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Experimental investigations of turbulent fragmenting stresses in a rotor-stator mixer. Part 1. Estimation of turbulent stresses and comparison to breakup visualizations

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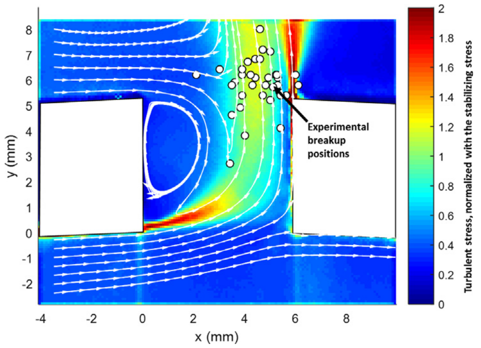
HIGHLIGHTS

- Two methods of estimating turbulent fragmenting stresses from PIV are suggested.
- Methods are compared on validity, reliability and compared to breakup visualizations.
- Both methods have limitations but result in similar estimations of stress.
- Three regions of high stress are identified in the rotor-stator region.
- Stress levels and spatial distribution complies with breakup visualizations.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite large industrial relevance, the relation between rotor-stator geometry, hydrodynamics and drop breakup is poorly understood, partly since no methods for measuring the fragmenting stresses acting on drops have been established. This study attempts to bridge this gap by developing, applying and evaluating two approaches for estimating local turbulent stresses based on particle image velocimetry data: namely one traditional but indirect approach based on the dissipation rate of turbulent kinetic energy, and another more direct approach based on the spatial turbulent spectrum that has proven useful in other high-intensity emulsification processing. The approaches are evaluated in terms of validity of underlying assumptions, how they compare to breakup visualizations in the same geometry and with regard to the reliability of primary measurables.

Results show three consistent regions of high stress in the rotor-stator region: in a plume extending into the stator-hole from the trailing edge, in the shear layers of the jet exiting the hole and in the macroscopic flow structure formed after the rotor blocks a stator hole. Following a drop travelling along an average velocity flow field, the measurement predict disrupting stresses exceeding the stabilizing stress at the stator hole exit, at approximately the same position where drop breakup is observed in breakup visualizations. Both methods are therefore able to predict the most likely breakup positions. It is also concluded that both methods have limitations, and that average stress alone cannot describe all aspects of the fragmentation process in rotor-stator mixers.

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Nomenclature

Abbreviations

CFD	computational fluid dynamics
FOV	field of view
ILT	intermediary length-scale TKE (approach for estimating stresses)
LDA	laser Doppler anemometry
LES	large eddy simulation
PIV	particle image velocimetry
RANS	Reynolds averaged Navier Stokes
RSM	rotor-stator mixer
SGD	sub grid-scale dissipation (approach for estimating stresses)
SGS	sub grid-scale (model)
TKE	turbulent kinetic energy

Latin symbols

C	constant in Eq. (14), –
C_S	Smagorinsky-Lilly constant, –
D	rotor diameter, m
E	turbulent power spectrum, $m^3\ m^{-2}$
E_{ii}	one dimensional power spectrum, $m^3\ m^{-2}$
G_d	intermediary length-scale velocity gradients, s^{-1}
H	stator slot height, m
k	turbulent kinetic energy, $m^2\ s^{-2}$
k_d	intermediate length-scale turbulent kinetic energy, $m^2\ s^{-2}$
$k_d^{(x)}$, $k_d^{(y)}$	x- and y-components of k_d, $m^2\ s^{-2}$
L	integral length-scale, m
l_d	limiting eddy length-scale ($l_d = 3\ d$), m
l_{DI}	lower limiting eddy length-scale of the inertial sub-range, m
l_e	eddy length-scale, m
l_{EI}	upper limiting eddy length-scale of the inertial sub-range, m
N	rotor speed, s^{-1}
N_P	power number, –
N_{slots}	number of stator slots, –
P_{shaft}	shaft power-draw, W
P_ε	total dissipated power accounted for by the measurements, W
r	distance, m
Re_λ	Taylor-scale Reynolds number, –
R_{ii}	autocorrelation, $m^2\ s^{-2}$
U	rotor tip-speed, $m\ s^{-1}$
u, v	velocity fluctuations, x- and y-components respectively, $m\ s^{-1}$
V	volume, m^3
w	stator slot width, m
x,y	stator-hole coordinate system (see Fig. 2)

