Ahmed U, Michael V, Hou R, Mothersdale T, Prosser R, Kowalski A, Martin P.
[An energy transport based evolving rheology in high-shear rotor–stator mixers](#). *Chemical Engineering Research and Design* 2018, 133, 398-406.

Copyright:

© 2018. This manuscript version is made available under the [CC-BY-NC-ND 4.0 license](#)

DOI link to article:

<https://doi.org/10.1016/j.cherd.2018.02.019>

Date deposited:

29/04/2018

Embargo release date:

21 February 2019

This work is licensed under a
[Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International licence](#)

An energy transport based evolving rheology in high-shear rotor-stator mixers

Umair Ahmed^{a,1,*}, Vipin Michael^b, Ruozhou Hou^c, Thomas Mothersdale^d,
Robert Prosser^b, Adam Kowalski^d, Peter Martin^c

^a*School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK*

^b*School of Mechanical, Aerospace and Civil Engineering, University of Manchester,
Manchester, M13 9PL, UK*

^c*School of Chemical Engineering and Analytical Sciences, University of Manchester,
Manchester, M13 9PL, UK*

^d*Unilever R&D, Port Sunlight Laboratory, Quarry Road East, Bebington,
Wirral CH63 3JW, UK*

Abstract

Rotor-Stator mixers such as the inline Silverson are widely used by the process industry. Existing literature on experimental and computational investigations of these devices focus on characterising the power draw and turbulent mixing of Newtonian fluids and non-Newtonian fluids such as emulsions. The current knowledge on the performance of these mixers in blending and mixing fluids with an underlying complex structure is limited. Modelling and simulation of such structured liquids has traditionally been challenging due to the complexity of the constitutive governing equations which are to be solved for the prediction of rheology. In this paper a novel approach to model evolving rheology is proposed. This approach incorporates important physical phenomenon such as the strain rate history effects in the generalised Newtonian fluid model. The new approach is used to model mixing in a pilot scale inline Silverson mixer via Computational Fluid Dynamics (CFD) simulations. A sliding mesh algorithm coupled to eddy viscosity turbulence closure is used. Experiments have been performed with the inline Silverson mixer placed in a recirculation loop for two different rotor speeds, and rheological measurements have been performed on the samples taken at the outlet of the mixer. Computational results are compared with the viscosity measurements and it is found that the model predictions for the evolution of viscosity are in reasonable agreement with the experimental data.

32 *Keywords:* Rheology, Structured liquids, Silverson, Mixing, CFD

33 **1. Introduction**

34 The mixing process plays a significant role in improving the homogeneity
35 and quality of a wide range of products in the process industries. Inline rotor-
36 stator mixers are widely used in processing due to their high efficiency and their
37 capacity to accelerate the mixing process by providing a focussed delivery of
38 energy [1]. However, the high energy dissipation rates and short residence times
39 within the mixer limit current understanding of the fluid dynamics within these
40 devices and consequently their relationship to overall mixer performance and
41 product quality [2].

42 Rotor-stator mixers consist of high speed rotors surrounded by close fitting
43 stator screens. The typical tip speeds during operation range from 10 – 50m/s,
44 and the gaps between the rotor and stator range between 100 – 3000 μ m [3],
45 generating high shear rates in the rotor-stator gap ranging from 20,000s⁻¹ –
46 100,000s⁻¹ [2]. The high kinetic energy imparted to the fluid by the rotating
47 blades is mainly dissipated local to the stator screen; the high rate of energy
48 dissipation makes such devices advantageous for physical processes such as mix-
49 ing, dispersion, dissolution, emulsification and de-agglomeration [4]. The high
50 energy dissipation rates and shear rates found in rotor stator mixers lend them-
51 selves to production of ever finer structures such as emulsions [5] and dispersion
52 of powders [6].

