Chemical Engineering Science 138 (2015) 140–152

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Taylor flow heat transfer in microchannels—Unification of liquid–liquid and gas–liquid results

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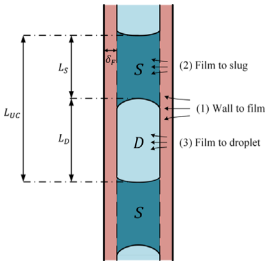
HIGHLIGHTS

- Heat transfer data on liquid–liquid Taylor flow in a 2 mm diameter tube.
- High sensitivity of liquid–liquid heat transfer rate to flow conditions.
- Validation of CFD model of liquid–liquid Taylor flow heat transfer.
- Developed a generalised model to interpret and predict Taylor-flow heat transfer.
- Unification of liquid–liquid and gas–liquid results using a single correlation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 June 2015
Received in revised form
7 August 2015
Accepted 8 August 2015
Available online 18 August 2015

Keywords:
Microchannels
Heat transfer
Enhancement
Correlation

ABSTRACT

The flow and heat transfer behaviour of liquid–liquid Taylor flow is examined by performing both experiments and CFD simulations for 1 and 2 mm vertical tubes with constant wall heat flux boundary conditions. Water and hexadecane are used as the disperse and continuous phases, respectively. The measured heat transfer coefficients are extremely sensitive to experimental uncertainties but, are in overall good agreement with the simulations. The simulations confirm the strong dependence on the flow conditions seen in the experiments.

A generalised model of heat transfer in gas–liquid and liquid–liquid Taylor flows is developed from a combination of resistances for wall-to-film, film-to-slug and film-to-bubble or droplet. Good estimates for these individual resistances are described and validated. The overall heat transfer coefficient obtained by a rigorous weighting of the individual resistances correlates the entire set of CFD (liquid–liquid) and experimental (gas–liquid) data with 20% relative standard deviation. The model captures the complex parametric dependencies and sensitivities in the data.

1. Introduction

Driven by the need for more effective heat transfer devices for product and process miniaturization, significant research efforts have focused on liquid cooling in microchannels. The ability of gas–liquid non-boiling Taylor flow to increase the heat transfer rate several-fold relative to liquid-only values has been demonstrated (Asadolahi et al., 2011, 2012; Betz and Attinger, 2010; Fukagata et al., 2007; Gupta et al., 2010; He et al., 2010; Horvath et al., 1973; Lakehal et al., 2008; Leung et al., 2012, 2010; Oliver and Wright, 1964; Walsh et al., 2010). Internal recirculations within the liquid slugs have been shown to explain the heat transfer enhancement. However, in gas–liquid Taylor flow, the contribution of the gas phase to the heat transfer is negligible, as the thermal capacity of the gas phase is much smaller than that of the liquid phase. Replacing the gas bubbles with immiscible liquid

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http://dx.doi.org/10.1016/j.ces.2015.08.012
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droplets to form liquid–liquid Taylor flow in microchannels has drawn increasing attention recently. This is because the disperse liquid phase has a thermal capacity of the same order as that of the continuous liquid phase and hence significant heat transfer enhancement can be expected. In addition, Taylor droplet flow in microchannels provides rapid internal mixing, as well as precise control of the reaction time and chemical composition in each droplet, making it very attractive to engineering applications. Nitration of benzene to toluene (Song et al., 2006), micro-separation (Ookawara et al., 2007), polymerase chain reaction (Urbant et al., 2008) and electronics cooling (Asthana et al., 2011; Fischer et al., 2010; Urbant et al., 2008) are some examples of novel applications of liquid–liquid Taylor flow.

There has been considerable research on the hydrodynamics and heat transfer of two-phase flow both numerically and experimentally. However, most of the studies have been carried out for gas–liquid two-phase flow with few on liquid–liquid flow. In recent years, there have been a few investigations of hydrodynamics of liquid–liquid Taylor flow in microchannels, including flow patterns (Foroughi and Kawaji, 2011; Kashid and Kiwi-Minsker, 2011; Kashid et al., 2007), liquid film thickness (Grimes et al., 2007; Mac Giolla Eain et al., 2013), pressure drop (Jovanović et al., 2011; Kashid and Agar, 2007; Mac Giolla Eain et al., 2015a, 2013) and mass transfer enhancement (Kashid et al., 2007). The flow characteristics of liquid–liquid two-phase flow are now well understood, as described in recent reviews (Bandara et al., 2015; Gupta et al., 2013).

