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Influence of jet–jet interaction on droplet size and jet instability in immiscible liquid–liquid system

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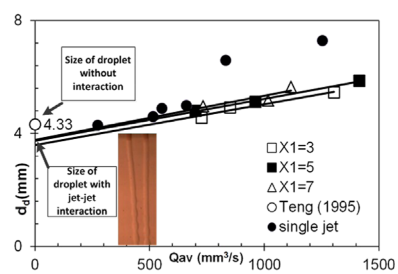
HIGHLIGHTS

- Experimental study of jet-jet interaction in immiscible liquid-liquid system.
- Jet breakup and droplet formation behaviour for single and multiple jets.
- Decrease in droplet size with jet-jet interfacial interaction.
- Influence of jet instability on jet breakup length and droplet size.
- CFD study on single jet instability.

GRAPHICAL ABSTRACT



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ABSTRACT

This work investigates the effects of multiple jet interactions and single jet instability on jet breakup and droplet size using experimental and computational techniques. In particular, the jet separation distance, jet breakup length and droplet diameter were measured as a function of initial nozzle separation distance and jet volumetric flow rate. It was found that the two jets moved closer to each other to reach an equilibrium separation distance that was approximately 70% of the spacing between the two nozzles. The distance at which the instabilities were first observed on the surface of the jet was also a function of the initial separation distance. However, it was weakly dependent on the jet velocity. The jet breakup length and resultant droplet diameter were both influenced by flow rate and nozzle separation distance. The jet breakup length was found to decrease with reduction in nozzle spacing at the high flow rates. Interestingly, a linear relationship between droplet diameter and breakup length was found that was largely independent of nozzle spacing and consist with conventional Rayleigh jet breakup theory. The implications of the experimental observations on the design of multi-jet systems are discussed. Furthermore, computational fluid dynamics simulations were also used to identify the mechanism and dynamics of jet instability in the single jet systems. The simulation results were analysed to study the effect of instability on various parameters such as jet breakup, droplet formation and size of emulsion droplets. It was found that at higher volumetric flow rates, the droplets size increased during the jet breakup due to an asymmetric instability. The asymmetric instability was caused by the pressure gradient in the continuous phase and was prevented in double jet systems.

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1. Introduction

Many industrial processes comprising micro channel and membrane emulsification process and many chemical reactions involving drop formation and drop detachment from a capillary. Extensive knowledge on drop formation and detachment process can be employed to develop and improve the industrial processes. Emulsion droplets can be formed from capillary, in which the produced droplets are dispersed into another immiscible liquid. Few models focus on liquid drop formation from multiple jets in another immiscible liquid, as this was the case in this study.

Jet breakup has been studied both experimentally and theoretically for a single jet. Rayleigh (1878) was the first researcher to theoretically model an infinite free inviscid jet injected into air. Tomotika (1935) extended Rayleigh's theoretical development by solving the general eigenvalue relation for the limiting case of a viscous liquid penetrating into another immiscible viscous liquid. The general eigenvalue equation was first solved numerically by Meister and Scheele (1967) for the cases of a viscous liquid jet in a gas (Weber, 1931), and an inviscid liquid jet in an inviscid liquid (Christiansen and Hixson, 1957). Meister and Scheele (1969) also performed their own experiments for 15 different immiscible liquid–liquid systems to study jets and droplet formation. They found that for the case of low flow rates droplets were formed and broke away at the nozzle tip. At higher flow rates a jet was formed that extended a finite length below the nozzle. Beyond a critical liquid velocity at the nozzle jet breakup was observed at a fixed jet length. Computational fluid dynamics has been employed recently (Bhatelia et al., 2011; Homma et al., 2006; Hua et al., 2007; Shinjo and Umemura, 2010; Soleymani et al., 2008; Timgren et al., 2009, 2010) for predicting the hydrodynamic characteristics of liquid jets and resultant droplet formation in immiscible liquid–liquid systems. Furthermore, Homma et al. (2006) identified three different breakup modes named *dripping* at low velocity where jet cannot be formed, *jetting* at jetting velocity and *atomization* at velocity higher than jetting velocity. Interfacial instability is one of the important mechanisms accounted for jet breakup in the microfluidic jet system.