53 Modelling of mixing in a pilot scale Silverson rotor-stator mixer has been
54 the subject of several recent investigations. Baldyga et al. [7, 8] and Jasińska et
55 al. [1, 9] have carried out CFD simulations of an inline Silverson 150/250 MS
56 in-line mixer focussing on estimating the product yield during chemical reac-
57 tion, distribution of particle aggregates and droplet size distributions. Recently
58 Baldyga et al.[10] and Michael et al. [11] have modelled the drop dispersion and
59 evolving rheology of dense emulsions in this mixer. The Reynolds Averaged
60 Navier-Stokes (RANS) method along with sliding mesh is used to simulate the

61 rotor-stator interaction.

62 This paper uses the CFD methodology of Michael et al [11] to model the tur-
63 bulent flow dynamics within the Silverson mixer but with specific developments
64 to characterise and model the evolving rheology of liquids containing wood and
65 other plant fibres. These systems are frequently processed by high pressure ho-
66 mogenisers, microfluidisation, ball mills and grinding where scale up is carried
67 out on the basis of pressure drop (i.e. energy) and frequently requires multiple
68 passes [12–14]. As the fibres are processed their size is reduced and the viscos-
69 ity increases [12] and thus this system behaves in an interesting manner where
70 the viscosity of the fluid and the efficiency of the mixer are coupled. In this
71 paper we choose to use the Silverson mixer because of our previous experience
72 in characterising its performance and availability.

73 The modelling of polymeric liquids is challenging owing to the complexity of
74 the underlying constitutive equations [15]. The total stress tensor $\underline{\underline{\sigma}}$ is decom-
75 posed into an isotropic and deviatoric part as $\underline{\underline{\sigma}} = -p\underline{\underline{I}} + \underline{\underline{\tau}}$ with p being the
76 pressure and $\underline{\underline{\tau}}$ the stress tensor. Transport equations of varying complexity for
77 the stress tensor have been proposed in literature [16]. This approach is however
78 computationally challenging especially for highly inertial flow conditions such
79 as that occurring in industrial high-shear mixing applications. A phenomeno-
80 logical model is thus the highly favoured approach in such situations wherein
81 the nonlinear flow behaviour is cast in the form $\underline{\underline{\tau}} = \alpha + \beta|\dot{\gamma}|^n$, where $|\dot{\gamma}|$ is pro-
82 portional to the square root of the second invariant of the strain rate tensor $|\underline{\underline{\dot{\gamma}}}|$.
83 This form is the Herschel-Bulkley equation and such models are classed as Gen-
84 eralised Newtonian Fluids (GNF): $\underline{\underline{\tau}} = \mu(|\dot{\gamma}|)|\underline{\underline{\dot{\gamma}}}|$. Such a formulation allows one
85 to retain the tensorial structure of the Newtonian constitutive model whilst still
86 being able to predict thixotropic effects such as time dependent shear-thinning
87 and yield stress. However owing to the simple proportionality between the stress
88 tensor and the instantaneous strain rate tensor the effect of the history of de-
89 formation on the stress is discarded in these models. Yet it is well known that
90 the rheological behaviour of polymeric liquids is affected by flow history [17].

91 We propose the introduction of a damage parameter to track the evolution

92 of the microstructure. Taking a cue from the first law of thermodynamics, the
 93 work done on the microstructure by the fluid is equated to an energy like variable
 94 (denoted here by E and referred to as the *mechanical* energy). The transport
 95 of mechanical energy is assumed to be governed by $\frac{DE}{Dt} = \nabla \cdot (\underline{\tau} \cdot \underline{u}) - \underline{u} \cdot \nabla p$.
 96 The second term on the right hand side is reversible and does not contribute to
 97 the microstructure evolution. The first term on the right hand side contains a
 98 strictly positive component which is taken to represent the irreversible growth
 99 of damage. The zero shear viscosity is modelled as a function of this damage.
 100 In this paper we solve this transport equation for mechanical energy of the
 101 fluid system to capture the effect of the fluid flow on the evolution of rheology
 102 in the mixer. In order to close this problem a precise form for the empirical
 103 parameters α and β of the Herschel-Bulkley model need to be specified. These
 104 parameters of the Herschel-Bulkley model are taken to be the yield stress τ_0
 105 and the consistency index k of the fluid. The power draw of the mixer is an
 106 experimentally measurable quantity and its product with process time gives
 107 the total mechanical energy. A functional relationship between this mechanical
 108 energy E and the viscosity μ is experimentally determined and adopted in this
 109 paper. This allows τ_0 , k and n to be determined as a function of energy (E).

