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Short communication

Rotor–stator devices: The role of shear and the stator

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ABSTRACT

High shear rotor–stator mixers are widely used in process industries including the manufacture of many food, cosmetic, pharmaceutical, and health care products. Many of these products involve emulsification where the drop size distribution affects the processing and the product properties. Therefore, an understanding of the mechanisms that breaks the drops is key for any design process. In rotor–stator devices there are two main mechanisms that can break drops, one due to the rotor and one due to the stator. For the inviscid systems studied, this article shows that when a rotor–stator device is used in a recycle loop the effective equilibrium drop size is largely unaffected by the presence of the stator and is mainly dependant on the rotor. The article also goes on to show that the effective equilibrium drop size data can be correlated on the agitator shear rate.

Keywords: Rotor–stator devices; Shear rate; Equilibrium drop size

1. Introduction

High shear rotor–stator mixers are widely used in process industries including the manufacture of many food, cosmetic, pharmaceutical, and health care products. Rotor–stator devices provide a focused delivery of energy, power and shear to accelerate physical processes such as mixing, dissolution, emulsification, and de-agglomeration. To reliably scale-up these devices we need to understand the relationship between rotor speed, flow rate, shear rate, and the energy dissipated by these devices.

For emulsification, the drop size distribution affects the processing and the product properties. In a two-phase process, the mass transfer rate between the phases is proportional to the interfacial area. This interfacial area changes with the drop size distribution which varies with the conditions inside the vessel and time. Hence successful process design depends on developing a mechanistic understanding of drop break-up in these reactors. There are two competing theories on drop break-up mechanisms. These are break-up due to turbulent eddies, i.e. energy dissipation rate, and break-up due to the agitator shear rate.

Break-up due to turbulent eddies is generally based on the work of Kolmogorov (1949) and (Hinze, 1955) which utilises the concept of eddy turbulence to define a limiting drop size. It is usually assumed that drop break-up occurs due to the interactions of drops with the turbulent eddies of sufficient energy to break the drop (Liao and Lucas, 2009).

Therefore, for a given fluid system the effective equilibrium drop size (this is the drop size after a sensible processing time, when the drop size reduction with time is very small and almost unmeasurable) is dependent on the energy per unit mass and thus should scale-up with this value when using geometrically similar vessels. For low viscosity dispersed phase dilute liquid–liquid systems, the drops are inviscid since the internal viscous stresses are negligible and only the interfacial tension surface force contributes to stability. The maximum stable equilibrium drop size, $d_{\max}$ can be related to the maximum local energy dissipation rate, $\epsilon_{\max}$, by Eq. (1) for isotropic turbulence (Leng and Calabrese, 2004; Davies, 1987).

$$d_{\max} = C_1 \left(\frac{\sigma}{\rho}\right)^{3/5} \epsilon_{\max}^{-2/5} \tag{1}$$

Fig. 1 presents drop size data from previously published literature for a silicone oil and water system as a function of the energy dissipation rate, ϵ; the gradient of the line has been set to $-2/5$ in agreement with Eq. (1). The lack of

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Nomenclature

D	agitator diameter (m)
$d_{3,2}$	volume to surface average diameter (m)
d_{max}	maximum stable diameter (m)
k_1	power flow constant
K_S	Metzner–Otto constant
N	agitation rate (s^{-1})
P	power (W)
Q	flow rate ($kg\,s^{-1}$)
ϵ	energy dissipation rate ($W\,kg^{-1}$)
ρ	density ($kg\,m^{-3}$)
N_Q	flow number ($=Q/\rho ND^3$)
Po	power number ($=P/(\rho N^3D^5)$)
Po_z	power number at zero flow rate ($=P/(\rho N^3D^5)$)
Re	Reynolds number ($=\rho ND^2/\mu$)

correlation between the effective equilibrium drop size and energy dissipation rate seems to point to the fact that this may not be the correct mechanism. This is not surprising since this theory applies to isotropic turbulence in the universal equilibrium regime, whereas it is known that breakup occurs close to the agitator where the turbulence is both non-isotropic and intermittent.

Break-up due to the agitator shear rate is based on a balance between the external viscous stresses and the surface tension forces (Liao and Lucas, 2009). If the break-up is due to the agitator shear rate then the effective equilibrium drop size is related to the maximum shear rate. This would mean that lower power number agitators can produce smaller drops than higher power number agitators, as low power number agitators may have a higher shear rate. This has been seen experimentally by Zhou and Kresta (1998). Bałdyga et al. (2001) states when scale-up is performed on a constant energy dissipation rate, smaller drops are observed at larger scales. This is likely due to the shear rate increasing at larger scales when the energy dissipation rate is kept constant.

