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Comparative performance of in-line rotor-stators for deagglomeration processes

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HIGHLIGHTS

- Mechanism of break up could be demonstrated to be erosion.
- Dispersion fineness is limited by the aggregate size: ~ 150–200 nm.
- Kinetics of break up could be quantified; effect of operating conditions identified.
- Effect of rotor-stator design (size and nb of holes and gap) on breakup discussed.

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ABSTRACT

In-line rotor-stators are used for a wide range of power intensive dispersion applications, including the breakup of immiscible liquid droplets or agglomerates. This study, performed within the DOMINO project at BHR Group, aimed at studying the performance of three different rotor-stator head designs for deagglomeration processes. A given test system, nanoscale silica particles-in-water, was used to identify the mechanism and kinetics of break-up and determine the smallest attainable size. Three rotor-stator head designs used were the GPDH-SQHS and EMSC screens from Silverson and Ytron Z-Lab from Ytron. These in-line rotor-stators were used in the recirculation loop of a stirred tank with a total dispersion volume of 100 l. Power input and residence time were varied by changing the rotor speed and dispersion flow rate. Breakup was found to occur through erosion regardless of the operating conditions or rotor-stator design. The smalleachieves a higher fraction of finesst fragments obtained were aggregates, rather than primary particles, and these were of a mean diameter of 150–200 nm; also independent of the operating conditions or rotor-stator head design. With a given rotor-stator operated at a given flow rate, increasing the rotor speed and hence the power input increased the break up kinetics. For a given design at a given specific power input, whilst the break up rate per tank turnover decreased when the flow rate was increased, the total processing time could be reduced. There were differences in the volume of the mixer head and chamber volumes; in addition, a smaller flow rate range could be covered with the Ytron design. Comparison of the different designs was therefore not straightforward. It could however be shown that the rotor-stator designs with a high number and small size of holes and/or gaps have a faster break up rate.

1. Introduction

Whilst the specific design of rotor-stators varies, high operating speeds (thousands of rpm) and flow through small openings (either small holes on the screens or gaps between the teeth and screens), which result in high levels of local energy dissipation rate and liquid velocities in the mixer head, are common features of these devices. They are therefore used in a range of power intensive applications for break up (of agglomerates or droplets), fast chemical reactions or foam generation. Zhang et al. (2012) provide a review of applications along with flow and power characteristics of different batch and in-line rotor stators relating to rotor-stators.

The findings reported in this paper, performed within the DOMINO project run at BHR Group, aimed at investigating the deagglomeration of nanoparticle clusters in a liquid with different in-line rotor-stator heads. Other process devices used by previous

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Abbreviations: CFD, Computational Fluid Dynamics; PBT, Pitched Blade Turbine; PSD, Particle Size Distribution

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Nomenclature

C	Off-bottom clearance of the impeller m
D	Impeller or rotor diameter m
d_{32}	Sauter mean diameter (area-weighted average particle size) μm
e	Electron charge C
F	Fines volume fraction -
F_T	Interaction forces acting on agglomerates N
F_A	Attractive forces acting on agglomerates N
F_R	Repulsive forces acting on agglomerates N
H	Surface to surface distance m
Ha	Hamaker constant J
k_b	Boltzman constant J K^{-1}
l	Macroscale of turbulence m
L_a	Aggregate size m
L_i	Agglomerate size m
N	Impeller or rotor speed s^{-1}
N_c	Number concentration of particles m^{-3}
N_T	Number of tank turnovers -
P	Power input W
Po_1	Rotor-stator power number 1 -
Po_2	Rotor-stator power number 2 -
Q	Volumetric flow rate m^3 s^{-1}
q_1	Particle size distribution function at the rotor-stator inlet -
q_2	Particle size distribution function at the rotor-stator outlet -
q_c	Coarse particle size distribution function -
q_f	Fines particle size distribution function -
R	Particle radius m
T	Tank diameter m
T	Temperature in Eq. (4) K
$t_{res}{}^{C}$	Residence time in the rotor-stator chamber s
$t_{res}{}^{MH}$	Residence time in the rotor-stator mixing head s
V	Volume of dispersion m^3
V_C	Volume of the rotor-stator mixing chamber m^3
V_{MH}	Volume of the rotor-stator mixing head m^3
V_{Tank}	Volume of dispersion in the tank m^3
z	Valence of ions -
Z	Fines volume fraction generated in a single pass through the rotor-stator -