Rapid development of processing and control of immiscible fluids in micro reactor, other microfluidic technology has experienced in recent years. It has been critical to fabricate micro fabrication technology to allow these developments to have same pace and success. In liquid–liquid systems (Hardt et al., 2001; Haverkamp et al., 1999; Nazir et al., 2013; Sugiura et al., 2001) have been studied micro channel flow of liquid mixtures. Micro-devices are being increasingly applied to emulsion manufacture because of their low energy consumption and ability to produce uniform droplet size distributions which often results in improved emulsion stability (Hessel et al., 2005). Droplet formation and breakup dynamics throughout the process of dripping and jetting was experimentally studied (Fu et al., 2012). The limitations, however, are the relatively low throughput for each device and multiple units are required in parallel for industrial-scale production rates. For micro-devices utilising the breakup of continuous liquid threads (jets), multiple parallel jets are closely positioned to each other in a single unit. For such an array, breakup and droplet formation is now influenced by the jet–jet interaction not previously described by classical breakup theory. Earlier work on stationary systems (Elemans et al., 1997; Knops et al., 2001) is limited in its application to this type of dynamic interaction (Phan and Evans, 2009).

The aim of this study is to investigate the influence of the interaction between two liquid jets on the breakup length and resultant droplet size as a function of liquid throughput. Moreover, instability associated with single jet was discussed experimentally and computationally to focus more on multiple jet system to produce highly stable emulsions at higher production rate. Finally, the influence of jet–jet interaction on the *swinging* phenomena is quantified.

2. Experimental methodologies

The experimental apparatus is shown in Fig. 1. It consisted of a clear acrylic column (30 × 30 × 100 cm) that contained the continuous liquid (canola oil). For this study, canola oil was (from Gold'n Canola™, Australia) used as the continuous phase. It should been noted that canola oil is also the main ingredient of the explosive for Australian mining industry. The nozzles were sufficiently long (length to diameter ratio greater than 20) to assure a fully developed velocity profile at the nozzle exits. Two circular nozzles (1.60 mm *ID*) were submerged 5 mm below the free surface of the continuous liquid inside the column. Three spacing (X_1 = 3, 5, 7 mm) between two nozzles were employed to study interaction between two jets. Single nozzle of same dimensions was employed for single jet analysis (not shown in Fig. 1). The nozzles were attached to a plenum chamber which was fed by a pump from a chamber containing the dispersed phase liquid (20% NaCl solution). A valve was used to control the flow rate. Jet behaviour was monitored using a high-speed camera (Fastec Imaging™, USA) at 125 frames-per-second. Jet diameter, breakup length, and resultant droplet size were measured by photographic visualization at different time frames. All the experimental measurements were performed at room temperature (25 °C).

Prior to the start of experiments, dispersed and continuous phase density and absolute viscosity were measured at room temperature using an Antone Paar density meter (DMA4100) and Vibro-viscometer (SV-10), A&D Co. Ltd.), respectively. Axisymmetric drop shape analysis (ADSA) was used to measure interfacial tension between salt solution and canola oil. There are four main steps involved in this measurement method. (Zuo et al., 2004). The value obtained was 0.021 N/m. This value was used for theoretical analysis and the CFD simulations. The measured values for density, viscosity and interfacial tension are given in Table 1.

High-speed video recordings were taken over a period of approximately 2 s. The characteristic lengths were obtained from the video recordings. The images were also analysed to determine the number of droplets produced. The data sets of at least 20 droplets were taken for average droplet size calculation. The jet length was then used in conjunction with the equivalent spherical diameter, d_d, values to calculate the cumulative total volume, V. The slope of V versus time was used to calculate Q_{av}. Consequently,

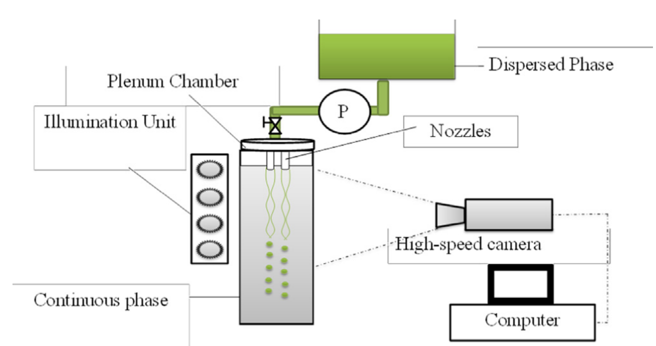

Fig. 1. Graphical representation of experimental setup.

Table 1
Physical properties of continuous and dispersed phases.

Property	C. phase	D. phase	Interfacial
μ (Pa s)	0.0603	0.0039	
ρ (kg/m^3)	913	1147	
γ (N/m)			0.021