Greek symbols

α	constant in Eq. (9), –
γ	interfacial tension, N m
Δ	PIV resolution, m
ε	dissipation rate of TKE, $m^2\ s^{-3}$
ε_{SGS}	SGS modeled dissipation rate of TKE, $m^2\ s^{-3}$
η	Kolmogorov length-scale, m
κ	wave number, m^{-1}
μ_D	disperse phase dynamic viscosity, Pa s
ν_C	continuous phase kinematic viscosity, m^2 s
ρ_C	continuous phase density, $kg\ m^{-3}$
σ	turbulent fragmenting stress, Pa
σ_{stab}	total stabilizing stress ($\sigma_{stab,1} + \sigma_{stab,2}$), Pa
$\sigma_{stab,i}$	stabilizing stresses due to Laplace pressure ($i = 1$) and viscous resistance ($i = 2$), Pa
$\sigma_{TI,TV}$	fragmenting stress in the turbulent inertial (TI) and turbulent viscous (TV) regimes, Pa
φ	angular rotor position, see Fig. 2, °

1. Introduction

Although commonly used for mixing and dispersion in the processing industry, fundamental knowledge of rotor-stator mixers (RSMs) (also known as high-shear mixers), is poor (Atiemo-Obeng and Calabrese, 2004, 2016; Zhang et al., 2012). The general principle of the RSM is that the rotor accelerates the fluid radially through one or several perforated stator screens, giving rise to intense turbulence upstream, inside or downstream the stator holes or slots. New insights have been obtained recently from single-drop breakup visualizations in RSM systems, showing drops in a batch RSM breaking downstream of the stator hole exit (Ashar et al., submitted for publication). However, the details of how hydrodynamic structures give rise to drop fragmentation and how RSM design influences hydrodynamics is still largely unknown. One reason for this is that no experimental technique for quantifying disruptive stresses has yet been developed or applied to RSMs.

From a theoretical perspective, turbulent stresses on the drop interface determine the dispersion efficiency (Kolmogorov, 1949; Hinze, 1955). However, the RSM flow field and turbulence are highly inhomogeneous (Mortensen et al., 2011; Utomo et al., 2009; Xu et al., 2014). Therefore, any fundamental understanding of RSM must be based on a local characterization of the turbulent flow. Experimental methods such as laser Doppler anemometry (LDA) (Utomo et al., 2009; Xu et al., 2014) and particle image velocimetry (PIV) (Mortensen et al., 2011) have been used to describe local fluid velocity fields and turbulent kinetic energy (TKE) in the rotor-stator region. Although these studies have increased our general understanding of the flow, they do not offer any suggestions for how to estimate turbulent fragmenting stresses.

The traditional approach for estimating turbulent stresses is from the dissipation rate of TKE (ε). Under a number of assumptions (homogeneous and isotropic turbulence, fragmenting drop with diameters inside the inertial subrange of the power spectrum and fragmentation in the inertial regime) the fragmenting stress (σ) scales with the dissipation rate of TKE (Hinze, 1955; Walstra, 2005):

$$\sigma \propto \varepsilon^{2/3} \tag{1}$$

Based on Eq. (1), the local maximum dissipation rate of TKE is often used for describing mixing and dispersion efficiency in impeller mixers (Zhou and Kresta, 1996, 1998). Several computational fluid dynamic (CFD) studies have reported local fields of dissipation rate of TKE for RSMs (Jasinska et al., 2015; Özcan-Taskin et al., 2011; Utomo et al., 2008, 2009; Xu et al., 2014). In some situations, such as mixing, these local CFD-predictions of ε appears to describe much of the process (Jasinska et al., 2013). However, except the large eddy simulation (LES) by Xu et al. (2014), previous CFD-studies are based on Reynolds averaged Navier Stokes (RANS) with two-equation closure of the turbulence modeling. This is