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Nature-inspired Inverted Fish Scale microscale passages for enhanced heat transfer

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ABSTRACT

The feasibility of achieving microscale heat transfer effects in macro geometries using conventional fabrication methods has recently been demonstrated. This paper looks at passive techniques, using nature-inspired Inverted Fish Scale geometrical design, to improve the heat transfer performance of the newly proposed system. In this study, an annular microchannel, with gap size of 300 μm, is formed by securing a cylindrical insert of mean diameter 19.4 mm within a cylindrical pipe of internal diameter 20 mm. The Inverted Fish Scale profile is introduced on the insert surface, so as to improve heat transfer through increasing the convective heat transfer coefficient of the flow, for a constant heat transfer area. Both experimental and numerical investigations are carried out to study the effect of the Inverted Fish Scale enhancement profile on the heat transfer and flow characteristics of the microscale flow. Single-phase liquid flow using distilled water is examined, with Reynolds number ranging from 1300 to 4600. The microchannel is considered hydraulically smooth, with length of 30 mm and hydraulic diameter of 600 μm. Results show that the Inverted Fish Scale (IFS) profile indeed has positive effect in enhancing heat transfer. The maximum convective heat transfer coefficient achieved in the whole study is 52.8 $kW/m^2 \cdot K$, using IFS insert with scale height of 0.21 mm and pitch length of 2.1 mm, at Reynolds number of 4300. This is more than twice the value using Plain insert at the same flow condition. The possible enhancement mechanisms include re-initialization of velocity and thermal boundary layers, flow recirculation and higher turbulence intensity. In addition, the thermo-hydraulic performance factor, which incorporates the undesirable increment in friction factor, is examined. The thermo-hydraulic enhancement of the IFS profile is generally found to be more effective for $1300 \lesssim Re \lesssim 3250$. In particular, the IFS insert with scale height of 0.21 mm and pitch length of 2.1 mm performs 43% better than the Plain insert, at Reynolds number of 1700. New correlations for the average Nusselt number and friction factor are proposed for the IFS microchannel, to be used in the design of compact heat exchangers. Based on calculations, the present system is able to remove heat flux of up to 375 W/cm^2. The pressure drop values of the system are all less than 3.3 bars, which may be overcome by a commercially available pump. The present study reiterates the feasibility of achieving microscale heat transfer effects in macro geometry systems, and demonstrates the effectiveness of the Inverted Fish Scale profile in enhancing heat transfer performance.

1. Introduction

Microscale passages are commonly observed in Nature, such as the lungs and kidneys in living beings. The transport processes become more efficient due to the increase in area-to-volume ratio of the microscale passages. The paradigm shift from macroscale to microscale systems was due in part to the rise of the electronics

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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	Enhancement or Increment factor [-]
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]
m	Mass flow rate [kg/s]
Nu	Nusselt number [-]
P	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]
$\boldsymbol{U}$	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^*	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
f	Fluid
hy	Hydrodynamic
i	Inlet
IFS	Inverted Fish Scale profile
m	Mean
o	Outlet
Plain	Plain profile
r	Radial
w	Wall

industry in the 20th century. Research on this topic was sparked in 1981 by Tuckerman and Pease [1], who demonstrated the capability of microchannels with hydraulic diameter of ~100 μm to remove high heat flux of ~790 W/cm^2 in electronics cooling. Subsequent research focused on the design and implementation aspect, as well as a fundamental understanding of the fluid flow and heat transfer phenomena in microscale flows [2]. The main advantages of miniaturization include significant size reductions in practical devices and low unit cost of microfluidic structures at mass production [3]. Next, with miniaturization comes the question of defining its extent. Kandlikar [4] proposed in 2002 that, conventional channels scale 3 mm and above, minichannel dimensions scale 200 μm to 3 mm, and microchannel dimensions scale 10–200 μm. In subsequent years, however, many researchers still classify microchannels broadly between 1 μm and 1 mm [5,6], or even simply $\leq$ 1 mm [7,8]. This paper adopts the generally accepted convention of $\leq$1 mm as the microchannel definition.

Microchannel cooling involves liquid cooling in copper or silicon micro-geometry heat dissipation elements, as well as two-phase flow boiling [9]. With the projected high cooling demand of at least 1000 W/cm^2 in advanced electronic cooling applications [10], two-phase flow boiling seems to be an attractive option in view of its higher transport efficiency. However, flow boiling instabilities pose a huge challenge to the practical implementation of evaporative microscale heat exchangers [10]. On the other hand, single-phase liquid flow with heat transfer enhancement features has 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 [11]. This concept was first proposed in 1987 [12], where the heat transfer enhancement techniques found in conventional channels were successfully introduced in microchannels.

The heat transfer enhancement techniques for single-phase liquid flow can be classified into two categories: passive and active [13]. Their applications in conventional channels and microchannels have been summarized [11]. Since the latter require external power, passive techniques are preferred for simplicity in design. Three possible mechanisms for the passive techniques have been proposed [14]: 1) decreasing thermal boundary layer, 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 [15]. These mechanisms are acutely considered in the present study in the attempt to enhance heat transfer.

Having explained the advantages of miniaturization, the main challenges for large-scale implementation lie in the intricacy and high cost of microfabrication technologies. The four main technologies are micromechanical machining, X-ray micromachining, photolithographic-based processes, as well as surface and surface-proximity-micromachining [5]. The processes, along with material compatibility and tolerances, have been reviewed [16]. Generally, microfabrication involves creating microchannels directly on the material surfaces, which makes it inherently complex. This paper adopts a different approach to creating the microchannel: by combining two macro geometries. This approach is relatively simple and less costly, since the macro geometries are engineered through conventional machining processes.

Furthermore, it has been proven that microscale heat transfer in macro geometry is indeed viable, and the heat transfer effects are comparable to that of microchannels. Kong and Ooi [17] 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 geometrical profiles. These profiles serve to