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Local Nusselt number enhancements in liquid–liquid Taylor flows

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ABSTRACT

Thermal management has emerged as a critical requirement to ensure the performance and reliability of electronic devices and systems. System level heat fluxes are approaching the limits of conventional forced air cooling, and there is a need to develop alternative cooling techniques for devices such as processors, power amplifiers and laser arrays. This paper examines the potential heat transfer enhancements of a two phase liquid–liquid Taylor flow regime. The primary focus of the work was to examine the influence of slug length and carrier phase variations on the local Nusselt numbers. An experimental facility was designed and commissioned to subject the flow to a constant heat flux boundary condition, a boundary condition commonly encountered in thermal management applications. Local temperature measurements were acquired using a high resolution infrared thermography system. Experiments were carried out over slug length, Capillary and Prandtl numbers that spanned several orders of magnitude in a minichannel geometry. Reductions in carrier slug length and increases in dispersed slug length were found to augment the heat transfer rates, with the greatest enhancements observed in flows with carrier slug lengths approaching the channel diameter. The thickness of the liquid film separating the dispersed slugs from the heated capillary walls was found to play a significant role in the removal of heat, with increases in film thickness resulting in a reduction in the heat transfer rates. Based on the characteristics identified, a novel correlation is proposed to model the flow in the thermally developing and fully-developed regions.

1. Introduction

Contemporary electronic devices and systems permeate virtually every aspect of our lives. These devices and systems generate large heat fluxes at component level, which is the result of two main trends: the escalation of power dissipation from components; and the reduction in available surface area from which to transfer heat. Today's microprocessors generate heat fluxes of order 100 W/cm^2, while in high end microprocessors this value is closer to 300 W/cm^2 [1]. Consequently, a significant body of research exists focused solely on the development of high heat flux removal technologies. The primary objective of these technologies is to dissipate these high heat loads while maintaining components within safe operating temperature limits. For decades this has been accomplished using forced air convection cooling, whose benefits include simplicity, low cost, ease of maintenance and high reliability [2,3]. However, escalating power dissipation levels necessitate higher air flow rates and hence, larger and more powerful fans, thereby exacerbating the problems associated with profile, noise and vibration control. Hence, conventional forced air convection cooling techniques are no longer sufficient, thus driving the need for alternative cooling modes to the fore. At present, liquid cooling is seen as the prevailing alternative. Liquid cooling yields significantly enhanced heat transfer coefficients compared to air based counterparts, thus allowing further advances in processer performance and miniaturisation. Examples of liquid cooling include: cold plates, [4], impinging jets, [5], spray cooling, [6], microgap cooling, [7], and microchannels, [8], with microchannels seen as the pre-eminent solution.

The use of microchannels for high power density cooling has been widely studied since the pioneering work of Tuckerman and Pease [9]. Theoretically, a microchannel flow possesses high surface-area to volume ratios, thereby generating high heat transfer coefficients. However, a result of the reduced channel dimensions is a laminar flow regime, [10], hence Nusselt numbers do not exceed those of equivalent macroscale systems. Accordingly, microchannel research is now focused towards methods of enhancing the heat transfer rates above macroscale systems. Potential enhancement methods include the addition of: specifi-

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Nomenclature

Ca	capillary number ($\mu U/\sigma$) (–)
c_p	specific heat capacity (kJ/kg K)
D	diameter (m)
h	convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	length (m)
L^*	dimensionless length (L/D) (–)
Nu	Nusselt number (hD/k) (–)
Pe	Peclet number (UD/α) (–)
Pr	Prandtl number ($\mu c_p/k$) (–)
Q	volumetric flow rate (m^3/s)
q''	heat flux (W/m^2)
R	radius (m)
Re	Reynolds number ($\rho UD/\mu$) (–)
T	temperature (°C)
U	bulk mean velocity (m/s)
We	Weber number ($\rho U^2 D/\sigma$) (–)
x	axial position (m)
x^*	inverse Graetz number ($x/DRePr$) (–)