The maximum shear rate is proportional to the agitator tip speed (Paul et al., 2004); however, this maximum shear rate constant is difficult to measure for all systems. It makes physical sense that this maximum shear rate constant is proportional to an average shear rate constant. Although, it is strictly only applicable in the laminar regime (Doraiswamy et al., 1994), the Metzner–Otto constant, K_S, is a good measure of the average shear rate near the impeller. It has been claimed that for power law fluids K_s varies with the power law index although for practical considerations this affect has found to be small. Tanguy and Thibault (1996) concluded that for practical considerations a constant value of K_S can be considered for shear thinning and shear thickening fluids. K_S has been found to vary linearly with the agitator flow number which is a function of Reynolds number (Wu et al., 2006). However, in the turbulent regime the flow number is constant, so again we have a constant (though higher) value of K_S.

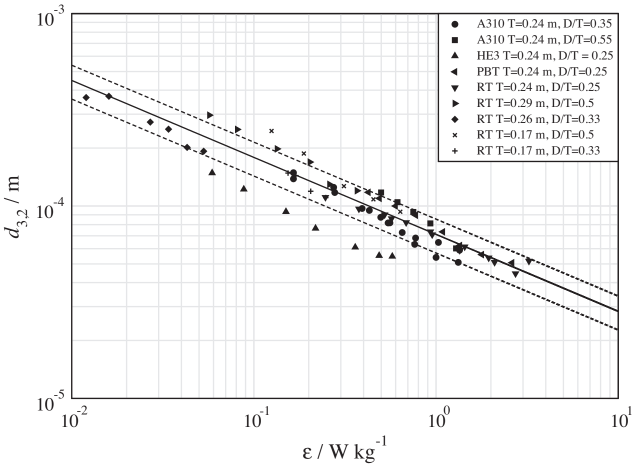

Fig. 1 – Variation of mean effective equilibrium drop size for a 5 cSt silicon oil and water system against the power per unit mass. Data taken from Zhou and Kresta (1998) and Musgrove and Ruszkowski (2000). Dotted lines are 20% from the best fit.

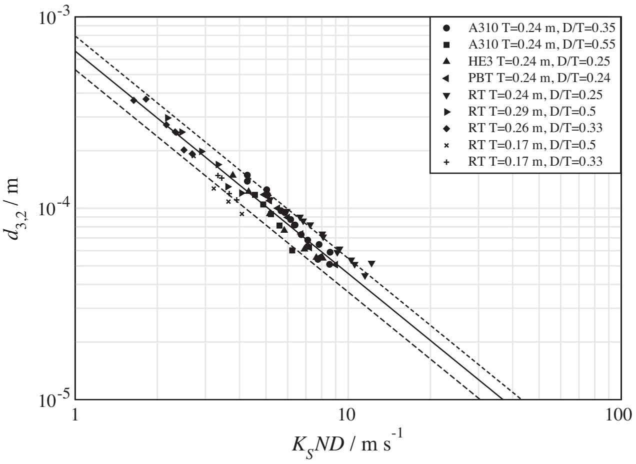

Fig. 2 – Variation of mean effective equilibrium drop size for a 5 cSt silicon oil and water system against the agitator blade shear rate. Data taken from Zhou and Kresta (1998) and Musgrove and Ruszkowski (2000). Dotted lines are 20% from the best fit.

This means the correlative shear rate used will be K_SND, i.e. the proportional constant multiplied by the tip speed. It should be noted here that this shear rate technically has units of $m\,s^{-1}$ instead of s^{-1}, but as previously mentioned, this is just a representative value as the true value is proportional to K_SND, which means that this proportionality constant must have units of m^{-1}.

Fig. 2 presents drop size data for a silicone oil and water system as a function of the agitator blade shear rate, K_SND, the best fit line gradient is equal to −1.2. The fact that all the values lie on the same line points towards shear rate being the dominant break-up mechanism.

Neither of these two mechanisms will predict the correct values for the drop size if the system undergoes coalescence. If there is coalescence within the system the bulk flow from the agitator is important as well, as this effects the circulation time, thus the time away from breakage. The systems studied within this paper are non-coalescing systems, which was checked over a period of several days.

2. Methodology

The experimental rig (Fig. 3) consists of an agitated mixing tank with an in-line Silverson 150/250 MS high shear rotor–stator mixer (Silverson Machines Ltd., Chesham, UK). The mixing tank has a 60 L capacity with a diameter of 0.420 m. To allow both analysis of equilibrium drop sizes and single pass drop size data the mixing tank was connected to the