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Scale-inspired enhanced microscale heat transfer in macro geometry

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ABSTRACT

This paper demonstrates the feasibility of achieving enhanced microscale heat transfer effects in macro geometry systems using conventional fabrication methods. An annular microchannel, of mean channel gap 300 μm and length 30 mm, is formed by securing a cylindrical insert of mean diameter 19.4 mm within a cylindrical pipe of internal diameter 20 mm. The Fish Scale (FS) profile is introduced on the insert surface to improve the convective heat transfer coefficient, for a constant heat transfer area. The effect of the FS enhancement profile on the heat transfer and flow characteristics are experimentally studied using water, with Reynolds number ranging from 350 to 4600. Results show that the FS profile enhances heat transfer by promoting early laminar-to-turbulent flow transition. The highest convective heat transfer coefficient achieved is 47.9 kW/m^2·K, using the FS profile with a scale height of 0.21 mm and scale pitch of 2.1 mm, at Reynolds number of about 4400. New working correlations for the average Nusselt number and friction factor are proposed for the enhanced FS microchannels. These correlations may be used in the future to design macroscale heat exchangers employing economical conventional fabrication techniques and yet exhibiting superior microchannel heat transfer capabilities.

1. Introduction

Microchannel heat transfer was pioneered in 1981 by Tuckerman and Pease [1]. Subsequently, numerous studies have been conducted to investigate microscale fluid flow and heat transfer characteristics [2,3]. Microchannel cooling involves liquid cooling in copper or silicon micro-geometry heat dissipation elements, as well as two-phase flow boiling [4]. In view that flow boiling instabilities pose a huge challenge to the practical implementation of evaporative microscale heat exchangers [5], single-phase liquid flow with heat transfer enhancement features shows potential to achieve comparable heat transfer performance, and at the same time, avoiding the high pumping power requirement and complexity of two-phase flow systems [6,7]. The heat transfer enhancement techniques for single-phase liquid flow can be classified into two categories: passive and active [6,8]. Since the latter require external power, passive techniques are preferred for simplicity in design. The generally accepted convention of $\leq$1 mm channel size as the microchannel definition [9–11] is adopted in this paper.

In recent years, there is a growing interest in the implementation of enhanced microscale heat transfer in macro geometry [12–17]. In this relatively simple and less costly approach, the microchannel is created by combining two macro geometries, which are engineered through economical conventional machining processes. Hence, superior heat transfer effects comparable to that of microchannels can be achieved without involving costly and complex microfabrication technologies [18,19]. Kong and Ooi [20] first proposed the idea of placing a cylindrical insert concentrically within a circular conventionally-sized channel, in order to create an annular microchannel. The study reported a heat transfer coefficient of at least 20 kW/m^2·K at Reynolds number of 5200, for a gap size of 300 μm. This demonstrates the feasibility of combining two macro geometries to achieve microscale heat transfer effects.

Moving on, the focus is to enhance heat transfer by designing inserts of different surface profiles. Using scales as geometrical profiles to disturb the fluid flow throughout the microchannel, the convective heat transfer coefficient can be improved as a result. Goh and Ooi [21] investigated the effect of the Inverted Fish Scale (IFS) profile on the heat transfer and flow characteristics of the microscale flow. While high heat transfer coefficients are achieved,

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Nomenclature

A	heat transfer surface area [m^2]
A_c	cross-sectional area [m^2]
c_p	specific heat [J/kg·K]
D	diameter [m]
D_h	hydraulic diameter [m]
e	scale height [m]
f	friction factor [–]
H	channel height [m]
h	heat transfer coefficient [W/m^2·K]
h_e	enthalpy per unit mass [J/kg]
k	thermal conductivity [W/m·K]
L	channel length [m]
$\dot{m}$	mass flow rate [kg/s]
Nu	Nusselt number [–]
P	scale pitch [m]
p	pressure [Pa]
Pr	Prandtl number [–]
Q	volumetric flow rate [m^3/s]
q	heat input [W]
r^*	ratio of inner to outer diameter of annulus [–]
Re	Reynolds number [–]
S_M	momentum source [kg/m^2·s^2]
S_E	energy source [kg/m·s^3]
T	temperature [K]
$\mathbf{U}$	velocity vector [m/s]
u	velocity [m/s]
y^+	dimensionless wall distance [–]
z	axial location [m]
$z_{hy}{}^*$	$z/(D_h\ Re)$ [–]

