Experimental Thermal and Fluid Science 35 (2011) 387–394

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Size prediction of drops formed by dripping at a micro T-junction in liquid–liquid mixing

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ARTICLE INFO

Article history:
Received 17 August 2010
Received in revised form 28 October 2010
Accepted 31 October 2010

Keywords:
Liquid drop
Micro T-junction
Dripping
Detaching time

ABSTRACT

In the present work, the formation of liquid drops by dripping at a micro-scale T-junction with a square cross-section ($90 \times 90\ \mu m^2$) was examined. The drop formation process consists of three stages: X–Y and X-growth stages and a detachment stage. In the X–Y growth stage, the tip of the disperse phase grows both in the longitudinal (X) and lateral (Y) directions to form a bulged shape until a maximum value of Y is reached. Then, in the X-growth stage, the bulged part continues to grow but only in X-direction, followed by the detachment stage to be separated out a single drop through a rapid necking process. The entire process is repeated at regular intervals. The volume of the drop is determined by the Y-directional size of the bulged part at the end of the X-growth stage (S_E) and the detaching time (Δt_{Detach}). Based on the measurement and a simple scale analysis, a correlation to represent the drop size was proposed with the flow rates and fluid properties taken as parameters, and physical interpretations on the correlation were provided as well.

1. Introduction

There have been numerous studies on the liquid micro-drop formation to control size and uniformity of the drops for application to lab-on-a-chip systems, the synthesis of microparticles, and other uses [1–6]. The drop formation methods can be grouped into three categories: coflow method [7], flow focusing method [8], and crossflow method [9,10]. Among the three methods above, the crossflow method is most suitable to generate drops for wide ranges of velocity and pressure [10]. In addition, it is reported that the crossflow method is more useful in cell encapsulation, a chemical reaction, etc. [11,12]. Therefore, a number of studies have been performed on the crossflow method (or T-junction) for drop formation [3,4] as illustrated in Fig. 1.

According to the inlet velocity of each phase, three different modes of the drop formation were reported as shown in Fig. 2: squeezing, dripping, and jetting [13]. In the squeezing mode (Fig. 2a), the disperse phase almost blocks the main channel and the drop is formed by the pressure build-up at the upstream of T-junction. This mode occurs at low velocities of the both phases and the drops are highly uniform in size but always larger than the channel diameter. Fig. 2b shows drops formed by dripping, where the drops are formed by the shear stress interaction at the interface between the fluids. This mode appears at a high velocity of the continuous phase but with the disperse-phase velocity remains low. Unlike the squeezing mode, the disperse phase does not block the main channel during the drop formation process. Sizes of drops formed by dripping are also highly uniform and controllable. In the jetting mode, as shown in Fig. 2c, drops are formed by the instability at the flat interface of the stratified flow. Jetting occurs when the velocities of the both phases are high, and the formed drops are generally not uniform. In summary, the dripping mode is most likely suitable for the generation of uniform micro-drops.

There have been many studies on micro-drops formation by dripping. Experimental conditions of previous works are listed in Table 1. Van der Graaf et al. [14] simulated the drop formation process at T-junction having the square cross-sections with their sides being 100 μm using the Lattice-Boltzmann method and compared that with the experimental results. Adzima and Velankar [15] measured the drop size with channel size variation. It is confirmed that the correlation for the squeezing mode can not be applied to dripping mode. Husny and Cooper-white [16] studied the effect of the disperse and continuous phases viscosities ranging from 1 to 6 mPa s and 5 to 50 mPa s, respectively, on the drop size, where the drop size decreases with increasing of the viscosities of the both phases. They also proposed a correlation to predict the drop size by equating the surface tension force and the drag force; but the correlation did not represent their experimental data with satisfaction. In addition, it is only applicable when the equivalent drop diameter is smaller than the hydraulic diameter of the main channel. Xu et al. [17] also proposed a correlation to predict the drop diameter also by balancing the surface tension force to the drag force shown as follows:

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doi:10.1016/j.expthermflusci.2010.10.009