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Fluid flow and heat transfer of liquid-liquid two phase flow in microchannels: A review

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ABSTRACT

The fluid flow and heat transfer behavior of liquid–liquid two phase flows have led to significantly improve the heat transfer rates in microchannels. Both numerical and experimental studies are reviewed in this paper to gain useful insights into the effect of a number of parameters such as film thickness, Peclet number, working fluid and flow geometry on hydrodynamic and thermal behavior of microchannels using liquid-liquid two phase flow. In addition, the paper summarises information about common correlations proposed to predict the pressure drop and heat transfer coefficient in the form of Nusselt number (Nu). The present study shows that there is little agreement across the literature between measured pressure drop and Nusselt number and predictions based on these correlations. Finally, the conclusions and important summaries, and some possible future development of this field are presented.

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Contents

1. Introduction

Dissipating high amount of heat flux is an important issue of modern thermal management with the ever increasing demands for high performance and miniaturisation [2]. According to the literature [3] traditional electronic cooling systems are no longer efficient enough to meet the needs of the developed high circuitry systems. Therefore a great deal of recent research has been dedicated to improve the microchannel heat sinks (MCHS) as an effective device for heat removal from microelectronic systems.

The concept of MCHS heat sinks is defined as small mass and volume devices with higher convective heat transfer coefficients and large surface area to volume ratio. It was first proposed by Tuckerman and Pease [4] in 1981. By using MCHS the heat transfer coefficient could be enhanced by periodic interruption of the thermal boundary layer, better flow mixing and increasing turbulence rate by generating secondary flow.

The magnitude of generated heat flux in computer technology is projected to increase from 300 W/cm^2 to 500 W/cm^2 and 1000 W/cm^2

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at hot spots, or even higher in some cases. It is vital to maintain the temperature of processors to <85 °C in order to have a reliable computer chip operation since hot spots in the processor decrease their efficiency [5]. Thus, single phase heat transfer is not a reliable method in cases with high heat flux and new methods need to be found to increase the heat transfer rates with suitable pressure losses.

Water is the most desirable coolant used in a MCHS. However, heat transfer of a two-phase flow in microchannels is significantly higher than with a single phase flow [2,6]. Research performed on two phase flow boiling heat transfer shows flow boiling is not a reliable method due to back flow and instabilities in the flow and so there are lots of difficulties in order to design a proper MCHS [7]. To overcome these problems, recent studies [1,8] have considered replacing the single liquid based two phase flow system with a two phase flow system of two immiscible liquids. In such a liquid–liquid two phase flow system without phase change, droplets of one of the liquids are periodically arranged in a carrier liquid in the microchannel. This is considered to be a superior technique since it not only solves the above-mentioned issues related to two phase flow boiling heat transfer [1,8], but it also leads to a remarkable increase in heat transfer arising from the much higher thermal capacity of liquid droplets in comparison to gas (vapour) bubbles [8].

Fig. 1 schematically shows the Taylor flow in a liquid-liquid two phase flow system, which consists of a thin film between the wall and droplets. However in sliding slug flow at low Capillary numbers (Ca), the droplets can move without creating a film between the wall and droplets. The main reason for heat transfer enhancement in liquid-liquid two phase flow is internal re-circulations which happen inside of both primary fluid and droplets as shown in Fig. 1.

Vast numerical and experimental studies focused on flow and heat transfer behaviour of two phase flow in microchannels have been reported. These have dealt with different parameters, conditions, instrumentation, and geometry dimensions, which indeed make an opportunity for comparison purposes to demonstrate more accurate methodology for solving the case studies.

The dispersion of mentioned results and information encourages many researchers to combine the information to develop general criteria. Additionally, due to the importance of two phase flow, Angeli and Gavriilidis [9] reviewed the hydrodynamics of Taylor flow in small channels. Furthermore, Talimi et al. [10] and Bandara et al. [11] reviewed the heat transfer of slug flow in microchannels. However, the heat transfer of liquid-liquid two phase flow has been developed recently and it is obvious that there is a lack of an in depth study to investigate the heat transfer of liquid-liquid two phase flow in microchannel.

The aims of the present review paper are (1) to review the fluid flow and heat transfer results of recent studies of liquid-liquid two phase flow in microchannels, (2) to summarize the most commonly-used correlations in order to calculate Nusselt number of liquid-liquid two phase flows, (3) to focus on key parameters effecting on heat transfer of liquid-liquid two phase flows, and (4) to present research gaps which need to be considered for future research work in the area.

2. Dimensionless parameters

Many dimensionless parameters have been used to develop liquid-liquid two-phase flow models. Some important parameters expressing the nature of fluid flow and heat transfer rate are Reynolds number, Capillary number, Weber number, Prandtl number, Nusselt number and Peclet number.

The Reynolds number expresses the ratio between inertial and viscous forces:

$$Re = \frac{\rho U D_h}{\mu} \tag{1}$$

where U, $D_H = \frac{4A}{P}$, ρ and μ, signify fluid velocity, hydraulic diameter of channel, fluid density and fluid dynamic viscosity, correspondingly.

Capillary number represents the ratio between viscous force and surface tension force (σ) between the two liquid phases:

$$Ca = \frac{\rho U}{\sigma}. \tag{2}$$

Weber number defines the ratio of inertial force to surface tension force:

$$We = \frac{\rho U^2 D_h}{\sigma}. \tag{3}$$

Prandtl number defines the ratio of momentum diffusion (v) to the rate of thermal diffusion (α):

$$Pr = \frac{v}{\alpha} = \frac{\mu\, C_p}{k}. \tag{4}$$

The Nusselt number shows the dimensionless heat transfer rate on walls:

$$Nu = \frac{h D_h}{k} = \frac{q_w D_h}{k(T_w - T_b)} \tag{5}$$

where k, T_w, T_b and q_w are thermal conductivity, mean wall temperature, bulk fluid temperature and heat flux, respectively.

Peclet number is a dimensionless number which represents the ratio of heat advection to heat diffusion in the area under consideration,

$$Pe \equiv \frac{V_{Droplet} D_h}{\alpha} \tag{6}$$

$$\alpha \equiv \frac{k}{\rho C_P} \tag{7}$$

where $V_{Droplet}$ and α are droplet speed and characteristic thermal diffusivity of the fluid, respectively.

3. Pressure drop

Numerous experimental and numerical investigations focusing on two phase flows have been conducted in the past. However, most of the researchers have studied the gas-liquid two phase flow but fewer researches have been carried out on liquid-liquid two phase flows.

Hydrodynamics and the pressure drop of water-toluene and ethylene glycol/water-toluene as liquid-liquid flow were numerically and experimentally investigated by Jovanovic et al. [12]. They utilized

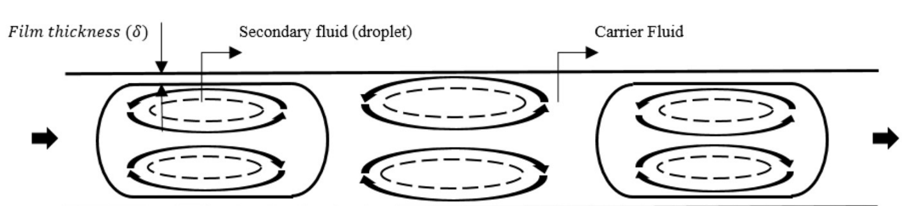

Fig. 1. Schematic diagram of two phase slug flow with recirculation in carrier fluid and droplets.

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