Chemical Engineering Science 177 (2018) 139–150

Contents lists available at ScienceDirect

Chemical Engineering Science

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

An experimental investigation of the probability distribution of turbulent fragmenting stresses in a high-pressure homogenizer

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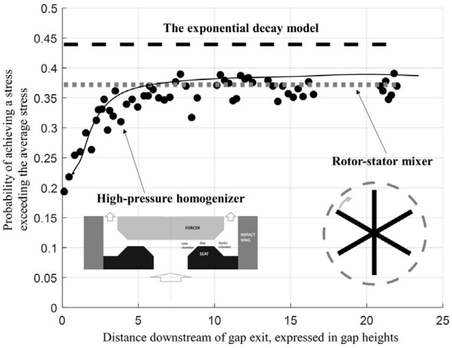
HIGHLIGHTS

- Particle image velocimetry was used to measure stress distributions in HPHs.
- Measured distributions are skewed and lognormal.
- Distributions in the HPH and the RSM are highly similar.
- Distributions in both systems deviate substantially from the commonly used model.
- This suggests that new fragmentation rate models are needed for RSMs and HPHs.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 August 2017
Received in revised form 9 October 2017
Accepted 27 November 2017
Available online 28 November 2017

Keywords:
Emulsification
Turbulence
Fragmentation
High-pressure homogenizer
Rotor-stator mixer

ABSTRACT

The high-pressure homogenizer (HPH) is, together with the rotor–stator mixer (RSM), the standard equipment for emulsification in many fields of chemical processing. Both give rise to intense turbulence which, in turn, gives rise to drop breakup. Previous investigations focus on average turbulent disruptive stress. However, turbulence is a stochastic phenomenon and drop breakup will be characterized by instantaneous stresses, or more specifically by the probability distribution of instantaneous turbulent stresses.

This study uses high-resolution particle image velocimetry (PIV) data to measure the probability distribution of turbulent stresses in the HPH. It is concluded that stress distributions approximately follow a lognormal model and that the skewness of the distributions decreases with increasing distance from the gap exit until a constant distribution shape is obtained at the position where the turbulence is fully developed. This converged stress distribution is similar to that obtained for RSMs in previous studies, suggesting that stress distribution shape is a general property. Moreover, large differences are observed when comparing these experimental stress distributions to the most widely used expression for describing this stochastic effect in fragmentation rate models. This indicates that the traditionally used fragmentation rate models can be fundamentally flawed, at least in relation to RSM and HPH emulsification.

1. Introduction

The high-pressure homogenizer (HPH) is among the most commonly used techniques for high intensity emulsification. It is considered the standard method for low to intermediate viscosity emulsification in food, pharmaceutical and cosmetics processing (Schultz, 2004). The HPH includes a high-capacity pump (~10–100 MPa), accelerating the fluid through an annular valve with a narrow gap (~10–100 μm). Upon exiting the gap, the average fluid kinetic energy is converted to turbulence that fragments

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https://doi.org/10.1016/j.ces.2017.11.045

Nomenclature

Abbreviations

CFD	Computational fluid dynamics
ED	Exponential decay (model)
HPH	High-pressure homogenizer
PIV	Particle image velocimetry
RSM	Rotor-stator mixer
TKE	Turbulent kinetic energy

Latin symbols

$\|U\|$	velocity magnitude, m/s
c	constant in Eq. (1), –
C_H	constant, –
d	emulsion drop diameter, m
e	eddy-energy, J
E	power spectrum of TKE, $m^3 s^{-3}$
E_{ii}	one dimensional power spectrum, $m^3 s^{-3}$
f_L, f_η	model functions in the model spectrum, –
h	gap height, m
k_d	TKE of small to intermediate length-scales, $m^2 s^{-2}$
l_d	limiting eddy length-scale ($l_d = 3d$), m
m_1, m_2, m_3	statistical moments of the stress distribution
Oh	Ohnesorge number, –
P	probability, –
q	probability of exceeding the average stress, –
R_{ii}	autocorrelation, $m^2 s^{-2}$
U_g	gap velocity, m/s
We	Weber number, –
x, y	coordinate system in the outlet chamber, m

Greek symbols

γ	interfacial tension, N m^{-1}
ε	dissipation rate of TKE, $m^2 s^{-3}$
η	Kolmogorov length-scale, m
μ_D	disperse phase viscosity, Pa s
ν_C	continuous phase viscosity, $m^2 s^{-1}$
ρ_C	continuous phase density, kg m^{-3}
σ	turbulent fragmenting stress, Pa
σ_{stab}	stabilizing stress, Pa
τ	eddy transport time-scale, s

the drops (Bisten and Schuchmann, 2016; Håkansson et al., 2011; Innings et al., 2011). (In addition to turbulence, cavitation does also play a role in the emulsification in HPHs, see the discussion by Bisten and Schuchmann, 2016). A schematic illustration of the HPH valve can be seen in Fig. 1A.