110 In Section 2 we present the mathematical formulation of the new energy
 111 based evolving rheology model giving further details on how viscosity may be
 112 related to energy. In Section 3 we briefly describe the test configuration in-
 113 vestigated. and outline the experimental procedure. Section 4 outlines the
 114 numerical procedure. Results are then presented and discussed in Section 5,
 115 with the conclusions summarised in the last section.

116 **2. Mathematical formulation of the new model**

117 The mathematical details of the new energy based model that incorporates
 118 the flow history into the rheology are presented. A switch to Einstein index
 119 notation is made henceforth. The rheology evolution is modelled via a modified

120 energy transport equation:

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho u_k E}{\partial x_k} = -u_k \frac{\partial p}{\partial x_k} + \frac{\partial \tau_{km} u_m}{\partial x_k}, \quad (1)$$

121 where p is the pressure and τ_{km} is the viscous stress tensor for an incompressible
122 fluid :

$$\tau_{km} = \mu \left(\frac{\partial u_k}{\partial x_m} + \frac{\partial u_m}{\partial x_k} \right). \quad (2)$$

123 The development of the rheology is considered as irreversible. The standard
124 Herschel-Bulkley formulation is used to account for shear thinning of the fluid:

$$\mu = \begin{cases} \mu_0 & |\dot{\gamma}| \leq \dot{\gamma}_0 \\ k |\dot{\gamma}|^{n-1} + \tau_0 |\dot{\gamma}|^{-1} & |\dot{\gamma}| \geq \dot{\gamma}_0 \end{cases}, \quad (3)$$

125 where $\dot{\gamma}$ is the shear rate, τ_0 is the yield stress and μ_0 is the limiting viscosity.
126 The new approach couples μ_0 to the mechanical energy equation via :

$$\mu_0 = A (1 - \exp(-BE)), \quad (4)$$

127 where A and B are model constants and can be calculated for a given fluid
128 through experimental trials. Furthermore, note that the yield stress and k in
129 Eq. (3) can be expressed as $\tau_0 = \tau_0(E)$ and $k = k(E)$ which is explored further in
130 Section 5. According to this method the development of rheology is considered
131 as irreversible and provides the strain rate history effects required for accurate
132 modelling of rheology.

133 3. Test configuration and experimental methods

134 The Silverson double screen 150/250MS in-line mixer has been experimen-
135 tally studied in several works [4, 18–21], measuring the power consumption and
136 mixer performance at different operating speeds. The mixer has two rotors
137 which rotate together within closely fitted stator screens. The rotors and stator
138 screens of the mixer are shown in Figure 1 and further details can be found in
139 [4, 19]. The mixer usually operates over a range of speeds varying from 3000 to
140 12000 rpm with the fluid flowing through the device at different flow rates.

Figure 1: Silverson 150/250MS mixer, (a) Rotor (b) Stator.

Figure 2 shows a piping and instrumentation diagram (P&ID) of the validation test configuration. A 50 L double-jacketed mixing vessel (R100) was used as the material holding tank. The vessel was also fitted with an anchor and a pitch blade turbine stirrer respectively to ensure that the material homogeneity inside the vessel was maintained all the time. Feed flowrate to the Silverson in-line mixer, which was also the recirculation flowrate of the loop, was regulated through the combination of a 1.5" lobe pump (J100) and a Coriolis meter (FT100). All the mechanical connections were made of 1.5" nominal size stainless steel pipes coupled with standard In Line Cleaning (ILC) or Swagelok fittings. A total of two tests were carried out, in which the test fluid containing

Figure 2: P & ID of the test configuration containing the Silverson 150/250MS mixer.

