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Experimental study on drop formation in liquid–liquid fluidized bed

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ABSTRACT

Drop formation in liquid–liquid fluidized bed was investigated experimentally. The normal water was injected via a fine-capillary spray nozzle into the co-flowing No. 25 transformer oil with jet directed upwards in a vertical fluidized bed. Experiments under a wide variety of conditions were conducted to investigate the instability dynamics of the jet, the size and size distribution of the drops. Details of drop formation, drop flow patterns and jet evolution were monitored in real-time by an ultra-high-speed digital CCD (charge couple device) camera. The Rosin–Rammler model was applied to characterize experimental drop size distributions. Final results demonstrate that drop formation in liquid–liquid system takes place on three absolutely different developing regimes: bubbling, laminar jetting and turbulent jetting, depending on the relative Reynolds number between the two phases. For different flow domains, dynamics of drop formation change significantly, involving mechanism of jet breakup, jet length pulsation, mean size and uniformity of the drops. The jet length fluctuates with time in variable and random amplitudes for a specified set of operated parameters. Good agreement is shown between the drop size and the Rosin–Rammler distribution function with the minimum correlation coefficient 0.9199. The mean drop diameter decreases all along with increasing jet flow rate. Especially after the relative Reynolds number exceeds a certain value about 3.5×10^4, the jet disrupts intensely into multiple small drops with a diameter mainly ranging from 1.0 to 1.5 mm and a more and more uniform size distribution. The turbulent jetting regime of drop formation is the most preferable to the dynamic ice slurry making system.

1. Introduction

The ice slurry technology (Egolf, 2004; Egolf and Kauffeld, 2005; Meewisse, 2004; Pronk, 2006) has been studied for approximately two decades and has already been accepted as a promising working fluid due to its technical merits, such as excellent cold heat capacities, good flow ability, quick response to the thermal load demand, safe, environment-friendly and highly efficient. So far, ice slurry has been widely applied in several fields, just as by Wang and Kumusoto (2001) exemplified in the application to multifunctional buildings.

The liquid–liquid circulating fluidized bed (LLCFB) for ice slurry production is a newly proposed ice making system using the technology of two-fluid drop formation in conjunction with the high efficient fluidization theory (Haid et al., 1994; Jamialahmadi et al., 1997), as shown in Fig. 1. Multiple small droplets formed by a specially designed atomizer flow upwards together with the ambient chilled liquid (No. 25 transformer oil) in the vertical fluidized bed and freeze out quickly by direct contact heat transfer. These small drops formed in liquid–liquid jet systems result in large interfacial area and enhance heat and mass transfer strikingly. More details about this dynamic ice slurry making system can review the previous work given by our group (Liang et al., 2006; Peng et al., 2007).

It is evident that the stage of drop formation plays a key role in the whole ice slurry making system. The mean size and size distribution of the drops have a direct effect on the quality of the ice crystals, which shows a great sensitivity to the rheological properties of ice slurry (Kitanovski et al., 2005). On the other hand, the contact area between two phases, a prime factor to enhance the heat transfer efficiency, relates intimately to the drop size. Thereby, the knowledge of drop formation in liquid/liquid systems is of great significance and in pressing need for the development of this new ice slurry generator.

Free surface flows involving drop formation either with or without liquid jets in another immiscible viscous liquid have been widely studied for more than a century. Much of the earlier literature has been reviewed by Shi et al. (1994), Richards et al. (1993,1994,1995), and more recently by Carsten et al. (2004), Milosevic and Longmire (2002) and Doshi (2003).

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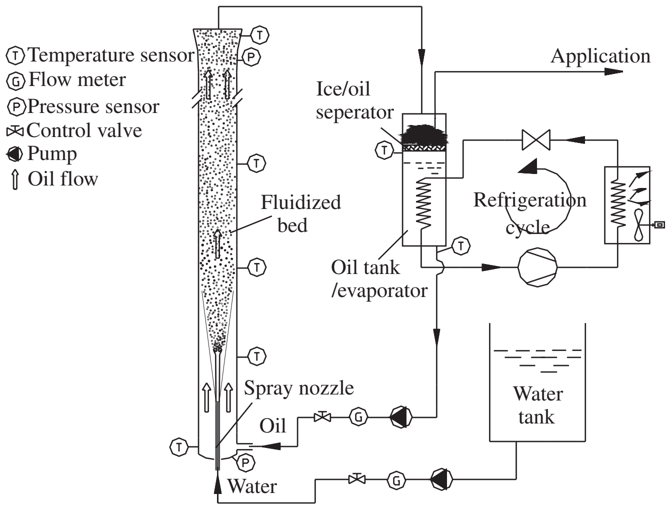

Fig. 1. Schematic diagram of LLCFB for ice slurry production.

