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Effect of developing flow and thermal regime on momentum and heat transfer in micro-scale heat sink

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Abstract

A developing micro-channel heat transfer and fluid flow has been investigated experimentally in rectangular micro-channels of $D_h = 440$ μm, having water as a working fluid. Infrared technique was used to design and built a micro-channel test section that incorporate internal fluid temperature measurements. The new method that provides information about the fluid temperature distribution inside the channel and provides validation for the methods used to determine the local and average Nusselt numbers. The experimental results have been compared with theoretical predictions from the literature and results obtained by numerical modeling of the present experiment. The experimental results of pressure drop and heat transfer confirm that including the entrance effects, the conventional theory is applicable for water flow through micro-channels.

These results differ from the conclusions of several researches. It was shown that data presented by some researches can be due to entrance effects. The present results highlight the importance of accounting for common phenomena that are often negligible for standard flows such as accounting for profile of inlet velocity, axial heat conduction, effect of the design inlet and outlet manifolds.

This paper, to the best of knowledge, is the first presentation on the method of the bulk fluid temperature measurements along micro-channel using IR technique, and calculation of the local heat transfer coefficient based on the local heat flux and the local temperature difference between the heated wall and the bulk fluid temperature.

Keywords: Micro-channels; Laminar flow; Entrance effect; Axial conduction; Infrared technique; Pressure drop; Heat transfer

1. Introduction

One potential solution to thermal management of a chip is to attach a micro-channel heat sink to inactive (back) side of the chip. Usually in a close-loop arrangement, coolant such as water is pumped trough the micro-channels to remove the heat generated. Due to the small size of the micro-channels, the heat transfer coefficient is very high. In an early work by Tuckerman and Pease [1], a micro-channel heat sink consisting of parallel micro-flow passages, was demonstrated to have very small thermal resistance. Since that time, this technology has been used in micro-electronics and other major application areas, such as fuel cell systems and advanced heat sink designs. These practical advantages of micro-channel heat sinks have stimulated researches in experimental, theoretical and also numerical field. Comprehensive surveys may be found in [2–5]. Experimental studies on micro-channel heat transfer and pressure measurements reported in the literature present strong dispersion of the results and sometimes disagree with the conventional theories of transport phenomena which are well verified in macro-scale flows.

Effect of entrance length on the pressure drop and the heat transfer for conventional channels was presented by Shah and London [6]. Kim and Kim [7] investigated numerically the influence of velocity and temperature distributions on the heat transfer and friction factor at both high-aspect-ratio and low-aspect-ratio micro-channels heat

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Nomenclature

A	cross-section area
C_p	specific heat
C^*	$Po_{\mathrm{exp}}/Po_{\mathrm{th}}$
D	diameter
f	friction factor
F	heated surface
h	heat transfer coefficient
H	micro-channel height
k_{f}	thermal conductivity of the fluid
k_{s}	roughness
K_∞	developing flow loss coefficient
L	length
$\ddot{m}$	mass flux
N	power
Nu	Nusselt number
P	pressure
Pe	Peclet number
Po	Poiseuille number
Pr	Prandtl number
q	heat flux
Re	Reynolds number
r_0	micro-channel hydraulic radius
T	temperature
u	velocity
u^*	friction velocity
W	micro-channel width
x, y, z	Cartesian coordinates
X^+	dimensionless hydraulic entrance length
X^*	dimensionless thermal entrance length

Greek symbols

α	aspect ratio
ε	uncertainty
η	dimensionless radius
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	shear stress

Subscripts

av	average
exp	experimental
f	fluid
h	hydraulic
in	inner
T	thermal
th	theoretical
w	wall

sinks. Petukhov [8] investigated heat transfer characteristics and drag of laminar flow of liquid in pipes.

Peng and Peterson [9] and later, Peng and Wang [10] investigated the convective heat transfer and flow friction for water flow in micro-channel structures. The experimental results indicated that the geometric configuration had a significant effect on the single-phase convective heat transfer and flow characteristics. Empirical correlations were suggested for calculating both the heat transfer and pressure drop.

Qu et al. [11] performed an experimental study of the pressure drop in trapezoidal silicon micro-channels with a hydraulic diameter ranging between 51 μm and 169 μm. A high ratio of channel length to diameter $180 < (L/D_{\mathrm{h}}) < 600$ determined fully developed laminar flow regime in which, the calculated friction factors found to be higher, by 8–38% than the expected values obtained by using the conventional theory. The authors justify the deviation in the results due to high relative roughness (3.5–5.7%) in the channel surface and proposed the numerical roughness–viscosity model to explain the experimental data.

Pfund et al. [12] measured the pressure drop, friction factor and Poiseuille number of water flowing along $(D_{\mathrm{h}}) = 128$–1050 μm rectangular micro-channels, at $Re = 60$–3450. In the laminar regime ($Re < 2000$) their data show good agreement with the conventional theory with regard to the non-dependence of Poiseuille number on Reynolds number but the measured values were higher than these corresponding to theoretical prediction.

Jiang et al. [13] investigated frictional losses in rectangular micro-channels of $D_{\mathrm{h}} = 300$ μm. The average value of the non-uniform relative roughness was measured by electron microscope and was found to be as high as 12%. The measured friction factors were larger than the values predicted by the conventional theory. This result was attributed to channel walls roughness and short length of the micro-channels, which did not allow one to neglect the effects of the hydrodynamic entrance region.

Mala and Li [14] investigated experimentally the pressure losses in micro-channels with diameters ranging from 50 μm to 254 μm. The relative roughness changed from 1.36% to 7.0%. The measurements indicated the existence of significant divergence between experimental values of pressure gradient and values predicted by conventional theory.

The effect of roughness on pressure drop in micro-tubes with diameter 620 μm and 1067 μm and relative roughness 0.71%, 058% and 0.321% was investigated by Kandlikar et al. [15]. For 1067 μm diameter tube, the effect of roughness was insignificant. For the 620 μm tube the pressure drop results showed dependence on the surface roughness.

Xu et al. [16] investigated deionized water flow in micro-channels with hydraulic diameter from 30 μm to 344 μm at $Re = 20$–4000. Two different experimental test modules