150

151 the fibrous thickening agent was processed by the Silverson in-line mixer run-

ning at 6000 and 11000 rpm respectively. Each test started with 50 kg of a well dispersed mixture containing 1 kg of fibre in water (i.e. 2% w/w) being manually loaded into the 50 L mixing vessel. The mixture was then circulated within the test loop by the lobe pump for 40 minutes. The Silverson in-line mixer was then switched on at the target speed and samples were periodically taken (SP02) over about 4 hours. Chilling water was allowed to circulate inside the double jacket of the 50 L mixing vessel to maintain the mixture temperature below 25 °C. All the collected samples were stored in sealed plastic bottles for off-line viscosity measurements. The torque was recorded [19] and used to calculate the mechanical energy.

Rheological measurements were carried out at 25°C using Anton Paar DSR301 rheometer with a 12.5 mm diameter 4 vane geometry in a serrated cup. The samples were conditioned for 10 mins at a stress of 1 Pa and then a controlled stress sweep was carried out. The rheological quantity used to characterise the experimental comparison is the value of viscosity at 200 s⁻¹.

4. Computational configuration and numerical methods

The simulations were performed using *Code_Saturne*, an open-source CFD code developed by EDF [22] (see <http://www.code-saturne.org>). *Code_Saturne* is an incompressible solver based on a collocated discretisation of the domain, and is able to treat structured and unstructured meshes with different cell shapes. It solves the Navier-Stokes equations with a fractional step method based on a prediction-correction algorithm for pressure/velocity coupling (SIMPLEC), and Rhie and Chow interpolation to avoid pressure oscillations. The code uses an implicit Euler scheme for time discretisation, and a second order centred difference scheme is used for the spatial gradients. Rotating meshes are handled via a turbo-machinery module, which solves the transport equations for the initial geometry, updates the geometry and then corrects the pressure as shown in Figure 3. The code has previously been validated in many industrial and academic studies, ranging from simulations of incompressible flows (with

181 and without rotating meshes) [23–25] to low Mach number variable density re-
 182 acting flows [26, 27].

Figure 3: Schematic of mesh handling in the turbomachinery module of *Code_Saturne*.

183 A 2-D computational domain has been used in the current investigation as
 184 shown in Figure 4a; this provides a comparable basis to the 2-D MRF config-
 185 uration adopted in earlier studies of Jasińska et al [1, 9]. The computational
 186 domain is meshed with 180000 cells and shown in Figure 4b. The mesh is refined
 187 in the regions near to the sliding interface located in the rotor-stator gaps (as
 188 shown in Figure 4c and Figure 4d). Grid sensitivity studies have been carried
 189 out and the grid size for mesh independent results is similar to that of Jasińska
 190 et al [1, 9]. Standard inflow conditions on the inlet faces and pressure outlet
 191 conditions on the outlet faces are specified. A no-slip condition is applied to the
 192 velocity at the walls along with the appropriate wall treatment through standard
 193 wall functions for turbulence and zero normal gradients for scalars. Symmetry
 194 conditions are used in the transverse direction. Similar boundary conditions
 195 have been used in the earlier study of Jasińska et al [1, 9] and Michael et al [11]
 196 for the same Silverson mixer.

197 5. Results and discussion

198 The model proposed in Section 2 is first tested with different parameters
 199 and then compared against experimental data. The turbulence is treated via
 200 the standard $k - \omega$ SST model proposed by Menter [28].

(a) Model configuration in 2D

(b) Computational grid

(c) Mesh near the inner rotating inter-
face

(d) Mesh near the outer rotating inter-
face

Figure 4: 2D computational domain and mesh for the Silverson 150/250MS mixer

	k	τ_0	Number of fluid passes
Case-A	fixed	fixed	1
Case-B	function of E	function of E	1
Case-C	function of E	function of E	Multiple

Table 1: List of different cases

	k	n	τ_0	$\dot{\gamma}_0$
Case-A	41.5	0.5526	0.8	$\tau_0/2\mu$

Table 2: Model parameters for Case-A

201 5.1. Initial simulations

202 Initially three different cases are considered as listed in Table 1. These
203 simulations are run for 3 seconds at a rotation speed of 6000 RPM and an
204 inflow rate of 680 kg/hr.

