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Effect of local spatial location on chord length distribution in stirred tank

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ABSTRACT

Measurement of dispersed modality at different spatial locations is performed in a 1000 ml borosilicate beaker at various dispersed volume fractions in both W/O and O/W system. It is found that mean chord length at different spatial locations shows a similar distribution in both W/O and O/W dispersion that the closer to impeller the smaller the mean chord length. Further, in dilute W/O dispersion (3%), results show that both number counts and mean chord length of droplets at impeller region are smaller than other locations; however, it gradually turns to be larger at higher dispersed fraction (20%). For O/W dispersion, it is found that number counts of small droplets in region around impeller become smaller than other locations with the addition of dispersed oil phase (10%). Flow characteristic measured by 2D angle-resolved particle image velocimetry in pure oil/water phase is employed to further explain the deviation. Besides, the critical dispersed fraction affecting the dispersed modality at different spatial location is discussed.

1. Introduction

In several industrial process including petroleum, chemical, food, mining and pharmaceutical, liquid–liquid dispersion is ubiquitous. As a key factor determining the interfacial areas which further influences process of heat and mass transfer of the dispersion, drop size distribution (DSD) plays a crucial role in the transportation of oil–water mixtures, the design of chemical reactor and extractor, and the emulsion separation. For dispersion in stirred tank, researchers (Kolmogorov, 1941; Hinze, 1955; Coulaloglou and Tavlarides, 1977; Tsouris and Tavlarides, 1994) attributed the evolution of DSD to the balance between breakage and coalescence in the turbulent flow. Kolmogorov (1941) and Hinze (1955) introduced phenomenal fundamentals of the hydrodynamic mechanism of drop breakage in the dispersion. Breakage occurs once the dynamic pressure force or viscous stress (acting on the drop caused by velocity fluctuation of continuous phase) exceeds the surface tension force and viscosity effect which tend to maintain and stabilize the drop (Hinze, 1955). Shinnar (1960) suggested that viscous stress can be neglected when droplet is much larger than the Kolmogorov scale (the upper limit of local dimensions of the viscous flow). In the meantime, from aspect of energy balance, Shinnar (1960) indicated that the breakage required sufficient turbulence kinetic energy to increase the surface energy caused by birth of daughter droplets. For the occurrence of drop coalescence in turbulent flow field, two dispersed drops must firstly collide and then contact sufficient time to drain out the trapped liquid film to a critical film thickness and finally rupture, resulting in the drop coalescence (Angeli and Hewitt, 2000). Shinnar (1960) discussed the effect of turbulence intensity on coalescence rate of drops and argued both acceleration and reduction exists. Higher local velocities fluctuations would increase the collision rate between droplets, while sufficient energy contained in these fluctuations may re-separate the droplets in the process of film drainage.

In recent decades, both experimental efforts and numerical models considering the effect of physical properties and flow condition on DSD have been performed. Stamatoudis and Tavlarides (1985) suggested that DSD is mainly dominated by continuous phase viscosity rather than the dispersed phase. Bąk and Podgórska (2012) investigated drop breakage and coalescence in dispersion with nonionic surfactants. It was found that coalescence rate is significantly reduced by addition of surfactant. Process of breakage and coalescence was suggested

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Nomenclature

C_{32}	Mean chord length, m
D_{32}	Sauter mean diameter, m
H	Tank height, m
H_{ll}, H_{ul}	Lower and upper limit in the Y axis
k_{angle}	Turbulent kinetic energy at certain angle, $m^2 s^{-2}$
$\bar{k}$	Mean turbulent kinetic energy, $m^2 s^{-2}$
N	Rotation speed, s^{-1}
p	Number density
R_{ll}, R_{ul}	Lower and upper limit in the X axis
T	Tank diameter, m
U	Instantaneous velocity, $m\,s^{-1}$
$\bar{U}$	Mean stream velocity, $m\,s^{-1}$
$U_{angle(i)}$	Mean velocity at each angle, $m\,s^{-1}$
$\bar{u}_\theta$	Angle-resolved mean velocity, $m\,s^{-1}$
$\bar{u}$	Ensemble-averaged mean component of the velocity in Eq. (5), $m\,s^{-1}$
u'	Fluctuating components of the velocity in Eq. (5), $m\,s^{-1}$
$\tilde{u}$,$\tilde{v}$,$\tilde{w}$	Root mean square of the fluctuating velocity, $m\,s^{-1}$
u_p	Fluctuating velocity due to blade passage, $m\,s^{-1}$
u''	Fluctuating velocity due to turbulence, $m\,s^{-1}$
x, y, z	Axial coordinates

Greek letters

$\Gamma_{i,j}$	Specific mean value of either angle averaged velocities, TKE ($\bar{k}$) or EDR ($\bar{\varepsilon}$) at each grid in Eq. (15)
$\bar{\Gamma}$	Mean value of $\Gamma_{i,j}$ on the fixed region
Δ	Side length of interrogation window, m
ε	Energy dissipation rate, $m^2 s^{-3}$
ε_{angle}	Energy dissipation rate at certain angle, $m^2 s^{-3}$
$\bar{\varepsilon}$	Mean energy dissipation rate, $m^2 s^{-3}$
ν	Kinematic viscosity, $m^2 s^{-1}$

