po_Z for Silverson L5M standard emulsor head with various hole sizes.

D_h (mm)	k_1	SE_1	Po_Z	SE_2
1.00	9.30	0.070	0.14	0.0084
1.59	8.14	0.031	0.12	0.0060
2.00	7.74	0.088	0.010	0.021
<i>*SE_1 and SE_2 are the standard errors for k_1 and Po_Z respectively.</i>				

similar fashion to in-line-rotor stators. The lowest flow number for each hole size in Figure 6 was obtained by completely closing the base of the stator, so in this particular case there is no axial flow, either positive or negative, through the base of the stator. It is therefore interesting to note here that this strong linear relationship still exists for these geometries, since all of the flow into and out of the stator is occurring through the holes in the screen and not through the base of the stator.

The values of the empirical constants k_1 and Po_Z obtained for the batch simulations are shown in Table 1. Comparing these values to values recorded in literature for in-line rotor stators (Håkansson, 2018), it can be seen that there is much similarity. This adds further validation to both the accuracy of our CFD model and also the conclusion that batch and in-line rotor-stators can be characterised in the same manner. These results also suggest that k_1 is dependent partly on the size of the holes in the screen. This can potentially be explained by comparing the flow through the rotor-stator with that through a perforated plate in a pipe. The Euler, Eu , number can be thought of as the ratio of the pressure forces to the inertial forces. It is of particular interest in fluid flows where pressure drop is important, such as the flow through the screen of a rotor-stator mixer. Here, we define that

265 Euler number as

$$\text{Eu} = \frac{\Delta p}{\rho N^2 D^2} \quad (10)$$

266 where Δp is the pressure drop. Therefore

$$P = \text{Po}_Z \rho N^3 D^5 + \Delta p Q = \text{Po}_Z \rho N^3 D^5 + \text{Eu} \rho N^2 D^2 Q \quad (11)$$

267 which can be rearranged to give

$$\text{Po} = \text{Po}_Z + \text{Eu} N_Q \quad (12)$$

268 Equation (12) shows that the second term in the full power number equation,
269 Equation (1), can be obtained by either considering the acceleration of fluid
270 due to the rotor, or by the pressure drop created by the rotor and the stator
271 screen, It is therefore evident that k_1 is related to the Euler number, and
272 since the Euler number varies with the design of the holes in a perforated
273 plate in a pipe (Malavasi et al., 2012), k_1 will likely vary with the design of
274 the stator. The recirculating flow entering the holes from the bulk region
275 will most likely give rise to some differences between k_1 and the standard
276 definition of the Euler number, but this consideration provides us with a
277 better understanding behind the physical meaning of k_1 and why it depends
278 on the geometry and design of the mixing head. The effects of geometry
279 changes on k_1 will not be discussed further here.

280 3.3. Comparison between in-line and batch rotor-stators

281 Equation (2) was developed solely for in-line rotor-stators due to the fact
282 that the flow number can easily be changed and calculated for a given stator

283 design using simply the flow rate in the piping. After considering the way
284 in which the flow rate was calculated for batch rotor-stators in this study, it
285 becomes apparent that comparing the flow in the two modes of operation will
286 give rise to some complications. By using the flow in the pipe to calculate N_Q
287 in in-line mode, the radial flow rate into the holes is not accounted for, and so
288 the flow rate used does not necessarily equal the total flow rate through the
289 actual screen of the mixing head. Without the use of any data, this fact can
290 already be used to potentially explain the phenomenon that often occurs in
291 in-line rotor-stators at very low flow numbers. At flow numbers approaching
292 zero in in-line mode, the true flow number can not reach zero, since there is
293 still flow entering and exiting through the holes or slots in the screen. This
294 has already been shown in batch mode in Figure 6, and suggests that the
295 phenomenon observed at low flow rates in in-line rotor stators is simply a
296 result of the usage of only a part of the true flow rate in the calculation for
297 N_Q . This is consistent with what was suggested in the study conducted by
298 Jasińska et al. (2015), however this new information suggests that the flow
299 number used in that study, and in the majority of the studies conducted
300 previously in this field, has not been calculated correctly.

Figure 7: CFD prediction of power number as a function of flow number for in-line Silverson L5M with screen hole sizes of (a) 1.00 mm, (b) 1.59 mm, (c) 2.00 mm. Black dashed line - Linear fit of high values of $N_{Q,i}$, Red dashed line - Linear fit of $N_{Q,t}$.

