Chemical Engineering Science 171 (2017) 638–649

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Experimental investigations of turbulent fragmenting stresses in a rotor-stator mixer. Part 2. Probability distributions of instantaneous stresses

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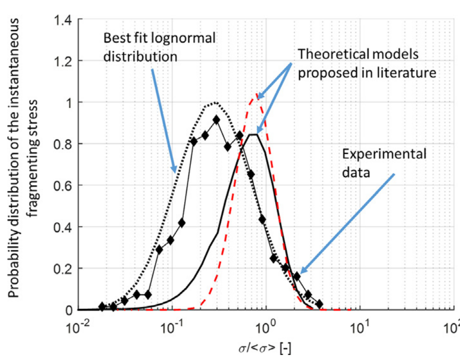
HIGHLIGHTS

- Instantaneous local turbulent stresses in the RSM were measure using PIV.
- It is concluded that stress distributions are approximately lognormal.
- The stress distribution width varies with rotor speed and position.
- Previously suggested models underestimate the distribution width.
- Even positions with low average stress have significant breakup probabilities.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 April 2017
Received in revised form 14 June 2017
Accepted 21 June 2017
Available online 23 June 2017

Keywords:
Rotor-stator mixer
High-shear mixer
Fragmentation
Turbulence
Intermittency
Emulsification
Mixing

ABSTRACT

Drop fragmentation in high intensity turbulent emulsification processing equipment–such as rotor-stator mixers (RSMs)–has traditionally been described in terms of a stress balance; between the stabilizing stress of the drop and the time-averaged turbulent stress at the most intense position of the flow. As shown in part 1 of this series, this approach is often a fruitful first approximation. However, the instantaneous local stress experienced by drops differs from the time-averaged local stress due to hydrodynamics in general and the stochastic nature of a turbulent flow in particular.

This study estimates the probability distribution of instantaneous turbulent stresses in an RSM from velocity fields obtained using particle image velocimetry. Results show that regions with low average stress still have a substantial probability of having instantaneously high stresses. This explains why low probability breakup is observed at these positions in visualization experiments.

Results also show that the probability distribution of instantaneous stresses is approximately lognormal. The results are compared to two commonly used models for how to take the stochastic variations into account: the exponential decay model, and the multifractal emulsification model. It is concluded that both models predict reasonable distributions shapes but underestimate the width of the stress distribution.

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http://dx.doi.org/10.1016/j.ces.2017.06.038

Nomenclature

Abbreviations

FOV	field of view
LES	large eddy simulation
PIV	particle image velocimetry
RSM	rotor-stator mixer
TKE	turbulent kinetic energy

Latin symbols

a_1–a_5	fitting constants in Eq. (21), –
C, C_L, C_η, p_0, β	model constants in Eq. (11), –
C_{ED}	constant in the ED model, –
C_{MF}	normalization constant in the MF model, –
C_S	Smagorinsky-Lily coefficient, –
d	drop diameter, m
D	rotor diameter, m
E	turbulent power spectrum, m^3 m^{-2}
$f(a)$	multifractal spectra, –
$F(l)$	normalized number density of turbulent eddies, –
f_L f_η	high and low wave number modifications to the model spectrum, –
H	stator slot height, m
I	number of measured instantaneous velocity fields, –
k	TKE, m^2 s^{-2}
$k'(l)$	TKE of a single eddy of length-scale l, m^2 s^{-2}
k_d	TKE contained in intermediary length-scale eddies ($\eta < l < l_d$), m^2 s^{-2}
l	Eddy length-scale, m
L	turbulent integral length-scale, m
l_d	limiting eddy length-scale, m
N	rotor speed, s^{-1}
$n(l)dl$	number density of turbulent eddies, m^{-3}
P	probability, –
p_1, p_2	parameters in the lognormal distribution, –
Re	RSM Reynolds number, –
Re_L	turbulent Reynolds number, –
T	tank diameter, m
u, v	instantaneous velocity in x and y directions, m s^{-1}
w	stator slot width, m
We	Weber number, –
x, y, z	coordinates, m

