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# The effect of scale and interfacial tension on liquid–liquid dispersion in in-line Silverson rotor–stator mixers

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ABSTRACT

The effect of scale, processing conditions, interfacial tension and viscosity of the dispersed phase on power draw and drop size distributions in three in-line Silverson rotor–stator mixers was investigated with the aim to determine the most appropriate scaling up parameter. The largest mixer was a factory scale device, whilst the smallest was a laboratory scale mixer. All the mixers were geometrically similar and were fitted with double rotors and standard double emulsor stators. 1 wt.% silicone oils with viscosities of 9.4 mPa s and 339 mPa s in aqueous solutions of surfactant or ethanol were emulsified in single and multiple pass modes. The effect of rotor speed, flow rate, dispersed phase viscosity, interfacial tension and scale on drop size distributions was investigated.

It was found that for all three scales, power draw is the sum of the rotor and flow contributions, with proportionality constants, $Po_Z$ and $k_1$, that are practically scale independent. Sauter mean drop size appeared to correlate better with tip speed than energy dissipation rate. For ethanol/water solutions, mean drop size correlated well with Weber number based on interfacial tension, but for surfactant solutions effective interfacial tension gave better correlations with Weber number.



*Keywords:* Rotor–stator mixer; Emulsification; Scale-up; Tip speed; Energy dissipation rate; Weber number

## 1. Introduction

Mixing of two or more immiscible liquids to form a stable emulsion is an important processing step in the manufacture of products such as shampoos, salad dressings, bitumen, pharmaceuticals and many others, and is commonly carried out in in-line high shear rotor–stator mixers. In-line rotor–stator mixers are attractive as they can combine multiple process operations, and they may be used in continuous processing in a single pass mode or batch processing in a multiple pass mode.

Despite the widespread application of in-line rotor–stator mixers, the current understanding of their performance is still rather limited. Frequently, the development of new emulsion-based products is based on experience, and process parameters are typically selected by trial and error at increasing scales. To accurately scale-up emulsification in rotor–stator mixers it is important to understand the effect of process and formulation parameters on droplet size to predict and control the characteristic properties of multiphase products from the laboratory scale through to the manufacturing scale.

The first step in scaling up of high shear mixers is to determine the power draw necessary to accomplish the required degree of emulsification in two-phase systems. The full expression for power draw in turbulent flow is given by (Baldyga et al., 2007; Cooke et al., 2008; Kowalski, 2009):

$$P = Po_Z \rho N^3 D^5 + k_1 M N^2 D^2 \quad (1)$$

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## Nomenclature

*Symbols*

$A, A_1 \ldots A_x$ constants
$A_F$ fraction of outer stator open area
$A_h$ area of stator holes/openings ($m^2$)
$A_s$ surface area of stator ($m^2$)
B number of batch vessel turnovers
$b, b_1 \ldots b_x$ exponents
$C, C_1 \ldots C_x$ dimensionless empirical constants
$C_p$ specific heat capacity at constant pressure ($J\,(kg\,K)^{-1}$)
D rotor diameter (outer rotor) (m)
$D_{r,i}$ inner rotor diameter (m)
$D_{r,o}$ outer rotor diameter (m)
$D_{s,i}$ inner stator diameter (m)
$D_{s,o}$ outer stator diameter (m)
$d$ droplet diameter (m)
$d_{0,1}$ diameter below which 10% of the sample population reside (m)
$d_{0,5}$ number median diameter (m)
$d_{0,9}$ diameter below which 90% of the sample population reside (m)
$d_{32}$ volume surface mean diameter (Sauter mean drop diameter) (m)
$d_{max}$ maximum stable drop diameter (m)
$E_0$ Gibbs elasticity ($N\,m^{-1}$)
$E_{sd}$ surface dilational modulus ($N\,m^{-1}$)
$E_V$ energy density ($J\,m^{-3}$)
$f_V$ continuous volume frequency distribution
$HI$ homogenisation index
$h_r$ rotor height (m)
$h_s$ stator height (m)
$k_1$ 'flow' power constant
$M$ mass flow rate ($kg\,s^{-1}$)
N rotor speed ($s^{-1}$)
$n_{b,i}$ number of inner rotor blades
$n_{b,o}$ number of outer rotor blades
$n_h$ number of stator holes
$n_{hr}$ number of stator holes per row
$n_r$ number of stator rows
P power (W)
$P_h$ perimeter of stator openings (m)
$P_T$ 'torque on rotor shaft' power term (W)
$p$ pressure (Pa)
$\Delta p$ pressure difference across the mixing head (Pa)
$Po_Z$ 'zero flow' power constant
Q volumetric flow rate (impeller pumping capacity) ($m^3\,s^{-1}$)
$R^2$ coefficient of determination
s skewness for a log-normal distribution
t time (s)
$t_D$ diffusion adsorption time scale (s)
$t_{def}$ droplet deformation time scale (s)
$t_m$ mixing time (s)
$t_R$ total residence time in the mixing head (s)
$U_T$ tip speed ($m\,s^{-1}$)
$V_H$ volume of mixing head (swept outer rotor volume) ($m^3$)
$V_h$ homogenisation volume ($m^3$)
$V_T$ volume of mixing tank ($m^3$)
$w$ span for a log-normal distribution
$x, x_1, x_2$ exponents
$y, y_1, y_2$ exponents