301 Figure 7 displays the power number as a function of the flow number for
 302 various screen hole sizes in the in-line mixer. The flow rate here was calcu-

lated in two different ways in order to investigate the effect of recirculation as mentioned previously. The total flow number, $N_{Q,t}$, was calculated using the total positive radial flow across the inside surface of the holes in the screen, ie. the same analysis as batch mode. In-line mixers should exhibit no negative flow through the base, since the base is usually a narrow inlet. The total flow through the stator is therefore the positive radial flow in the holes of the screen. The imposed flow number, $N_{Q,i}$, was calculated using the imposed flow rate at the velocity inlet. This is the way in which the flow number would be calculated experimentally in in-line mixers, using a flow meter positioned in the inlet or outlet pipeline. At high flow numbers when using the imposed flow number, the power number is proportional to the flow number as expected. At low flow numbers, the power number starts to rise above the linear fit. This is very likely the phenomenon which has previously been discussed.

When using the total flow number, the correlation for each hole size shifts in a positive direction with regards to the flow number. This is due to the fact that the flow into the holes of the screen is now being taken into account. It can be also be seen that when using the total flow number, the linear correlation extends down all the way to the lowest data point, at which there is no imposed flow rate. This strongly suggests that the increase in power number at low flow rates is caused by the incorrect estimation of the flow number when using the imposed flow rate in the pipe. This seems logically sound, since there can never truly be zero flow through the stator whilst the rotor is rotating at high speeds. The rise in power number at low flow rates is not as extreme in these results as in results previously obtained (Jasińska

et al., 2015), however this is likely due to the fact that the in-line mixer used in this study is a single rotor-single stator configuration, whereas previous results were obtained using double rotor-double stator configurations.

Figure 8 shows the power number as a function of the total flow number for the batch and in-line Silverson L5M, as predicted by the CFD simulations. It can clearly be observed that both batch and in-line mixers share the same correlation, and that the way in which rotor-stator mixers are characterised is not dependent on the mode of operation, but on the design of the rotor and the screen. Although this conclusion has been implicitly suggested previously (Håkansson et al., 2017), no study as of yet has shown explicit evidence of this behaviour of rotor-stator mixers. These results might suggest the same conclusion as that from the study of Carrillo De Hert and Rodgers (2017); that the droplet size distribution of an emulsion produced in a batch rotor-stator can be matched with that produced in an in-line rotor stator by using a mass balance and accounting for the residence time of the droplets actually in the mixing head. The results shown in Figure 8 suggest that for the same flow number, the amount of energy is transferred into the fluid, and hence the amount of energy available for droplet break-up, is practically the same for both modes of operation.

Figure 8: CFD prediction of power number as a function of total flow number for Silverson L5M mixer operating in batch and in-line mode with screen hole sizes of (a) 1.00 mm, (b) 1.59 mm, (c) 2.00 mm. Black dashed line - Linear fit of concatenated data.

3.4. Imposed flow rate versus total flow rate in in-line mode of operation

It is clear from the results discussed in the previous sections that in order to properly characterise power in in-line rotor-stators, one must take into

350 account the recirculating flow into the holes of the screen when calculating
 351 the flow number of the mixer. In this study we have achieved this using
 352 CFD, however optical flow characterisation methods such as PIV could also
 353 be used to achieve this. These methods are usually less attractive since they
 354 require expensive equipment and collecting data may take too long for it to
 355 be a feasible option in industry. It is therefore desirable to develop a model
 356 in order to predict the total flow rate from known imposed flow rate and the
 357 geometry of the rotor and the stator.

Figure 9: Total flow number as a function of imposed flow number in Silverson L5M with in-line mixing assembly and various screen hole sizes as predicted by CFD. Solid lines show $N_{Q,t}$ predicted by the correlation developed in this study, Equation (13).

