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Flow and heat transfer characteristics in micro and mini communicating pressure driven channel flows by numerical simulations

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ABSTRACT

The flow and heat transfer characteristics are investigated in micro and mini communicating channel pressure driven flows by 2D numerical simulations using a computational method. The continuum based Navier–Stokes and continuity equations are solved by the Spectral Element Method (SEM). Flow and heat transfer characteristics are determined for $10 < Re < 227$. The 2D communicating channel physical domain contains many blocks within the parallel upper and lower walls. A periodic computational domain of length $2\hat{L}$ and an aspect ratio of $r = \hat{a}/(2\hat{L})$ is used, where $\hat{a}$ is the height of block within the channel and $\hat{L}$ is the periodic length. For low Reynolds number, viscous forces dominate and two stationary symmetric vortices are generated between blocks with very laminar parallel viscous flow in the upper and lower communicating channel. For moderate Reynolds numbers, numerical results show a transition scenario with two Hopf flow bifurcations, as the flow evolves from a laminar to a time-dependent flow regime. The first Hopf bifurcation B_1 occurs at a critical Reynolds number (Re_{c1}) leading to a periodic flow characterized by a frequency ω_1. A quasi periodic flow sets in for higher Reynolds numbers through a second Hopf flow bifurcation B_2 occurring at a critical Reynolds number ($Re_{c2} < Re_{c1}$) with two frequencies ω_1 and ω_2, and a linear combinations of ω_1 and ω_2. The existence of either regime will depend on the previous flow regime, the process of furthering the Reynolds number from one condition to another, and the aspect ratio r. Numerical results show that Nusselt numbers are at least 50% larger in quasi periodic than in periodic and laminar flow regimes. The existence of periodic and quasi periodic flows leads to a heat transfer enhancement at the same Reynolds number.

1. Introduction

Different channel geometrical configurations have been used to enhance heat and mass transfer by flow mixing enhancement in microelectronic cooling and biomedical devices such as oxygenators and kidney dialyzers. Communicating channels are currently being used in micro fluidic devices in biomedical and biological processes such as injection, separation, detection and counting of particles, viruses, bacterias and molecules (in nano fluidic devices). Periodic geometrical inhomogeneities, or large roughness features on the channel walls or between walls, are used in compact heat exchangers and microelectronic devices for producing chaotic passive Lagrangian mixing and heat transfer enhancement. In these devices, high transport rates with reduced energy cost in term of pressure drop and pumping power must be combined with reduced size and weight.

Flow and heat and mass transfer enhancement characteristics in different mini and macro channels have been experimentally and numerically investigated for laminar and transitional flow regimes [1–16]. These investigations determined that laminar flow undergoes a flow bifurcation at a critical Reynolds number (Re_c) significantly lower than the critical Reynolds number for Poiseuille plane channel flow. At this bifurcation, the flow becomes periodic and oscillates with a characteristics frequency $\omega = 2\pi/T$, where T is the oscillation time period. Amon et al. [7,8] and Majumdar and Amon [9,10] experimentally and numerically studied the heat transfer enhancement in laminar and transitional flow regimes in communicating channels. They found a transition scenario characterized by a periodic flow with one fundamental frequency ω. In these channels, the heat transfer rate increases when the flow passes from a laminar to a transitional regime due to flow mixing enhancement after the flow bifurcation, which is accompanied by

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Nomenclature

B_i	Hopf bifurcation	y	crosswise coordinate
H	inlet half-height in one branch of the channel	$\vec{v}$	non dimensional velocity
$\hat{L}$	periodic length	ν	kinematic viscosity
p	non dimensional pressure	μ	dynamic viscosity
Re	Reynolds number	ρ	density
Re_{ci}	critical Reynolds number	ω_i	fundamental frequency
t	non dimensional time		
T_i	time period	*Subscript*	
$\overline{U}, V$	mean velocity	1,2,i	first, second
x	streamwise coordinate		