Greek symbol

ε	surface roughness [m]
ε^*	dimensionless surface roughness [–]
η	thermo-hydraulic performance factor [–]
ρ	density [kg/m^3]
τ	stress tensor [Pa]
μ	dynamic viscosity [Pa·s]

Subscript

c	copper
Cr	critical
f	fluid
hy	hydrodynamic
I	inlet
FS	Fish Scale profile
m	mean
o	outlet
Plain	plain profile
r	radial
w	wall

the friction factor of the enhanced microchannel can reach up to about 10 times that of the Plain microchannel. Hence, it is of interest to study the Fish Scale (FS) profile for its streamlined flow characteristics, since it is designed to mimic the natural forward swimming direction of fishes for minimal flow disturbances. The streamlined FS profile is potentially useful for heat transfer applications where low fluid pressure drop is of critical importance, such as electronics cooling.

For passive heat transfer enhancement techniques, three possible mechanisms have been proposed [22]: (1) decreasing thermal boundary layer thickness, (2) increasing flow interruptions, and (3) increasing velocity gradient near the heated surface. In addition, the redeveloping thermal boundary layer concept to enhance heat transfer is experimentally verified [23]. The effect of early flow transition in enhancing heat transfer has also been established [24,25].

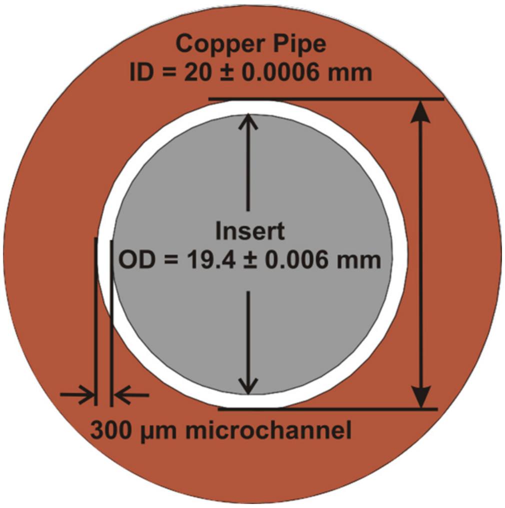

Fig. 1. Front view of flow channel of interest.

On another note, recent literature concludes that the classical theory on mass and momentum conservation apply for flow characteristics in single-phase microchannel flow [26,27]. While earlier studies on microchannels [28,29] report early laminar-to-turbulent flow transition, at Reynolds numbers less than 1500, subsequent studies after 2002 found no early transition at $Re < 2000$ [30–32]. In particular, Sharp and Adrian [33] confirmed in 2004 that the transition to turbulent flow occurs at approximately the same Reynolds numbers as in macroscale channels.

The present study aims to experimentally investigate the effect of the Fish Scale (FS) enhancement profile on the heat transfer and flow characteristics of the microscale flow. Single-phase flow using distilled water with Reynolds number range of 350–4600 is examined. Two heat fluxes of 13.3 W/cm^2 and 53 W/cm^2 are used. The mean channel gap size is 300 µm, and the microchannels are considered hydraulically smooth. The novelty of this paper lies in the derivation of working correlations for the average Nusselt number and friction factor in the enhanced FS microchannels, which are potentially useful in industrial applications.

2. Experimental method

2.1. Research methodology

As shown in Fig. 1, the 300 µm annular microchannel is created by placing a cylindrical insert within a circular channel. Both the insert and the channel are of macro scale, with the insert outer diameter being 19.4 mm and the channel inner diameter being 20 mm. Although the hydraulic diameter of the annular microchannel is 600 µm, this paper uses a gap size of 300 µm to describe the microchannel, following the convention in parallel plates. This is in view that sufficiently small annular gap exhibits similar flow characteristics to flow in parallel plates [34].