358 Figure 9 shows the total flow rate as a function of the imposed flow rate
 359 for various hole sizes in the screen. The results suggest that for each hole
 360 size there is a strong linear relationship between the imposed and total flow
 361 numbers, however the intercept and the slope vary with hole size or total hole

362 area of the screen. The intercept is related to the amount of fluid flowing
 363 through the mixer when the inlet and outlet valves are shut, or the amount
 364 of fluid flowing into and back out of the holes. This, of course, increases
 365 with total area of the holes. It would also make sense physically that this
 366 flow scales with the square of the total area of the holes, since flow rate
 367 in tubular flows is proportional to R^4 , where R is the radius of the tube
 368 or pipe. In this case the tubes are the holes in the screen. The slope of
 369 the relationships in Figure 9 describes the relative amount of flow which is
 370 entering through the holes in the screen. The slope in Figure 9 was found
 371 to inversely proportional to the square of the area of the holes with a y -
 372 intercept equal to unity. The magnitude of the intercept equalling unity
 373 can be expected because theoretically if there were no holes, the total flow
 374 would equal the imposed flow. At extremely large areas, it is likely that this
 375 relationship will not be linear, but will approach an asymptote near zero,
 376 since a negative slope in Figure 9 would seem illogical. Since typical stators
 377 would never have such large ratios between the hole area and rotor diameter,
 378 it is sufficient to assume a linear relationship with the square of the holes
 379 area. This model will also only work for stators with a single screen, since
 380 these mixers don't usually exhibit the sharp increase of power number with
 381 decreasing flow number at low flow numbers. This trend is observed solely
 382 in mixers with a double-screen configuration (Jasińska et al., 2015), in which
 383 the flow is much more complex to model in this manner. It is likely that the
 384 area is not the only screen geometry variable to use in this correlation, since
 385 Mortensen et al. (2017) showed that for the same area, the flow and power
 386 numbers can change. The hydraulic radius of the holes in the screen might

387 be a good variable to include as this takes into account the effect described
 388 in the study just mentioned. This, however, will not be considered in this
 389 study.

390 The following model can therefore be used to predict the total and correct
 391 flow number in an in-line rotor-stator

$$N_{Q,t} = N_{Q,i} + 0.33 \left(\frac{A_h}{D^2} \right)^2 [0.51 - N_{Q,i}] \quad (13)$$

392 This model essentially states that the true flow through the mixing head,
 393 $N_{Q,t}$, is equal to the imposed flow, $N_{Q,i}$, plus the flow moving back into
 394 the rotor swept region through the holes, $N_{Q,r}$, which is a function of the
 395 geometry of the rotor and the stator and also the imposed flow number. It
 396 should be noted that there are some exceptional cases in which this model
 397 cannot possibly be used. For example, when the rotor speed approaches
 398 zero, both the imposed and total flow numbers approach infinity. However,
 399 when the rotor speed is zero, a flow number in this sense would be of little
 400 use anyway. The accuracy of this model is shown in Figure 9 by the solid
 401 lines, and also in the parity plot displayed in Figure 10. This correlation is
 402 also extremely beneficial in that it provides an easy method for determining
 403 the amount of recirculating flow, since the power and imposed flow rates are
 404 both easily known to us for in-line mixers. It would therefore also be useful
 405 to study how the relative amount of recirculating flow affects the droplet size
 406 of an emulsified product, since this correlation could be used to tune the
 407 quality of the product based on the mixing head geometry.

Figure 10: Parity plot for model used to predict total flow number shown in Equation (13).

4. Conclusions

In this study, CFD has been used to investigate and compare the power and flow characteristics in a Silverson L5M rotor-stator mixer operating in batch and in-line mode. CFD results were validated with experimental torque measurements. Flow number in the batch mode of operation was varied by constricting the base of the stator. It was found that batch rotor-stator mixers can be characterised using the well developed model which is already in use for in-line mixers, provided that the base is small enough that no flow is allowed to exit through it. For a given design of rotor and stator, the characterisation model is practically the same regardless of whether the mixer is in the batch or the in-line configuration. When the mixer is operating

in in-line mode, one must take into account not just the imposed flow in the pipeline, but also the recirculating flow entering the holes of the stator. At low imposed flow rates, previous investigations showed a deviation away from the standard model; an increase in power number with decreasing flow number. It can be concluded from this study that this deviation is due to the flow entering the holes at low imposed flow rates. This study also proposes a model which can be used to predict the correct flow number, flow in the pipe plus flow into the holes, based on known operating parameters, namely the geometry of the rotor and stator and also the imposed flow in the pipeline. This correlation can also be used to predict the amount of recirculating flow since the power and imposed flow numbers are easy to measure for in-line mixers. Potentially the correlation could be used to help tune the quality of emulsified products. Overall, this study provides useful insight into the fundamental workings of rotor-stator mixers and will hopefully enable more justified design choices to be made by anyone using a rotor-stator mixer. This study also highlights areas in which further research would be highly beneficial, such as studying the effect of geometry changes on the constant k_1 .

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