Greek

Γ	Breakup frequency s^{-1}
λ_k	Kolmogorov microscale m
ε_a	Porosity of nanoparticle clusters -
σ_T	Tensile strength of agglomerates Pa
κ	Reciprocal of the double layer thickness m^{-1}
ψ_0	Surface potential due to the surface charge on the particle V
ε	Average volume fraction of aggregates -
$\bar{\varepsilon}$	Average volume fraction of aggregates -
χ	Static permittivity -
τ	Turbulence stresses acting on agglomerates Pa
ρ	Dispersion density kg m^{-3}
ν	Kinematic viscosity m^2 s^{-1}

researchers include the sawtooth impeller (Xie et al., 2007), batch rotor- stator (Xie et al., 2007; Pacek et al., 2007), high pressure devices (Xie et al., 2008; Sauter and Schuchmann, 2012), stirred bead mills (Kowalski et al., 2008, Schilde et al., 2011) and ultrasonicators (Sauter et al., 2006, 2008). Some of the studies included numerical modelling to develop both an understanding of the flows within process devices which are not accessible for measurements and also models describing the deagglomeration process (Baldyga et al., 2006, 2007a, 2007b, 2008a, 2008b, 2009). Different equipment suit different purposes for example, ultrasonic dispersers and batch rotor-stators are typically used at smaller scales, high pressure devices as secondary devices, i.e. once the dispersion has reached a certain degree of fineness so that the nozzles or channels will not be blocked, stirred bead mills for concentrated dispersions (above about 15% w-w). Different inline rotor-stator designs used in this study were the General Purpose Disintegrating Head (GPDH) with an outer Square Hole Screen (SQHS) or Emulsor Screen (EMSC) with the Silverson 150/250MS and Ytron Z-Lab. The study follows on from our previously reported work on the flow and power characteristics of these rotor-stator heads in a single phase system (Özcan-Taşkın et al., 2011). The characteristic power numbers, Po_1 and Po_2, from Eq. (1) are listed in Table 1.

$$P = Po_1 \rho N^3 D^5 + Po_2 \rho N^2 D^2 Q \tag{1}$$

where P is the power (W), ρ the dispersion density (kg/m^3), N the rotor speed (s^{-1}), D the rotor diameter (m) and Q the volumetric flow rate through the rotor-stator (m^3/s).

The Computational Fluid Dynamics (CFD) study revealed important features of the flow field generated by these rotor-stator heads. The zone of high energy dissipation rate was found to be located between the inner rotor and outer screen and within jets when using the GPDH–SQHS and EMSC geometries, where breakage would be expected to occur. With the Ytron Z mixer, a more uniform distribution of the energy dissipation rate was noted throughout the whole chamber, which is only slightly larger than the rotor-stator head and pumping wheel assembly (Özcan-Taşkın et al., 2011). In addition, the fluid in the chamber appeared to be re-circulated back into the mixer head when using the GPDH–SQHS and EMSC designs, with a higher circulation flow for the EMSC. This means that the dispersion can enter the zone of high energy dissipation rate many times during one pass through the GPDH–SQHS and EMSC. This effect was not observed in the Ytron Z geometry, which occupied practically the whole chamber, and recirculation was mainly within the teeth of the stator.

Table 1
Power numbers for the three rotor-stator geometries (Özcan-Taşkın et al., 2011).

	Po_1	Po_2
GPDH-SQHS	**0.13**	**9.1**
EMSC	**0.11**	**10.5**
Ytron Z Lab	**0.18**	**10.6**

Commercially available nanoparticle powders typically exist in the form of much larger clusters. Of these, aggregates are held together by sintering bridges and cannot be broken up, but agglomerates, which are held together by weaker bonds such as, van-der-Waals and hydrogen bonds, can be disintegrated further provided that the energy input in the processing environment is sufficiently high (Bałdyga et al., 2008a). The following expression proposed by Tang et al. (2001) based on the earlier work by Rumpf (1962) has commonly been used to calculate the tensile strength of agglomerates, σ_T, (Baldyga et al., 2006, 2007a, 2007b; Özcan-Taşkın et al., 2009) which is related to the porosity of the