Greek Symbols

α	thermal diffusivity (m^2/s)
δ	film thickness (m)
ε	void fraction (–)
ε_m	modified void fraction (–)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
σ	interfacial tension (N/m)

Subscripts

BM	bulk mean
C	continuous oil phase
D	dispersed water phase
Dev	developed
Ent	entrance
in	inlet
$Plug$	plug flow
$Pois$	Poiseuille flow
S	slug flow
T	total
W	wall
x	local axial position

cally engineered nano-particles to enhance the thermal conductivity of the fluid [11], microencapsulated phase change materials (MPCM) [12], vortex promoters to the channel surface [13] and multiphase flows [14]. Research, by authors such as Betz and Attinger [15] and Che et al. [16], has shown that multiphase flows offer the best potential for increased heat transfer rates. Thermally, multiphase flows have been studied from both boiling and non-boiling perspectives. In a boiling multiphase flow regime, the surface temperature exceeds the saturation temperature of the coolant. This results in a change in phase within the heat exchanger, which generates very high local heat transfer coefficients. However, boiling heat transfer can be difficult to control and quantify; and it requires sealed vessels for containment. Nonetheless, a considerable body of research exists in this area [17–19]. Alternatively, the use of non-boiling multiphase flows to remove high heat loads has received considerably less attention in the literature and is the focus of the present study. Non-boiling multiphase flows are generated when two immiscible phase are pumped into a channel at a variety of flow rates. The generated flow regimes are the result of surface and body force interactions and include: churn, annular, wavy, slug and stratified [20]. At the micro-scale, however, surface forces dominate over the gravitational, resulting in the slug or Taylor flow regime being the most commonly encountered. A Taylor flow regime consists of a series of slugs dispersed at regular intervals, suspended in a continuous carrier phase, which also forms slugs and is illustrated in Fig. 1. The dispersed slugs occupy the majority of the capillary cross-section, with only a thin axisymmetric film of the carrier phase separating the dispersed slugs from the capillary walls.

Some of the earliest works examining the heat transfer rates in non-boiling two-phase slug flows were those of Prothero and Burton [21], who noted that segmenting a continuous stream of liquid with gaseous bubbles was almost twice as effective in transferring heat as Poiseuille flow. Examining the phenomenon, Oliver and Young [22] noted that two distinct mechanisms were responsible for the enhanced heat transfer rates generated by such a flow regime: the increased velocity of the liquid phase, resulting from the addition of the gaseous phase, and an internal circulation within the liquid phase. Analysing the problem analytically, Muzychka et al. [23] came to similar conclusions, that the improved thermal performance is attributable to the modified velocity profile in the liquid slug and the internal circulation. A number of studies have examined the problem experimentally, [15,24,25], and have reported Nusselt number enhancements up to 600% over conventional Poiseuille flows, [26]. In the majority of these studies, the flow regime consisted of gaseous bubbles dispersed in a continuous liquid medium. However, the thermophysical properties of gases render them less attractive as coolants. Their comparatively

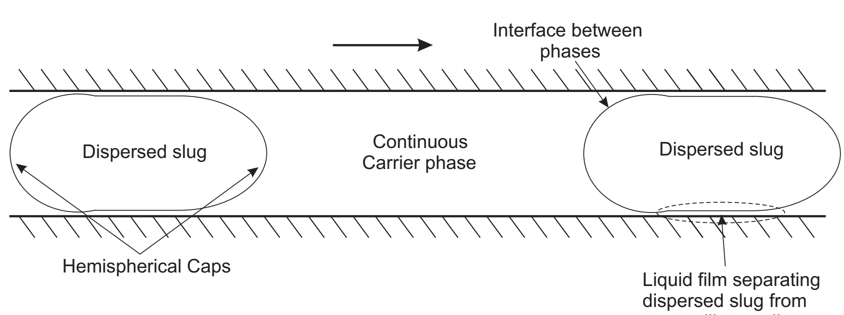

Fig. 1. Taylor flow regime consisting of slugs dispersed at regular intervals in a continuous carrier phase.