an increase in the pressure drop. Nishimura and Kunitsugu [12] experimentally investigated the fluid mixing in grooved channels at a constant flow rate founding self-sustained oscillations whose onset depends on the length of the cavity. Nishimura et al. [13] experimentally investigated the influence of the imposed oscillatory frequency on mass transfer enhancement of grooved channels with different cavity lengths for pulsatile flow. They found that the mass transfer enhancement at intermediate Strouhal numbers depends on both the cavity length and Reynolds number, and that the mass transfer enhancement is higher in laminar than turbulent flow. Adachi and Uehera [14] performed numerical investigations of flow and temperature fields for steady state and self-sustained oscillatory flows in grooved channels for various channel geometrical configurations. They found that expanded grooved channels perform more efficiently than contracted grooved channels. Del Valle et al. [15] and Guzman and Del Valle [16] carried out numerical investigations to determine flow mixing and heat transport characteristics for laminar and transitional flow regime in a typical channel with grooves on one side of the channel. They determined a transition scenario of two Hopf bifurcations as the flow evolves from a laminar to transitional flow regime, similar to that of Ruelle–Takens–Newhouse scenario at the onset of turbulence. Significant heat transfer enhancement was also found during the transition scenario to higher Reynolds number flow [15,16]. Transition scenarios at the onset of chaos and turbulence have been numerically investigated and reported by Guzman and Amon [17–19] in converging–diverging wavy channels for high transitional Reynolds numbers. It has been found that the flow develops a second bifurcation in addition to the first flow bifurcation for $\mathrm{Re} > \mathrm{Rec}_1$, which enhances flow mixing and heat transfer. Thus, transition scenarios from laminar to transitional flows, with one, two or more Hopf bifurcations develop in different geometric channel configurations and they depend on the geometrical, flow and fluid parameters. Further studies of transition scenarios in symmetric and asymmetric wavy channels have been reported by Guzman et al. [20,21] for different aspect ratios. The reported results demonstrated the existence of a frequency-doubling transition scenario to high transitional flow regimes develops for high aspect ratio [23–27].

Micro communicating channels flows have been used for many biological processes [28]. For incompressible fluid, although the continuum hypothesis still holds, the Lattice Boltzmann Method (LBM) has demonstrated its advantages for solving the Boltzmann Transport Equations (BTEs) for flow and heat transport in different microchannel configurations in terms of quality results and Lagrangian particle tracking, among other features. Guzman and collaborators have been studying the Eulerian and Lagrangian characteristics of very viscous and time-dependent transitional flow regimes in two-dimensional micro and mini plane, grooved and wavy channels. Numerical results have demonstrated that incompressible flow and biological processes within microchannels can be properly described by the determining Lagrangian characteristics such as particle and interface tracking and stretching fields, and using the LBM. These are important features for processes such as injection, separation, detection and counting [29–31].

This article presents both the flow and heat transfer characteristics in micro and mini communicating channel as the flow regime evolves from a very laminar viscous to a transitional time-dependent flow regime by the time dependent, incompressible continuity, Navier–Stokes and energy equations. The flow and heat transfer characteristics from a laminar to a transitional regime are investigated for an aspect ratio $r = 0.0405$ and $10 < \mathrm{Re} < 227$. A periodic computational domain is used for investigating the flow mixing and heat transfer characteristics.

2. Formulation and numerical approach

The symmetric communicating channel is shown in Fig. 1. A non-dimensional geometric parameter, named aspect ratio, is defined as $r = \hat{a}/(2\hat{L})$, where $\hat{a} = 2a$ and $\hat{L} = L + l$ is the periodic length. The flow is from left to right. A time-dependent incompressible flow of a Newtonian fluid (air at 25 °C) is considered.

For determining and describing the flow and heat transport characteristics the continuum based mass conservation, Navier–Stokes and energy Eqs. (1)–(3) are used. The boundary conditions for the flow problem are periodicity in the streamwise x-direction, which corresponds to a fully developed flow, and non-slip for the upper and lower walls. The heat transfer boundary conditions correspond to adiabatic walls and periodicity in the streamwise x-direction, whereas constant heat generation rate is specified within the block.

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\nabla P + \frac{1}{\mathrm{Re}} \nabla^2 \vec{v} \tag{2}$$

$$\frac{\partial \theta}{\partial t} + \vec{v} \cdot \nabla \theta = -\frac{1}{\mathrm{Re} \cdot \mathrm{Pr}} \nabla^2 \theta + U''' \tag{3}$$

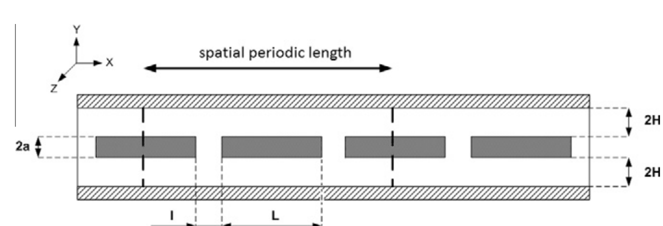

Fig. 1. Symmetric communicating channel dimensions: $l = 0.015$ m, $L = 0.040$ m, $2a = 0.005$ m, and $2H = 0.01$ m. The spatial periodic length contains two blocks.