교반분산계의 액적 깨짐에 대한 유체동력학적 모델

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A Hydrodynamic Model on the Drop Breakup of Agitated Dispersions

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Introduction

Industrial operations, such as liquid-liquid mixing and multi-phase reaction, involve the formation of stirred dispersions of immiscible liquids. In such systems the drop breakup and coalescence process due to the turbulent intensity in vessel can profoundly influence the overall performance by altering the interfacial area available for heat, momentum and mass transfer between phases. The result of this drop breakup and coalescence process is ultimately represented by the particle size distribution of a specified system.

Particle size distribution is an important characteristic of deformable dispersion systems, for example, aerosols, bubbles, aqueous emulsions, and polymeric emulsions. In a polymerization reactor to produce two or more incompatible polymer mixture, the prediction of particle size distribution is one of the most important factors that affect productivity and product quality. One of the popular methodologies for simplifying these uneasy tasks is to make use of the concept of average particle size based on the Weber number theory [1], which only considers the maximum stable drop diameter.

As typical emulsion systems like as oil-in-water phase usually occur within the boundary of the inertial subrange in turbulent flow field, many researchers expressed lots of correlation equations on the attention that the breakup of a drop takes place when the ratio of inertial to elastic stresses exceeds a critical value. These expressions are later extended to include the dispersed phase holdup [2], the effect of surfactant or stabilizer concentration [3], and the effect of viscosity of dispersed phase [4].

When a liquid-liquid dispersion has very low interfacial tension coefficient or a turbulent field is very strong, the drop size of this emulsion system is usually very small compared with that of common oil-in-oil system. This flow field may belong in the viscous shear subrange. Then, the models so far developed in the inertial subrange fail to predict the drop size of the system. In this study, a breakup model based on the hydrodynamic force balance is suggested to describe the drop size under the viscous shear subrange, assuming that the coalescence between neighboring drops is negligible.

Drop Breakup Model in Viscous Subrange

A drop exposed to a turbulent flow field will be subject to either inertial or viscous force, or in-between. If the drop is much larger than the microscale of turbulence, the viscous force can be neglected. On the contrary, the inertial force can be neglected if the drop is much smaller than the turbulent microscale. A criterion to determine which force is dominant is the Kolmogorov's length scale defined by

$$\eta = \left({\upsilon_c}^3 / \varepsilon \right)^{1/4} \tag{1}$$

where υ_c is the kinematic viscosity of continuous phase, and ε is the local energy dissipation rate per unit mass.

For drop sizes of $L >> d >> \eta$, dynamic force rather than viscous shear force controls the breakup process, where L is the macroscale of turbulence, i.e., the order of impeller blade width and d is a particle diameter. Correlation models that have any form of theoretical base for the inertial subrange can be found elsewhere. For example, a representative model with experimental works can be found in the works of Calabrese et al. [5], and their final expression is given as

$$d_{\max} = A_1 \left(\frac{\sigma}{\rho_c} \right)^{3/5} \varepsilon^{-2/5} \left[1 + B_1 \left(\frac{\rho_c}{\rho_d} \right)^{1/2} \frac{\mu_d (\varepsilon d_{\max})^{1/3}}{\sigma} \right]^{3/5} \tag{2}$$

If the maximum stable drop size is much smaller than the Kolmogorov's length scale, the drop breakup presumably would be dominated by viscous force rather than inertial effect. In the viscous shear subrange, $d >> \eta$, the magnitude of the fluctuation components of the velocity vector is differently expressed as

$$u^2 \propto d_{\max}^2 (\varepsilon / \upsilon_c) \tag{3}$$

Since the velocity gradient is uniform in the viscous shear range, it has a value of the order of $(\varepsilon/\upsilon_c)^{0.5}$ [6]. Then, the disruptive stress is proportional to $\mu_c(\varepsilon/\upsilon_c)^{0.5}$, where μ_c is the viscosity of continuous phase, which when balanced with the surface force per unit area $\sigma/d_{\max}$ gives

$$d_{\max} = C\sigma\mu_c^{-1}\upsilon_c^{0.5}\varepsilon^{-0.5} \tag{4}$$

However, this expression does not have any viscosity ratio term which plays an important role in the viscous shear subrange, as already confirmed by the experimental works [7].

As a matter of course, it is likely to consider additional term for describing the viscosity ratio. The hydrodynamic forces affecting drop stability in the viscous shear subrange are the disruptive force due to shear field and the cohesive force as a resistance against the disruptive force. Cohesive force is mainly composed of the surface force and the resisting viscous force within a drop. The resisting viscous stress within a drop can be expressed as

$$\begin{aligned} \tau_v = \mu_d\left(\frac{du_d}{dr}\right) &\propto \mu_d\left(\frac{\rho_c}{\rho_d}\right)^{1/2}\left(\frac{du}{dr}\right) \\ &\propto \mu_d\left(\frac{\rho_c}{\rho_d}\right)^{1/2}\left(\frac{\varepsilon}{\nu_c}\right)^{1/2} \end{aligned} \tag{5}$$

where du_d/dr is the fluctuating velocity gradient within the drop and du/dr is the fluctuating velocity gradient just outside the drop as shown in Fig. 1. Then, the force balance between the disruptive force and the cohesive force derives the maximum stable drop size in the viscous shear subrange as

$$d_{\max} = \frac{A_2\sigma(\mu_c\rho_c\varepsilon)^{-1/2}}{\left[1 - B_2\left(\frac{\mu_d}{\mu_c}\right)\left(\frac{\rho_c}{\rho_d}\right)^{1/2}\right]} \tag{6}$$

Two constants A_2 and B_2 in this model are related to the tank geometry, the physical properties of fluids and operation conditions. So, the constants can be determined by the regression fittings of experimental data. This model has two features in that it contains the velocity gradient term expressed in the viscous subrange and the hyperbolic type of viscous ratio term explaining no breakup of drop when the viscosity ratio approaches a certain limit as shown in Fig. 2.

Conclusion

Correct prediction of drop size in agitated liquid-liquid dispersions requires which flow regime the system belongs to. In this study, a model suitable for the viscous subrange was proposed on the basis of the hydrodynamic force balance.

Acknowledgement

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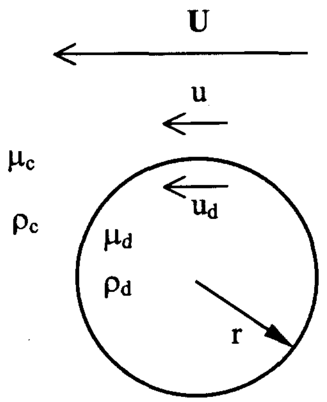

Fig. 1. Fluctuating velocities acting within and outside a drop.

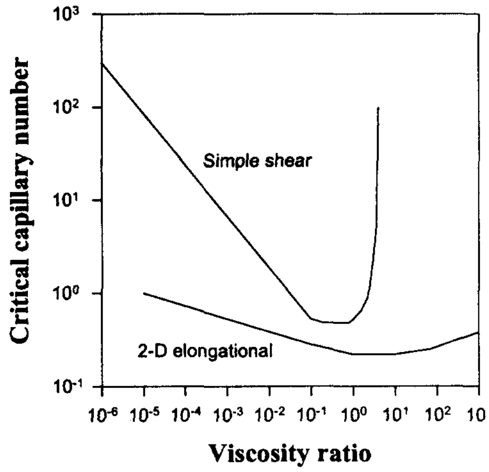

Fig. 2. Critical capillary number for drop breakup vs. viscosity ratio.