205 5.1.1. Case-A

206 This case is used as an initial calculation to test the implementation of the
207 new model. The values used for yield stress, yield strain, k and n are given
208 in Table 2. As this case is performed to test the methodology: the low shear
209 behaviour incorporates the mechanical energy. The high shear limit behaviour
210 is much less dependent on the viscosity build: consequently, for $\dot{\gamma} > \dot{\gamma}_0$, a
211 simple (constant) inverse power law dependence has been assumed. The values
212 for constants in (Eq. (4)) are $A = 3.3 \times 10^2$ and $B = 3 \times 10^{-3}$. Note that
213 these are calculated by using data from multiple experiments at different mixer
214 conditions (data fitting not reported here). Figure 5 shows the variation of
215 energy and viscosity of the fluid in the Silverson mixer. It can be noticed that
216 work done on the fluid by the mixer blades is converted into the energy contained
217 in the fluid which results in increased viscosity.

Figure 5: Viscosity and Energy variation in the Silverson 150/250MS mixer for Case-A

5.1.2. Case-B

In this case the yield stress τ_0 and yield strain are calculated as functions of mechanical energy calculated in Eq. (1) :

$$\tau_0 = \frac{|\mu - C|}{D} \quad \text{and} \quad \dot{\gamma}_0 = \frac{\tau_0}{2\mu}, \quad (5)$$

where $C = 8.2448 \text{ Pa.s}$ is the viscosity of the fluid at $\tau_0 = 0$ and $D = 1.2064 \text{ s}$ is the inverse of the shear rate. Note that the expression for τ_0 and the values for C and D in Eq. (5) are obtained by fitting a curve to the experimental data for yield stress and viscosity at different rotation speeds of the Silverson mixer (fitting of the data not shown here), while the expression for the yield strain in Eq. (5) is obtained by using the linear relation between the yield stress and yield strain as $\tau_0 = 2\mu|\dot{\gamma}_0|$. The continuity of the viscosity requires that in Eq. (4) $\mu_0 = k|\dot{\gamma}|^{n-1} + \tau_0|\dot{\gamma}|^{-1}$ which leads to :

$$k = \frac{\mu_0 - \tau_0/|\dot{\gamma}_0|}{|\dot{\gamma}|^{n-1}}. \quad (6)$$

Now substituting Eq. (6) into Eq. (4) yields :

$$\mu = \begin{cases} \mu_0 & |\dot{\gamma}| \leq \dot{\gamma}_0 \\ \mu_0 - \tau_0 \left(|\dot{\gamma}_0|^{-1} - |\dot{\gamma}|^{-1} \right) & |\dot{\gamma}| \geq \dot{\gamma}_0 \end{cases}. \quad (7)$$

Figure 6 a and Figure 6 b show the variation of viscosity and energy in the mixer when the modified τ_0 and the expression in Eq. (7) are used. Note that the distribution of energy in the mixer is significantly different when compared with those of Case-A. These difference arise due to the modified definitions of k and τ_0 . Figure 6 c shows the local variation of τ_0 as predicted by using Eq. (5) and Eq. (7). It can be seen in Figure 6 that the local values of τ_0 are higher than the ones used in Case-A. This implies that the local variation of energy control k and the yield stress and can consequently lead to variations in local viscosity in the fluid.