*Greek symbols*

$\beta$ constant
$\Gamma$ surface excess concentration ($g\,m^{-2}$)
$\varepsilon$ mean energy dissipation rate per unit mass of fluid ($W\,kg^{-1}$)
$\varepsilon_T$ 'torque on rotor shaft' energy dissipation rate per unit mass of fluid ($W\,kg^{-1}$)
$\eta_K$ Kolmogoroff's length scale of turbulence (m)
$\theta$ temperature (K)
$\theta_b$ temperature due to bearing friction (K)
$\theta_c$ temperature correction between the temperature probes (K)
$\Delta\theta$ temperature difference across the mixing head (K)
$\mu$ fluid viscosity (Pa s)
$\mu_c$ continuous phase viscosity (Pa s)
$\mu_d$ dispersed phase viscosity (Pa s)
$\rho$ fluid density ($kg\,m^{-3}$)
$\rho_c$ continuous phase density ($kg\,m^{-3}$)
$\rho_d$ dispersed phase density ($kg\,m^{-3}$)
$\sigma$ surface/interfacial tension ($N\,m^{-1}$)
$\sigma_{eff}$ effective interfacial tension ($N\,m^{-1}$)
$\sigma_{rms}$ root mean squared difference
$\tau$ residence time (s)
$\tau_s$ cohesive surface tension stresses ($kg\,m^{-1}\,s^{-2}$)
$\tau_v$ cohesive viscous stresses ($kg\,m^{-1}\,s^{-2}$)

*Dimensionless groups*

$N_c$ circulation number, $\frac{Qt_m}{V_T}$
$N_Q$ flow number, $\frac{Q}{ND^3}$
$Po$ power number, $\frac{P}{\rho N^3 D^5}$
$Re$ Reynolds number, $\frac{\rho ND^2}{\mu}$
$We$ Weber number, $\frac{\rho_c N^2 D^3}{\sigma}$
$We_{eff}$ effective Weber number, $\frac{\rho_c N^2 D^3}{\sigma_{eff}}$

Eq. (1) has been validated for pilot plant (Kowalski et al., 2011) and small scale (Hall et al., 2011) Silverson mixers.

Expressions for Sauter mean diameter have been reported for a range of formulations and processing equipment, with most of the previous work summarised by Leng and Calabrese (2004). In many practical applications of geometrically similar devices it is convenient to correlate Sauter mean diameter with energy dissipation rate per unit mass or rotor tip speed:

$$d_{32} \propto \varepsilon^{b_1} \tag{2}$$

$$d_{32} \propto U_T^{b_2} \tag{3}$$

Theoretical correlations for maximum stable drop size in turbulent liquid–liquid dispersions are based on mechanistic models (Hinze, 1955), which assume that drops are broken if the disruptive stress is greater than the cohesive stress (Leng and Calabrese, 2004). The disruptive stress is related to energy dissipation rate calculated within a cascade model of homogeneous isotropic turbulence. In dilute liquid–liquid systems with low viscosity dispersed phases, viscous stresses are negligible and only cohesive forces due to interfacial tension