The rotor-stator mixer (RSM), also referred to as the high-shear mixer, is often considered the standard method for emulsification of products with high fluid viscosity (e.g. due to high volume fraction of dispersed phase) (Schultz, 2004). Experiments reveal that drop breakup in the RSM is also due to turbulence (Ashar et al., submitted for publication; Håkansson et al., 2017a), however, the source of this turbulent field differs from the HPH. The RSM consists of a rotor mounted inside of a perforated stator screen. The rotor accelerates the fluid and forces it radially through the stator slots, giving rise to a turbulent jet adhering to the leading stator slot wall (Mortensen et al., 2011, 2017, submitted for publication; Utomo et al., 2008; Xu et al., 2014). The RSM flow is periodic with the rotor frequency (Mortensen et al., 2011), as is the turbulence created in the slot (Håkansson et al., 2017a). A schematic illustration of the rotor-stator region of the RSM can be seen in Fig. 1B.

Predictions and modelling of industrially relevant emulsification processing equipment such as HPHs and RSMs have attracted much research interest, as a step towards design optimization, model based product formulation or for improving fundamental understanding (Almeida-Rivera and Bongers, 2010; Håkansson et al., 2013; Janssen and Hoogland, 2014; Jasinska et al., 2014; Maindarkar et al., 2015). Two different approaches have been used in predicting emulsification. The first (often referred to as the Kolmogorov-Hinze approach) is based on an analysis of the average stresses, comparing the Laplace pressure and viscous stresses stabilizing a drop to the average turbulent stress exerted on the drop by the turbulent flow (Hinze, 1955; Kolmogorov, 1949; Davies, 1985; Vankova et al., 2007). The ratio of these disrupting to stabilizing stresses is referred to as a Weber number. Under a large range of experimental conditions, the largest drops surviving a turbulent flow can be described by a critical Weber number that only depends on the disperse to continuous phase viscosity ratio (Calabrese et al., 1986; Vankova et al., 2007; Walstra, 2005). The second approach uses a transient population balance model (PBM) to describe the change in the drop size distribution. Drop

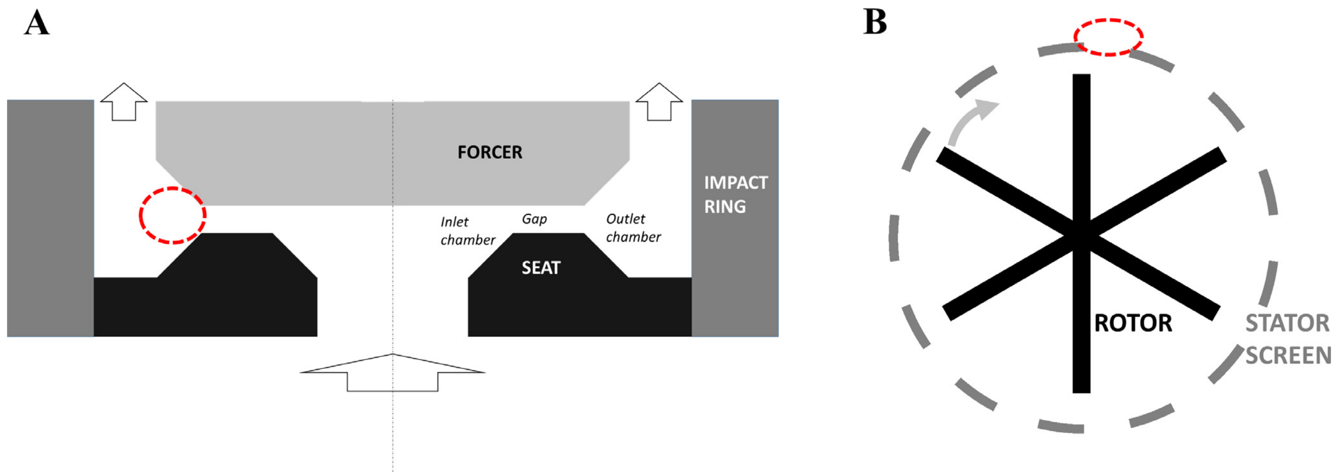

Fig. 1. Schematic illustration of the difference between the HPH (A) and the RSM (B). Also inserted in the figures are the drop breakup position in a HPH as suggested by experiments from Innings et al. (2011) and in a batch RSM as suggested by experiments from Ashar et al. (submitted for publication) (RSM). (For the difference between batch and inline operation, see Håkansson et al., 2017c). The breakup positions are marked using red dashed ellipses.