5.1.3. Case-C

The mathematical formulation for this case is exactly the same as that used for case-B; the only difference being the fluid from the outlet of the mixer is re-introduced at the inlet of the mixer to check the influence of the history effects of energy contained in the fluid on the viscosity. Figure 7 a and Figure 7 b show the changes in viscosity and energy when the fluid is recycled from the outlet of the mixer to the inlet of the mixer. An increase in energy contained in the fluid can be seen when compared with case-B (see Figure 6 and Figure 7) which consequently leads to an increase in the viscosity of the fluid as shown in Figure 7 a. Note that the values of τ_0 are different from those reported in case-B (see Figure 6 c). This variation in τ_0 implies that the history effect of the work done on the fluid is contained in the fluid in the form of mechanical energy and leads to variations in yield stress and viscosity over time after multiple passes of the fluid. In this case when the fluid is recycled the value of the yield stress increases.

5.2. Comparison with experimental data

The simulation results are now compared with experimental measurements. In these simulations the flow rate is set to 300kg/h and two different rotation speeds of 6000 RPM and 11000 RPM are used to match the experimental settings. The fluid from the mixer outlet is recycled into the inlet of the mixer as

Figure 6: Variation of viscosity, energy and yield stress in the Silverson 150/250MS mixer for Case-B

Figure 7: Variation of viscosity, energy and yield stress in the Silverson 150/250MS mixer for Case-C

done in the experiments. Figure 8 shows the viscosity and energy variation in the mixer at the two different rotation speeds. It can be seen that the energy contained in the fluid increases with an increase in the rotation speed. Some differences in the evolution of viscosity can be seen in the wake of the mixer blades at different rotation speeds as shown in Figure 8 a and Figure 8 c. These variations in viscosity arise due to the differences in the energy transfer from the mixer blades to the fluid at different rotation speeds.

Figure 9 shows the predicted viscosity compared with the rheological measurements of the outlet samples. Note that in the simulations the viscosity at the exit plane is averaged on the exit surface area to increase the sample size for averaging of viscosity. The power draw calculated in the experiments is converted into mechanical energy as :

$$E = \frac{Pt}{M}, \quad (8)$$

where P is the power draw, t is the time and M is the total mass of the fluid in the mixer. It can be seen in Figure 9 that the predicted viscosity is in reasonable agreement with the experimental data and the model is able to capture the correct qualitative trends in the viscosity variation with a change in energy. The viscosity increases with an increase in E , and this increase is directly related to the rotation speed of the mixer as shown in Figure 8. Some differences in the predicted viscosity and the experimental data can be seen in Figure 9. These differences arise due to several reasons including the uncertainty regarding the performance of the turbulence model used, and also due to the uncertainty in the experimental measurements. The increase in viscosity in the experiments occurs over multiple passes of the fluid in the full equipment which includes a pump and a mixing vessel (shown in Figure 2), while no attempt is made to include this equipment in the simulations. Furthermore, the energy from the experiments is obtained via the total power draw of the mixer which includes frictional and other mechanical losses in the mixer and these losses are not present in the simulations.

Figure 8: Prediction of variation of viscosity and energy in the Silverson 150/250MS mixer for experimental conditions

Figure 9: Comparison of viscosity and energy with the experiments at different rotation speeds with an inflow rate of 300 kg/h

288 6. Summary and Conclusions

289 In this paper a new evolving rheology modelling approach based on mechan-
290 ical energy (E) is proposed. This model incorporates the strain rate history
291 effects into the Generalised Newtonian fluid (GNF) model. The new approach
292 is coupled with the modified Herschel-Bulkley formulation. A pilot scale in-
293 line Silverson mixer is chosen as the representative configuration to test the
294 predictive capabilities of the new model. Experiments have been performed to
295 determine the constants in the new modelling approach and also to validate the
296 viscosity predictions from the new model.

297 Initial simulations with only one flow through of the fluid in the mixer have
298 been carried out to determine the performance of the new modelling approach
299 and it is found that the model is capable of predicting an increase in viscosity
300 with an increase in the mechanical energy. Furthermore, the model is also
301 capable of predicting an increase in the yield stress with an increase in the local
302 viscosity in the mixer. In the case of recirculation of the fluid from the outlet
303 of the mixer into the inlet of the mixer the new model is capable of retaining
304 the history effects and is capable of predicting the change in viscosity. The
305 viscosity predictions from the new model are in reasonable agreement with the
306 experimental measurements at the rotation speeds and flow rates considered
307 in this paper. Further assessment of the model performance for different flow
308 conditions and the prediction of power draw forms part of the ongoing work.