Subscripts

i, j	Tensor indices
min	Minimum
max	Maximum

mainly take place in impeller zone and increment of rotation speed would enhance the coalescence rate. Single drop breakage experiment was performed by Maaß and Kraume (2012) and results supported the assumption of binary breakage. Besides, effect of impeller stages and vertical position on drop size distributions were also carried out by Giapos et al. (2005) and Maaß et al. (2010, 2011). For the numerical prediction of DSD evolution, population balance equations are mostly accepted (Coulaloglou and Tavlarides, 1977; Tsouris and Tavlarides, 1994; Prince and Blanch, 1990; Luo and Svendsen, 1996; Bąk and Podgórska, 2012). Prince and Blanch (1990) and Luo and Svendsen (1996) proposed phenomenological PBEs models to predicate the breakage and coalescence process in gas–liquid dispersion while Coulaloglou and Tavlarides (1977) and Tsouris and Tavlarides (1994) successfully applied in the pure liquid–liquid system. Bąk and Podgórska (2012) and Bąk and Podgórska (2013) extended its feasibility in the dispersion with surfactant and polymer. Wang et al. (2014) analyzed the effect of dispersed volume fraction on the predicative accuracy in PBEs modeling.

For the research of either fundamental mechanism of drop behavior or numerical models, accurate description of turbulence flow field is of significant importance. For analyzing complex turbulent flow fields in stirred tank, various experimental techniques including hot-wire anemometry, laser-doppler anemometry (LDA) and particle image velocimetry (PIV) were employed (Zhou and Kresta, 1996; Jaworski et al., 2001; Khan, 2005; Gabriele et al., 2009). Recently, owing to the ability tracking instantaneous flow field information and non-intrusive character, PIV has evolved to be an effective method for velocimetry in experimental fluid mechanics. Sharp and Adrian (2001) and Li et al. (2011) measured small scale flow structure around a Rushton turbine and presented the process of creation and development of tip vortices. Gabriele et al. (2009) showed both specific turbulent kinetic energy and energy dissipation rates distributions in both impeller and circulation region by conducting 2D angle-resolved technique. Combining shadowgraph technique and PIV/LIF (laser induced fluorescence) with fluorescent tracer particles, Sathe et al. (2010) clearly reported the shape, size, velocity, acceleration of dispersed bubbles and the velocity field of surrounding liquid separately by employing two cameras with different optical filters and recording instantaneous motions of two phases through spectroscope. In research of liquid–liquid system (Kumara et al., 2010; Morgan et al., 2012, 2013), emphasis was placed on the investigation of stratified flow in pipe including measurement of instantaneous local velocities and consequent estimation of mean velocities, root mean squared velocities and Reynolds stresses. Works applying non-intrusive optical techniques in measurement of turbulent information of dispersed flow in stirred tank is still lacking. Svensson and Rasmuson (2006) analyzed the effect of dispersed volume fraction on flow structure with the change of locus of the vortex centre and velocities distribution at the eject zone around Rushton turbine. Owing to the rigid transparency demand of PIV observation, even with technique matching refraction index of two phases (Tabib and Schwarz, 2011; Tabib et al., 2012), measurement is still limited in the dilute dispersion (Laurenzi et al., 2009). In our previous work, the maximum dispersed aqueous volume fraction is 1.3% (Liu et al., 2016).

In present work, our purpose is to discuss the key parameters influencing the oil–water mixing, as the dispersed modality and relevant drop breakage and coalescence. Since the opacity appeared during the mixing could disable the measurement of PIV, instant velocities of pure water and oil phase are measured using a 2D angle-resolved PIV system, turbulent kinetic energy (TKE) and local energy dissipations rate distributions (EDR) are estimated and compared between different locations. Results in Liu et al. (2016) indicated TKE and EDR between pure oil phase and 1.3% dispersion show a similar distribution in different spatial locations. Thus, PIV result of pure phase is reasonable as a reference for the following chord length analysis. Drop number counts (DNC) and mean chord length of droplets at different spatial locations are measured with Focused Beam Reflectance Method (FBRM) and discussed between different dispersed fraction in both W/O and O/W system.

2. Experimental setup and methods

In this part, two sets of experiments are performed, where Section 2.1 describes method measuring drop size distribution by FBRM while process of tracking flow field information by PIV is introduced in Section 2.2.

2.1. *Measuring method of DSD*

Experiments are carried out in 1000 ml borosilicate glass beaker (width = 100 mm, height = 155 mm) equipping with a four pitched blade impeller (diameter D = 50 mm, width = 7.5 mm, height = 5.0 mm, inclination angle 45°) which located in the vertical middle line of the beaker and 18 mm away from the bottom. Avoiding direct sampling or diluting the mixture, instantaneous chord length distribution is measured by the Focus Beam Reflectance Method (FBRM D600L, Mettler Toledo). Being fixed at 30 mm away from impeller shaft, probe is placed at four different spatial regions