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Numerical investigations of developing flow and heat transfer in raccoon type microchannels under inlet pulsation ☆

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ABSTRACT

The present study investigates numerically the simultaneously developing unsteady laminar fluid flow and heat transfer inside a two dimensional wavy microchannel caused by a sinusoidal varying velocity component at an inlet. The flow was both thermally and hydro dynamically developing while the channel walls were kept at a uniform temperature. The simulation was performed in the laminar regime for Prandtl number 7(water) and Reynolds number ranging from 0.1 to 100. A Wavy microchannel having non-dimensional hydraulic diameter 1 with varying pulsating amplitude and frequency represented by the Strouhal number was designed for the given Reynolds number range. Based on the comparison with steady flow in a wavy channel it was found that imposed sinusoidal velocity at the inlet can provide improved heat transfer performance at different amplitudes (0.2, 0.5, 0.8) and frequencies (1, 5, 10) while keeping the pressure drop within acceptable limits.

1. Introduction

Heat transfer under pulsating inlet condition is of interest to researchers as it is frequently encountered in different engineering practices as well as in bio-fluid systems. Though flow development and heat transfer in channels and ducts is quite well studied, transport phenomena in microchannel with pulsating flow condition are yet to be fully understood. Active cooling using single phase fluid flow in micro-sized channels is of interest for cooling applications such as electronic equipment, microreactors, microcombusters and micro heat pumps. The different heat transfer enhancement techniques for single phase flow in microchannels and minichannels are discussed by Marks et al. [1]. One of the passive enhancement techniques that may be used to enhance the heat transfer rate of microchannel is wavy periodic channel. Therefore wavy passages have been considered in several earlier studies as a means to enhance heat transfer when employed in traditional high Reynolds number, presently for low Reynolds number and micro fluidic system by Xin and Tao [2].

A conventional microchannel heat sink generally employs straight channel in which the streamlines of the coolant are nearly straight. Whereas, in wavy channel a self sustained oscillatory flow is developed. These self sustained oscillation leads to the destabilization of the laminar boundary layer which enhances the mixing between the core and near wall fluid. When liquid flows through curved passages, secondary flow (Dean Vortices) may be formed. This accelerates the expansion and contraction of the flow element and thus improves the mixing as well as heat transfer. This mechanism has been studied by many researches as Patankar et al. [3], Wang and Yang [4] for improved heat transfer in microchannel. Some artificial means to improve the heat transfer for creeping flows in wavy microchannel was employed by many researchers such as Quddas et al. [5] and Xia et al. [6]. An experiment was carried out by Hsieh and Huang [7] where they inducted different kinds of passive ribs in wavy microchannel for improving the heat transfer at very low Reynolds number ($Re < 1$). An experimental study was carried out by Sui et al. [8] where they found that the heat transfer performance of the wavy microchannels is compared with those of straight baseline microchannels with the same cross section and length. It is found that the heat transfer performance of wavy microchannels is much better than that of straight baseline microchannels; at the same time the pressure drop penalty of the wavy microchannels can be much smaller than the heat transfer enhancement. A numerical and experimental study of flow and heat transfer was carried out by Gong et al. [9] in a wavy microchannel with hydraulic diameter 500 μm and Reynolds number considered $50 < Re < 150$. They concluded that wavy surface in microchannel can be a potential candidate for heat transfer improvement with the proper selection of geometry and flow parameter without employing any extraneous mixing aids.

Chattopadhyay et al. [10] investigated simultaneous flow development for circular channel and found no evidence of heat transfer enhancement in straight ducts. However, the situation was different for

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Nomenclature

A_w	wavy amplitude in mm
A	amplitude of pulsating flow, mm
D_h	hydraulic diameter, mm
f	frequency of pulsation
h	average heat transfer coefficient
k	thermal conductivity, W/m-k
Nu_{avg}	average Nusselt number
P	pressure
Pr	Prandtl number
Re	Reynolds number
St	Strouhal number
T	temperature
U_{in}	inlet velocity
U_m	mean velocity
u	axial velocity local

Greek symbols

Δ	difference in the value of variable between inlet and outlet of channel
η	enhancement ratio
λ	wave length or pitch of the wavy channel, m
μ	dynamic viscosity
ρ	density of the working fluid, kg/m^3

microchannels characterized by low Reynolds number. Nandi and Chattopadhyay [11] conducted a study on simultaneously developing flow in a plane and axi-symmetric microchannel in the Reynolds number ranging from 0.1 to 100 with a varying amplitude up to 80% and frequency up to St = 10. They have observed that the effect of pulsation is significant only at low Reynolds number compare to moderate Reynolds number where augmentation due to pulsation is less. Recently, numerical study carried out by Nandi and Chattopadhyay [12] on simultaneously developing flow in a Serpentine type wavy microchannel in the Reynolds number range of $0.1 \leq Re \leq 100$. It was observed that the pulsation at the inlet was found to enhance heat transfer with a reduced pressure drop even at low Reynolds number.