Greek symbols

γ	interfacial tension, N m^{-1}
Δ	spatial resolution of the PIV fields, m
η	Kolmogorov length-scale, m
κ	wave number, m^{-1}
μ_D	disperse phase viscosity, Pa s
ν	fluid viscosity, m^2 s^{-1}
ρ_C	continuous phase density, kg m^{-3}
ρ_D	disperse phase density, kg m^{-3}
σ	turbulent fragmenting stress, Pa
σ_{stab}	stabilizing stress, Pa
φ	rotor position, °

Operators

$\langle\cdot\rangle$	averaging over the instantaneous fields
std$(\cdot)$	standard deviation over the instantaneous fields
skew $(\cdot)$	skewness deviation over the instantaneous fields

1. Introduction

Rotor-stator mixers (RSMs) (also referred to as high-shear mixers) are commonly used for emulsification and mixing in chemical engineering processing. Although significant advances have been made during the last decade, the drop breakup process and its relation to RSM hydrodynamics are still relatively poorly understood (Atiemo-Obeng and Calabrese, 2004, 2016). This can be seen most clearly when comparing it to other emulsification processes, such as the high-pressure homogenizer, where a large number of breakup visualization studies and experimental hydrodynamic investigations are now available, which has led to a substantial increase in the general understanding (see Bisten and Schuchmann, 2016 for a recent review). By analogy, we suggest that in-depth experimental characterization of RSM hydrodynamics and comparisons to drop breakup visualization could provide new insights into RSM emulsification as well.

The RSM gives rise to a highly turbulent flow (Mortensen et al., 2011) and drop breakup visualizations suggest a turbulent mechanism of drop breakup (Ashar et al., submitted for publication). Traditionally, theoretical attempts to predict or correlate drop diameters resulting from turbulent emulsification to design and operating conditions have been based on a stress analysis, comparing the average turbulent disruptive stress, $\langle\sigma\rangle$, to the stabilizing stress, σ_{stab}. The ratio between the average fragmenting stress and the stabilizing stress defines a dimensionless number

$$We = \frac{\langle\sigma\rangle}{\sigma_{stab}}. \quad (1)$$

Stabilization occurs due to Laplace pressure and viscous resistance (Calabrese et al., 1986; Davies, 1985; Hinze, 1955; Vankova et al., 2007),

$$\sigma_{stab} = \frac{4\gamma}{d} + \frac{\mu_D}{d}\sqrt{\frac{\langle\sigma\rangle}{\rho_D}}. \quad (2)$$

Eq. (1) has traditionally, either by itself or in combination with other dimensionless numbers, been used to model under which conditions drops break and for interpreting emulsification experiments (e.g. Boxall et al., 2012; Calabrese et al., 1986; Gupta et al., 2016; Hinze, 1955). This approach to modeling stable drop diameters is often referred to as the Kolmogorov-Hinze theory.

The traditional approach has proven useful as a first approximation. However, it has often given unsatisfactory results for predictions, especially for RSMs (Håkansson et al., 2017; Hall et al., 2013). Moreover, the Kolmogorov-Hinze theory relies on two assumptions that can be questioned. First, it assumes that the three-dimensional turbulent flow can be characterized by a single mean-efficient or maximum stress level, often estimated from the mean effective or maximum dissipation rate of turbulent kinetic energy (TKE). However, the turbulent flow in emulsification equipment is inhomogeneous (Håkansson et al., 2011; Kresta and Wood, 1993; Mortensen et al., 2011; Utomo et al., 2009; Xu et al., 2014), which must be taken into consideration when discussing drop breakup.

Secondly, the turbulent stress at each location in the flow is not constant. Instantaneous stresses do not equal the average stress (as assumed in the Kolmogorov-Hinze theory) but vary stochastically over time. This complication to the Kolmogorov-Hinze theory was noted by Kolmogorov (1949) in his original discussion of drop breakup, and he continued investigating the effect in later studies (Kolmogorov, 1962). These stochastic fluctuations have been extensively studied in fluid mechanics literature and are often referred to as "intermittency" (Pope, 2000, p. 259; Sreenivasan, 2004). However, with a few notable exceptions (Baldyga and