309 References

- 310 [1] M. Jasińska, J. Baldyga, M. Cooke, A. J. Kowalski, Specific features of
311 power characteristics of in-line rotor-stator mixers, *Chemical Engineering*
312 and Processing: Process Intensification 91 (2015) 43–56.
- 313 [2] V. A. Atiemo-Obeng, R. V. Calabrese, RotorStator Mixing Devices, in:
314 Handbook of Industrial Mixing, John Wiley & Sons, Inc, Bath, UK, 2004,
315 pp. 479–505.

- 316 [3] A. T. Utomo, Flow patterns and energy dissipation rates in batch rotor-
317 stator mixers, Ph.D. thesis, University of Birmingham (2009).
- 318 [4] A. Kowalski, M. Cooke, S. Hall, Expression for turbulent power draw of
319 an in-line silverson high shear mixer, Chemical engineering science 66 (3)
320 (2011) 241–249.
- 321 [5] S. S. Davis, C. Washington, G. Liversidge, L. Sternson, S. Kline, F. Labo-
322 ratories, Lipid Emulsions as Drug Delivery Systems, Ann. New York Acad.
323 Sci. 507 (1987) 75–88. doi:10.1111/j.1749-6632.1987.tb45793.x.
- 324 [6] N. G. Özcan-Takin, G. Padron, A. Voelkel, Effect of particle type on the
325 mechanisms of break up of nanoscale particle clusters, Chem. Eng. Res.
326 Des. 87 (4) (2009) 468–473. doi:10.1016/j.cherd.2008.12.012.
- 327 [7] J. Baldyga, A. Kowalski, M. Cooke, M. Jasinska, et al., Investigations of
328 micromixing in a rotor-stator mixer, Inzynieria Chemiczna I Procesowa
329 28 (4) (2007) 867–877.
- 330 [8] J. Bałdyga, Ł. Makowski, W. Orciuch, C. Sauter, H. P. Schuchmann,
331 Deagglomeration processes in high-shear devices, Chemical Engineering Re-
332 search and Design 86 (12) (2008) 1369–1381.
- 333 [9] M. Jasińska, J. Bałdyga, S. Hall, A. W. Pacek, Dispersion of oil droplets
334 in rotor?stator mixers: Experimental investigations and modeling, Chem.
335 Eng. Process. Process Intensif. 84 (2014) 45–53. doi:10.1016/j.cep.
336 2014.02.008.
- 337 [10] J. Bałdyga, M. Jasińska, A. J. Kowalski, Effect of rheology of dense emul-
338 sions on the flow structure in agitated systems, Chem. Eng. Res. Des. 108
339 (2016) 3–12. doi:10.1016/j.cherd.2015.11.026.
- 340 [11] V. Michael, R. Prosser, A. Kowalski, CFD-PBM simulation of dense emul-
341 sion flows in a high-shear rotorstator mixer, Chem. Eng. Res. Des. 125
342 (2017) 494–510. doi:10.1016/J.CHERD.2017.08.002.