All the above studies of flow in the wavy microchannel, heat transfer enhancement mainly depends on geometry modification, optimization of amplitude of wavy channel, Reynolds number and transitional component of the flow. In most of the techniques the desired thermal mixing was often accompanied by a large pressure drop. Otherwise, the improvement in heat transfer was largely marginal. An important observation made is that wavy passage does not provide any significant heat transfer enhancement when the flow is steady, particularly at very low Reynolds number. However if the flow is made unsteady through any external means, significant increase in heat transfer are observed without relying on roughness of elements, transition to turbulence, and complicated geometry. Again, it is observed that significant amount of work on microchannels has been done both experimentally as well as numerically but the literature on simultaneously developing flow in microchannels is found to be very rare. Further, it is noted that even for the conventional channels there are conflicting reports in literature about heat transfer augmentation due to pulsating flow at the inlet. Accordingly, in this work, study in the grey area of simultaneously developing flow in microchannels under inlet pulsation is performed.

2. Problem formulation

Fig. 1 represents a schematic diagram of wavy microchannel used in this present investigation where D is the hydraulic diameter and L is the length of the microchannel. There are a number of geometric parameters important to characterize the wavy channel configuration. The traditional Raccoon channel is modeled where crest and trough are facing each other by a phase of 0^0. The height of the modeled channel that varies sinusoidally is described by the function:

$$y = A_w \sin\left(\frac{2\pi}{\lambda} x\right) \quad (1)$$

The wave amplitude A_w and wavy length $\boldsymbol{\lambda}$ are kept constant here ($A_w = 0.2$ and $\boldsymbol{\lambda} = 1$) to study the impact of pulsating flow at inlet on thermal performance at this geometry. The nondimensional channel length was 24 with 1 straight section at the inlet and the outlet. The wavy section spanned the middle 22 length of the channel with a hydraulic diameter of 1. The Prandtl number of the fluid was taken to be 7(water). The numerical simulation was performed by solving the time dependent continuity, momentum and energy equations for a incompressible fluid with the following assumptions made; (1)Continuous Newtonian fluid, Reynolds with unsteady laminar flow and heat transfer, (2) Specific heat, thermal conductivity and viscosity are single variable functions of temperature, and (3) Negligible gravity and radiation heat transfer. Therefore the governing equations based on these assumptions are:

Continuity equation:

$$\frac{\partial u_i}{\partial t} + \nabla.(\rho u) = 0, \quad (2)$$

Momentum equation:

$$\frac{\partial u_i}{\partial t} + \frac{\partial\left(u_i u_j\right)}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\nabla^2 u_j, \quad (3)$$

Energy equation:

$$\frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i} = \frac{1}{Re \cdot Pr}\nabla^2 T. \quad (4)$$

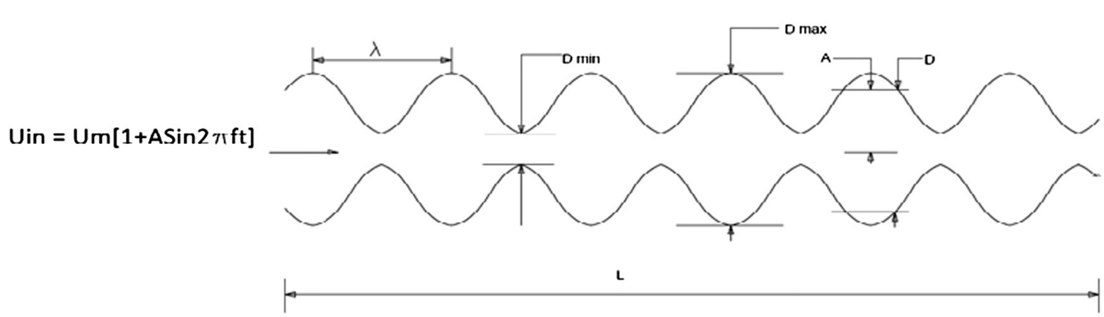

Fig. 1. Schematic diagram of a wavy microchannel.