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A unified model for Digitized Heat Transfer in a microchannel

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ABSTRACT

Digitized Heat Transfer (DHT) is a novel method of adaptive thermal management for high powered devices that uses discrete microdroplets to remove heat. In this paper, the heat transfer characteristics of DHT are investigated for parallel plate and axisymmetric circular microchannels using scale analysis and numerical simulations. DHT in axisymmetric microchannels are also studied using experimental tests. Through scale analysis, it is found that DHT is quantified by the Nusselt number (Nu) and is a function of the Reynolds number (Re), Prandtl number (Pr), nondimensional axial distance (x/D_H), and droplet aspect ratio (Æ). In simulation and experiment, Nu shows a direct relationship with Re and Pr as well as an inverse relationship with Æ. Using the Graetz problem as a model, new scaling relations are proposed for the axial distance, x, and Nu in an effort to collapse the Nu curves that exist for different flow parameters. To align the characteristic oscillations of Nu found in DHT, x is scaled by the droplet circulation length, L_{circ}, to create a new nondimensional axial distance, $x_{\text{circ}} = \frac{x}{L_{\text{circ}}}$. In order to match the overall magnitude, Nu scaling is derived based on the two different modes of heat transfer that occur before and after one circulation length. Prior to one circulation length, heat transfer is characterized by thermal boundary layer growth and the scaling parameter is determined to be $f_1 = \sqrt{\frac{RePr}{\text{Æ}}}$. After one circulation length, recirculation of heat is dominant and a scaling parameter f_2 is found to be a linear function of $1/\text{Æ}$. f_2 is modeled by the equation $f_2 = \frac{c_1}{\text{Æ}} + c_2$ where c_1 and c_2 are dependent on Re and Pr. The two scaling constants are merged using an inverse tangent weighting function (w) so that a fully scaled Nusselt number, Nu^*, is defined by $Nu[(1/f_1)(1-w) - (1/f_2)w]$. Using this unified model, numerical and experimental data are reduced to a single curve that depicts the heat transfer to any digitized flow. In the future, this model will be helpful in comparing various DHT systems as well as enabling the design of powerful and efficient DHT based thermal management systems.

1. Introduction

One of the largest challenges facing current and future electronic devices is adequate thermal management. Improper cooling of devices results in high temperatures that can reduce performance, decrease life spans, or even cause catastrophic failure. This problem has only been exacerbated as devices have become smaller and more powerful. Already, high performance devices are producing heat fluxes on the order of 10^3 W/cm^2 [1,2] and are expected to increase to rates greater than 2500 W/cm^2 [3]. In comparison, traditional forms of cooling such as air based forced convection is only capable of heat removal on the order of 10^{-1} W/cm^2. Clearly, traditional forms are insufficient for state-of-the-art systems, however they are also rapidly becoming insufficient for basic personal computer demands as well. To address the growing demands, engineers have turned to liquid based cooling with various implementation schemes that are capable of significantly higher heat transfer rates.

Some of the liquid cooling schemes that have been previously studied include microjet devices [4], thermionic cooling [5,6], thermoelectric microcoolers [7], and microchannel cooling [8]. Each of these methods have unique advantages and disadvantages, but they all seek a balance between performance, cost, and reliability. While some of these methods have achieved extremely high heat transfer rates, they sacrifice cost and reliability. For example, Silverman et al. reported 2000 W/cm^2 in microjet devices using liquid metals [9] and Hirshfeld et al. reported 1500 W/cm^2 in