Meister and Scheele (Meister, 1966; Meister and Scheele, 1967,1969a,b; Scheele and Meister, 1968) worked initially to develop an understanding of the jet and drop formation in liquid/liquid systems both experimentally and theoretically. Although most of them are only for the case of a quiescent continuous phase, the result makes a great contribution. Moreover, they tried to perform an overall force balance on the drop as it detached from the nozzle, starting with the fundamental and pioneering studies (Harkins and Brown, 1919; Christiansen and Hixson, 1957), based on which they also developed an expression for the drop size and presented a correlation for prediction of the transition point from dripping to jetting. Chen et al. (2001) carried out experiments by injecting aqueous solutions of NaCl and $AlCl_3$ into a pool of n-dodecane, in order to achieve a correct estimation of drop size in liquid–liquid drop formation from flat tip nozzles. They have found that the mean deviation of the correlation of Scheele and Meister (1968) can be reduced to a few percents if different characteristic diameters are used in the computation. Moreover, Carsten et al. (2004) demarcated the dripping regime of drop formation from the jetting one by studying the influence of the material and process parameters on the transition point. Additionally, they pointed out that small droplets were obtained at high velocities of the continuous phase and at low interfacial tensions.

In order to examine the effect of the external flow, Kitamura et al. (1982) experimentally varied the motion of the continuous phase to be either faster, the same as, or slower than the jet down to the case of a stagnant continuous phase. They found that the jet shortened as the absolute value of the continuous phase velocity relative to the jet increased from zero. For the same objectives, Anna et al. (2003) used a flow-focusing geometry which was introduced by Ganan-Calvo and Gordillo (2001) to study drop breakup where the disperse phase was injected into a co-flowing continuous phase and both liquids were forced to flow through an orifice. It was shown that the size of the generated droplets is much smaller than the orifice diameter and the size distribution is a function of the flow rates or flow rate ratios of both phases.

With respect to numerical simulation approaches, Richards et al. (1995) compared several methods (Georgiou et al., 1988; Schulkes, 1994a,b; Shan and Chen, 1993) and finally developed a dynamic simulation method based on the VOF/CSF numerical technique to investigate the 2-D full transient of liquid drop and jet formation under the conditions corresponding to liquid flow rates near and above the formation of a jet with the Reynolds number exceeding 400. Results of their numerical simulations showed significantly more accuracy than previously simplified analyses in predicting the jet dynamics, including the jet evolution, velocity distribution, and volume of drops. Wilkes et al. (1999) were the first to solve the full, axisymmetric Navier–Stroke equation for the formation of drop of Newtonian liquid at finite Reynolds numbers. Although recognizing that VOF is a powerful technique for simulating complex free surface flows with liquid breakup and coalescence, they preferred to use the finite element method (FEM) because of its long and distinguished track record in simulating complex, steady free surface flows. Analogous to investigations on dripping into air (Zhang and Basaran, 1995), Zhang and Stone (1997) used the boundary integral method for Strokes flow in numeral simulation and found that the viscosity ratio has virtually no effect on the primary drop volume but influences significantly the necking and breakup behavior of the separating drop. However, because of the considerable computation times in those days, the previous numerical investigations were either performed in one-dimension (Eggers and Dupont, 1994; Ambravaneswaran et al., 2002) or in two-dimension (Schulkes, 1994a,b; Zhang and Stone, 1997; Zhang, 1999a,b; Wilkes et al., 1999; Richards et al., 1993,1994,1995; Doshi et al., 2003).

Although the previously cited studies of liquid–liquid drop formation have captured some of the gross features of the phenomenon, particular knowledge for the new application to generate ice slurry was wondrously inadequate. The major goal of the present work is to obtain quantitative information on the dynamics of drop formation based on the platform of LLCFB, focusing mainly on drop flow patterns, jet length pulsation, mean size and size distribution of the drops. Further, three absolutely different mechanisms of drop formation were addressed and investigated. As a consequence, the well-defined conditions of drop formation for the dynamic ice slurry generating system were discussed.

2. Experimental set-up and methods

Fig. 2 shows the schematic diagram of experimental set-up, a modified and simplified version of Fig. 1. It consists essentially of a fine-capillary spray nozzle through which the liquid used to form drops is delivered at a constant volumetric flow rate by means of a booster bump (12WZ-8, the maximum volumetric flowrate: $20\,L\,min^{-1}$). The inner diameter (ID) of the spray nozzle used uniformly in experiments is 0.12 mm and the outer diameter is 0.3 mm. It is fixed at the tip of a copper jet-pipe of nominal ID 5 mm and height 350 mm, which is located vertically at the bottom of the fluidized bed with spray directed upwards and on the centerline where the continuum velocity is at a maximum. A steady, non-pulsating flow of the continuous phase was generated using a centrifugal pump (YG50-100), which covers a flow rate range $0.01\,L\,s^{-1} \leqslant Q_{c,in} \leqslant 6.19\,L\,s^{-1}$, and finally entered the vertical fluidized bed having a sufficiently large inner radius as compared with the nozzle radius with their ratio $R_f/R = 200$ so that the ambient wall effects can be neglected (Zhang, 1999b). The continuum enters the fluidized bed horizontally, about 300 mm below the spray nozzle head. The arrangement of the location of the spray nozzle can firstly provide the steady, fully developed, laminar hydrodynamic flow of the continuous phase around the injection point. When the two phases flow co-currently, the radial motion of the continuum is rather weak, so is the collision between the dispersed drops. Drop-coalescing is thus alleviated favorably to focus the investigations on the mechanism of drop formation. Secondly, the residence time of the drops in the system circuit is prolonged to obtain fine ice crystals frozen thoroughly at the outlet.

An ultra-high-speed digital CCD (charge couple device) camera by NIKON (Japan) was employed to monitor in real-time the process of drop formation and drop flow patterns in the fluidized bed. The