Most recently, with the rapid development of modern imaging and optical diagnostic instrumentation, a number of techniques have emerged to investigate and characterise fluid flow in micro-scale systems quantitatively. Several authors investigated velocity distributions in microscopic liquid–liquid two-phase flow using micro-particle image velocimetry (micro-PIV). Kashid et al. (2005), (2008) carried out experiments to visualize the internal circulations in the slug and compared the PIV velocity fields qualitatively with those obtained from CFD simulations. With high-speed confocal scanning microscopy, three-dimensional and complex circulating flow patterns were identified inside the droplet by Kinoshita et al. (2007). Miessner et al. (2008) investigated the 3D velocity distributions in disperse oil/water two-phase flows in a rectangular channel ($100\ \mu m \times 100\ \mu m$) by scanning the volume and using micro-PIV. The velocity fields in both phases were obtained simultaneously and secondary vortices were observed inside and outside the droplet. Ghaini et al. (2011) adopted laser induced fluorescence (LIF) to visualize the wall film for a variety of aqueous-organic two-phase systems in 1 mm capillaries. Internal circulation patterns within the liquid slugs were identified by observing the variations in the local fluorescent dye concentrations. These techniques permit the observation of hydrodynamics and mixing effects with a high spatial resolution and provide useful insights into the physical mechanisms governing heat transfer in Taylor flow.

While the flow pattern and mass transfer enhancement in liquid–liquid segmented flows in microchannels have been demonstrated in both simulations and experiments, studies of heat transfer in this flow regime have mostly been restricted to computational approaches. Urbant et al. (2008) calculated the heat transfer characteristics of the flow of water droplets in continuous oil phase in capillaries with diameters of 100 and 1000 μm. Their work focused on short droplets, $<1d$, but a single run for a droplet length of $1.65d$ in the larger channel was also conducted to illustrate the heat transfer performance of flow with longer water droplets. Significant heat transfer enhancement over that for single-phase flow was reported due to the recirculating flow inside the water droplets and the oil slugs. The heat transfer rate was found to increase with the length of the water droplets. They explained that the presence of the thin film of the carrier fluid between the wall and the elongated water droplet could lead to considerable augmentation of the heat transport in the radial direction. However, Janes et al. (2010) who performed oil–water segmented flow heat transfer experiments in a meandering channel with 90° bends and a spiral channel of square cross-section drew a different conclusion concerning the effect of the water droplets on heat transfer. They highlighted that the water droplets only play a minor role in overall heat transfer due to the low thermal penetration through the thick oil film.

Fischer et al. (2010) performed two-dimensional, axisymmetric simulations to study the heat transfer for liquid–liquid slug flow in a microchannel using 5 cS silicone oil, water and polyalphaolefine as the working fluids. For some simulations, the droplet phase was loaded with 3 vol% Al_2O_3 nanoparticles. Up to a four-fold increase in the Nusselt number relative to the single liquid flow was reported. The effect of Marangoni flow induced by the temperature gradient at the liquid interfaces was included in their modelling. They found that the Marangoni effect decreased the heat transfer as it opposed the recirculating flow in the slug. They also found that the nanoparticles inside the droplets only provided a small additional heat transfer enhancement (3–5%). Che et al. (2015) carried out 3D numerical simulations of the heat transfer process to study the droplet heat transfer in microchannel heat sinks. The effects of the length of the droplets, the aspect ratio of the channel cross-section, and the Péclet number were analysed. Nusselt numbers in the range 10–15 were found for the droplet-based heat transfer in their rectangular microchannels with a constant wall temperature boundary condition. Talimi et al. (2013) performed single phase CFD simulations inside the slug region for Taylor flow in square-section channels and predicted heat transfer rates approximately four times greater than the experimental data used in the comparison.

To date, only two experimental studies that examine the heat transfer performance of liquid–liquid flow are available in the literature. Asthana et al. (2011) reported experimental measurements of the flow and heat transfer of mineral oil droplets dispersed in a continuous water phase in a serpentine channel of square cross-section ($100\ \mu m \times 100\ \mu m$). Laser induced fluorescence (LIF) and micro-Particle Image Velocimetry (micro-PIV) techniques were employed to measure the temperature and velocity fields, respectively. The recirculation zones inside the water slug and the resulting enhanced radial heat transfer were clearly demonstrated. A heat transfer enhancement of up to four-fold in slug flow compared with that for water alone was observed. Most recently, Mac Giolla Eain et al. (2015b) carried out heat transfer experiments on liquid–liquid Taylor flows with a constant wall heat flux boundary condition. Local wall temperature measurements were made in both developing and fully-developed regions using a high resolution infrared thermography system. They examined the influence of slug length and carrier phase properties on the local Nusselt numbers. Enhancements up to six times over single phase flow were observed by introducing a second immiscible liquid phase. They noted that reductions in carrier slug length and increases in the droplet length result in improved thermal performance.

Some studies have led to the development of correlations to model the thermal behaviour of two-phase Taylor flow, but mostly only for gas–liquid flows (Kreutzer et al., 2001; Leung et al., 2012; Oliver and Wright, 1964; Walsh et al., 2010). Mac Giolla Eain et al. (2015b) proposed a correlation to predict the Nusselt number in liquid–liquid Taylor flows with constant wall heat flux boundary condition. The correlation consists of separate expressions for the thermal entrance and fully-developed regions. The deviation between the correlation predictions and the experimental measurements ranged from $\pm 10\%$ to $\pm 30\%$. However, only the slug