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Nomenclature

A	liquid A
a	sharpness of weighting function
Æ	droplet aspect ratio
B	liquid B
b	location of transition in weighting function
c_p	specific heat
c_1	coefficient of f_2 scaling function
c_2	coefficient of f_2 scaling function
D	diameter of axisymmetric channel
D_H	hydraulic diameter
DHT	Digitized Heat Transfer
$EWOD$	Electrowetting On a Dielectric
$\mathbf{f}$	body force
f_1	Nu scaling constant for $x_{circ} < 1$
f_2	Nu scaling constant for $x_{circ} > 1$
h	heat transfer coefficient
H	height of parallel plate channel
k	thermal conductivity
L	length along x-axis
L_A	length of a droplet of fluid A
L_B	length of a droplet of fluid B
L_D	length of a droplet
N_Γ	ratio of diffusion time scale to convection time scale
Nu	Nusselt number
Nu^*	scaled Nusselt number
Nu_{avg}	time averaged Nu
Nu_{Graetz}	Nu curve for the Graetz problem
n	liquid fraction
p	pressure
Pe	Peclet number
Pr	Prandtl number
q''	heat flux
r	axis in radial direction
Re	Reynolds number with D_H as the characteristic length
Re_L	Reynolds number with L as the characteristic length
t	time
T	temperature
T_w	temperature at inner wall of channel
T_b	droplet bulk temperature
T_0	inlet temperature
u	velocity component parallel to the x-axis
U	bulk velocity along the x-axis
$\mathbf{v}$	velocity vector
w	scaling weight function
x	axis parallel to the line of symmetry in a fixed reference frame
x'	axis parallel to the line of symmetry in a moving reference frame
x_{circ}	axial distance nondimensionalized by circulation length
x^*	Graetz number
X_T	length along x which a flow becomes thermally fully developed
y	axis normal to the wall in a parallel plate channel
α	thermal diffusivity
δ_s	dirac delta function
δ_T	thermal boundary layer thickness
κ	curvature of the interface
λ	length of droplet fluid A and B combined
μ	dynamic viscosity
ρ	density
σ	surface tension
τ_{diff}	diffusion time scale
τ_{circ}	recirculation time scale
θ	nondimensional temperature
θ_w	nondimensional wall temperature
θ_{avg}	average nondimensional temperature

microchannels [10]. While effective for high heat flux cooling, these methods are limited by high pumping pressure, susceptibility to mechanical failure, and lack of adaptability. A relatively new method of cooling that is the focus of this paper is Digitized Heat Transfer (DHT) [11–13], a method that has the potential to provide a reliable, highly adaptable, and efficient thermal management solution.

DHT is a method of thermal management that utilizes discrete microdroplets translating across heated surfaces to remove excess heat. Several methods of droplet transport have been proposed including dielectrophoresis [14], acoustic waves [15] thermocapillarity [16], and electrowetting [17,18]. Among these methods, Electrowetting On a Dielectric (EWOD) has become the most popular due to its low energy consumption, high actuation velocities, and programmability. EWOD uses electrodes beneath a dielectric layer to manipulate droplet wetting behavior. On an array of electrodes, voltage can be applied such that the electrode beneath the leading edge of the droplet is always activated. This in turn will cause droplet motion in the direction of the activated electrode. One of the primary advantages of this method is its mechanical simplicity. The system does not require any pumps or valves, thus creating a system that is less prone to failure. Furthermore, droplet paths are fully programmable and can be reconfigured by simply editing a computer program. This allows for real time droplet path optimization for changing temperature distributions. Fig. 1 shows a conceptual representation of a simple DHT device that could transport discrete droplets using any of the methods mentioned previously. As seen in the theoretical device, droplets can be transported across the heated surface along hundreds of different paths, creating a flexible and adaptable system. While electrodes are patterned directly onto the heated surface in Fig. 1, an alternative configuration could pattern electrodes on a separate plate that is placed opposing the heated surface. Coolant would flow between the heated surface and the actuation plate, thus creating a more modular system. In terms of heat transfer, digitized flows have shown higher heat transfer rates than continuous flows with equivalent mass flow rates [12,13]. While heat transfer to digitized flow has been studied previously [12,13,19–25], most of these studies have been limited to specific Reynolds numbers, Prandtl numbers, and aspect ratios. Amongst these studies, multiple parameters were simultaneously

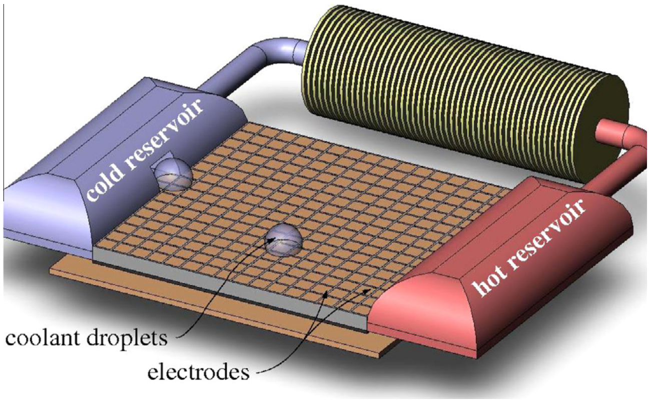

Fig. 1. DHT concept device.