- 343 [12] E. H. Qua, P. R. Hornsby, H. S. Sharma, G. Lyons, Preparation and char-
344 acterisation of cellulose nanofibres, *J. Mater. Sci.* 46 (18) (2011) 6029–6045.
345 doi:10.1007/s10853-011-5565-x.
- 346 [13] S. H. Osong, S. Norgren, P. Engstrand, Processing of wood-based mi-
347 crofibrillated cellulose and nanofibrillated cellulose, and applications re-
348 lating to papermaking: a review, *Cellulose* 23 (1) (2016) 93–123. doi:
349 10.1007/s10570-015-0798-5.
- 350 [14] S. Iwamoto, A. N. Nakagaito, H. Yano, M. Nogi, Optically transparent com-
351 posites reinforced with plant fiber-based nanofibers, *Appl. Phys. A Mater.*
352 *Sci. Process.* 81 (6) (2005) 1109–1112. doi:10.1007/s00339-005-3316-z.
- 353 [15] R. G. Larson, *The structure and rheology of complex fluids*, Oxford Uni-
354 versity Press, New York, NY, 1999.
- 355 [16] A. Morozov, S. Spagnolie, Introduction to complex fluids, in: S. Spagnolie
356 (Ed.), *Complex fluids Biol. Syst.*, 1st Edition, Springer Verlag New York,
357 New York, NY, 2015, Ch. 1, pp. 3–52.
- 358 [17] F. A. Morrison, *Understanding rheology*, Oxford University Press, 2001.
- 359 [18] M. Cooke, J. Naughton, A. Kowalski, A simple measurement method for de-
360 termining the constants for the prediction of turbulent power in a silverson
361 ms 150/250 in-line rotor stator mixer, in: *Sixth International Symposium*
362 *on Mixing in Industrial Process Industries*, Niagara on the Lake, Niagara
363 Falls, Ontario, Canada, 2008.
- 364 [19] M. Cooke, T. Rodgers, A. Kowalski, Power consumption characteristics of
365 an in-line silverson high shear mixer, *AIChE Journal* 58 (6) (2012) 1683–
366 1692.
- 367 [20] G. Ozcan-Taskin, D. Kubicki, G. Padron, Power and flow characteristics of
368 three rotor-stator heads, *The Canadian Journal of Chemical Engineering*
369 89 (5) (2011) 1005–1017. doi:10.1002/cjce.20553.

- [21] S. Hall, M. Cooke, A. Pacek, A. Kowalski, D. Rothman, Scaling up of sil-
version rotor–stator mixers, *The Canadian Journal of Chemical Engineering*
89 (5) (2011) 1040–1050.
- [22] F. Archambeau, N. Mechitoua, M. Sakiz, Code Saturne: A Finite Volume
Code for Turbulent flows, *International Journal on Finite Volumes* 1 (1).
- [23] U. Ahmed, D. D. Apsley, I. Afgan, T. Stallard, P. K. Stansby, Fluctuating
loads on a tidal turbine due to velocity shear and turbulence: comparison
of CFD with field data, *Renew. Energy* 112 (2017) (2017) 235–246. doi:
10.1016/j.renene.2017.05.048.
- [24] N. Jarrin, S. Benhamadouche, D. R. Laurence, R. Prosser, A synthetic-
eddy-method for generating inflow conditions for large-eddy simula-
tions, *Int. J. Heat Fluid Flow* 27 (2006) 585–593. doi:10.1016/j.
ijheatfluidflow.2006.02.006.
- [25] N. Jarrin, R. Prosser, J. C. Uribe, S. Benhamadouche, D. R. Laurence,
Reconstruction of turbulent fluctuations for hybrid RANS/LES simulations
using a Synthetic-Eddy Method, *Int. J. Heat Fluid Flow* 30 (3) (2009) 435–
442. doi:10.1016/j.ijheatfluidflow.2009.02.016.
- [26] U. Ahmed, R. Prosser, Modelling flame turbulence interaction in RANS
simulation of premixed turbulent combustion, *Combust. Theory Model.*
20 (1) (2016) 34–57. doi:10.1080/13647830.2015.1115130.
- [27] U. Ahmed, R. Prosser, A Posteriori Assessment of Algebraic Scalar Dis-
sipation Models for RANS Simulation of Premixed Turbulent Combustion,
Flow, Turbul. Combust. 100 (1) (2018) 39–73. doi:10.1007/
s10494-017-9824-z.
- [28] F. Menter, Two-equation eddy-viscosity turbulence models for engineering
applications, *AIAA Journal* 32 (8) (1994) 269–289.