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Review

Slug flow heat transfer without phase change in microchannels: A review

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ABSTRACT

Two-phase flow without phase change can radically increase the heat transfer rate in microchannels due to the internal recirculation of the fluids. In this paper, both numerical and experimental studies on the hydrodynamics and heat transfer of two-phase flow without phase change in small channels and tubes are reviewed. These two-phase flows are either made up of gas–liquid or immiscible liquid–liquid slug flows. This review includes a general introduction of the hydrodynamics of two-phase flow in microchannels and shows that there is little agreement between measured and predicted pressure drop. Furthermore heat transfer rates are examined in the form of Nusselt number (*Nu*) correlations based on different flow parameters. Values are compared using a standard flow regimes for two-phase slug flow indicating huge variability (over 500%) in the *Nu* values obtained from reported correlations. We attribute this to insufficient description and consideration of the flow conditions. Finally a perspective on future research directions in the field is suggested, including control through wettability and the use of novel liquids.

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1. Introduction

The use of microchannels for fluid conduits has significant advantages in a variety of applications. Some of these applications include heat exchangers, micro-reactors, lab-on-a-chip, micro-electronics, and micro-electro-mechanical systems (MEMS). In heat exchangers, the amount of heat that can be removed scales as the surface area of the cooling channels, so massively parallel microchannels have the potential to transfer large heat fluxes. High heat flux removal has become particularly important with the increase in transistor density in microelectronics. For example, traditional air cooling has become ineffective in the latest microelectronic systems due to the reduced equipment size, increased heat flux and increased resistance to air flow by compact packing of components in the systems. Therefore, micro-electronic cooling has gained significant interest over the past few decades. Cooling techniques such as falling film cooling, spray cooling, and heat pipes were introduced. However, these techniques proved not to be as effective as expected to cool chips (Ebadian and Lin, 2011), and other low-cost, efficient heat removal methods may be required.

The concept of heat removal by means of liquid flow in microchannels was first introduced by Tuckerman and Pease for electronic cooling. A heat removal rate of 0.79 kW/cm^2 with single phase flow was demonstrated (Tuckerman and Pease, 1981; Asthana et al., 2011). While impressive, single-phase heat transfer is still limited to comparatively low heat fluxes. Computer chips currently require cooling rates up to approximately 1 kW/cm^2 (Bar-Cohen et al., 2006), meaning new solutions need to be found for the next generation of devices that maximize heat transfer rates with minimal pressure drops.

The heat transfer rate for boiling flow in microchannels is much higher than that of its single-phase counterpart due to the large heat of vaporization (Asthana et al., 2011; Betz and Attinger, 2010). Mudawar and Bowers (1999) have shown that flow boiling can dissipate heat at a rate of 10 kW/cm^2, which is 10 times higher than that for single phase flow (Asthana et al., 2011; Mudawar and Bowers, 1999). Even though flow boiling has been shown to be effective for electronic cooling, it has the drawback of being difficult to control due to back flow and instabilities in the flow. These instability constraints may be overcome while maintaining hight heat transfer rates by using a separate fluid phase such as gas or an immiscible liquid into a main continuous liquid – the so-called two phase flow without phase change.

The potential of two-phase flow to provide a high heat transfer rate compared to traditional single phase flow is due to two main reasons; internal recirculation within the liquid slugs which promotes the radial mixing of fluids, leading to a greater radial heat transfer rate, and the higher local fluid velocity in the secondary phase plug leading to a higher heat transfer coefficient (refer to Muzychka et al., 2011a). Above a critical capillary number there exists a thin liquid film between the channel wall and the secondary phase fluid droplet, which has a significant effect on heat and mass transfer. A detailed explanation of this will be given in Section 2.1. This type of flow was named as Taylor flow after the pioneering studies of Taylor (1961). Fig. 1a illustrates the main properties of Taylor flow including the liquid film between the droplets and the wall. However, these fluid droplets can flow without creating a thin film at low capillary numbers (*Ca*) by sliding along the channel wall (Fig. 1b) due to the weak shear forces which cannot overcome the adhesion forces. We call this sliding slug flow/slug flow, while some researchers use slug flow for both two-phase flows with and without a thin liquid film (Walsh et al., 2010; Jovanovic et al., 2011).

Other than slug and Taylor flow, there are various other types of two-phase flow patterns such as dispersed bubbly flow, liquid ring flow, and liquid lump flow, which have been identified in flow visualization experiments (Serizawa et al., 2002; Kreutzer et al., 2005a). However, slug/Taylor flow is very easy to produce at non-boiling flow conditions, particularly in microchannels where surface tension forces often dominate. Extensive research work has been carried out on two-phase slug flow in microchannels particularly concerning hydrodynamic characteristics such as velocity of bubbles, void fraction, liquid film thickness, pressure loss and mass transfer enhancement (Bretherton, 1961; Kreutzer et al., 2005a; Leung et al., 2010; Suo and Griffith, 1964; Liu et al., 2005; Abadie et al., 2012). In fact mass transfer in microreactors can be the limiting factor in reaction rates and Taylor flow has been shown to significantly increase in mass transfer for gas–liquid and liquid–liquid two-phase flows compared to single-phase liquid flow of the same carrying fluid (Kashid et al., 2005; Di Miceli Raimondi et al., 2008; Kreutzer et al., 2005a). It has been shown that the mass transfer increases through the interface, and internal diffusion rates increase too as a function of capillary number.

Although there have been previous reviews on both experimental and numerical studies (Angeli and Gavriilidis, 2008; Gupta et al., 2010b; Muzychka et al., 2011b; Talimi et al., 2012) for two-phase flow and associated heat transfer phenomena, the field has progressed recently, particularly for microscale flows. The aims of the present review paper are (1) to detail the important two-phase flow parameters and current measurement techniques, (2) to address the

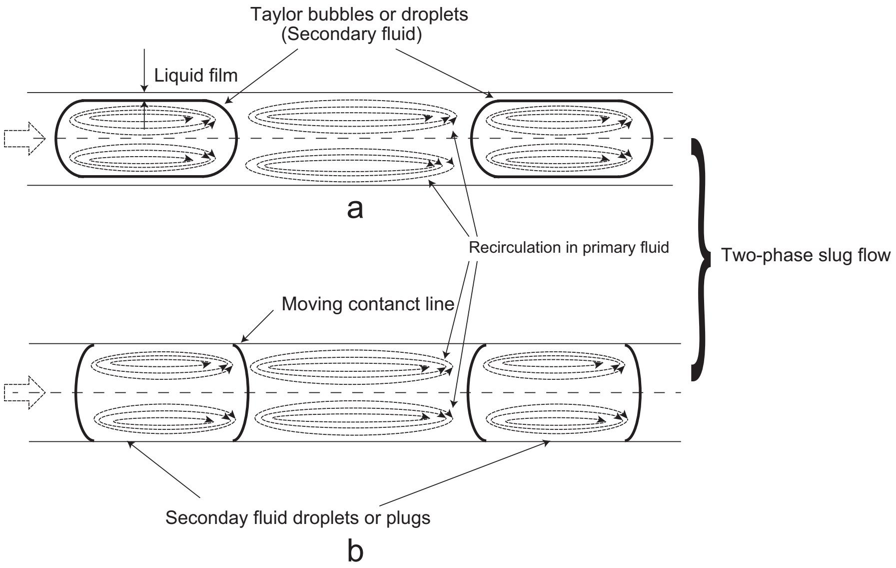

Fig. 1. Schematic diagram of a two-phase flow, (a) Taylor flow which has a thin liquid film and (b) sliding slug flow which does not have a liquid film.