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Investigations of thermal and flow behavior of bifurcations and bends in fractal-like microchannel networks: Secondary flow and recirculation flow

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ABSTRACT

In this work, the secondary flow and recirculation flow motions initiated at the bifurcations and bends in symmetric fractal-like microchannel networks with two branching levels were studied through three-dimensional simulations. The effects of Reynolds number and aspect ratio on the vortices generation were investigated. And the influences of these flow behaviors on the hydrodynamic and thermal characteristics of the fractal-like microchannel networks were demonstrated. It was found that for a fractal-like microchannel network, both the flow rate and the aspect ratio have large influences on the evolution of the vortices which therefore promoted the fluid mixing and enhanced the efficiency of the heat transfer greatly. As a result, the fractal-like microchannel network with a smaller aspect ratio of 0.333 was verified to have the lowest pressure drop and highest heat transfer performance compared with the other microchannel networks under investigation in our study.

1. Introduction

The broad applications of microfluidic systems in biomedical, biochemical, and micro-electro-mechanical fields have drawn more and more attentions and researches recently, which pushed the vigorous developments of the lab-on-a-chip [1,2]. On the other hand, with the rapid increase of the power density in the electronic and optical devices, an effective and reliable cooling method is urgently needed to satisfy the serious thermal management requirement. Comparing with the traditional air cooling technology, due to the potential possibility to remove a large amount of heat by using small quantities of liquids, the microchannel heat sinks with liquid coolants have presented a promising opportunity to develop micro-cooling devices with much higher heat transfer coefficients [3,4].

In order to improve the overall thermal performance, current studies on microchannel cooling systems mostly focus on different channel shapes of cross section and path configurations as well as microchannel arrays [5–12]. However, due to the nonuniform wall temperature distributions, which arises from the fluid temperature increasing along the channel length, the hot spot areas are still hard to be avoided. And the improvements are acquired at the expense of higher pumping power. Inspired by the natural flow system such as mammalian circulatory and respiratory, the fractal tree networks called “constructal” or “fractal” microchannel networks were originally introduced as heat sinks for electronic devices by Bejan [13]. Furthermore, the fractal-like optimized configuration was verified to have a lower global thermal resistance and a fluid-flow resistance or pumping power [14]. Recently, studies on constructal or fractal-like networks extended to engineering applications, such as micro-coolers, micro-reactors, fuel cells also demonstrate the high efficiency of heat transfer in comparison with traditional parallel straight and serpentine microchannels [15–18].

Although a considerable amount of analytical and optimized work has been done to understand and predict the performance of constructal or fractal-like microchannels [15,19–29], comparatively the deep study on the heat and mass transfer mechanisms limited by the complicated structure still needs to be explored further. In general, the fractal-like microchannels are typically composed of planar channels involving sudden changes

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in directions produced by bends and joints. Haller et al. [30] found that the pressure loss and the heat transfer in the bends and joints led to a higher cooling ability and a higher effectiveness for the cooling system. Thus the flows in these configurations reflect the influences of the microchannel structure on the characteristics of hydrodynamic and thermal fluid flow. Moreover, due to changes of the path configuration, the fluid will experience diffusion or mixing processes in the microchannels, which makes vortices generated in bends and bifurcations [19,30,31]. These vortices characterized by the secondary flow and recirculation flow make the fluid not always in the fully developed region both hydrodynamically and thermally, especially for complex and irregular flow channels such as the fractal-like microchannel networks. When the length of the hydrodynamically developing flow is comparable with the channel length, the effects of the developing flow should not be neglected any more. It will become a main factor in deciding the flow behavior [32,33]. However, few investigations of the secondary flow and recirculation flow in microchannels are available, as well as their influences on the performance of pressure drop and heat transfer.

Furthermore, it is still not possible to get a better understanding of the microscale hydrodynamic and thermal processes since the acquisition for an accurate pressure drop and heat transfer data in the microchannel is currently difficult. The pinpoint measurement heavily relies on the successful fabrication of a complicated microchannel system integrated with dedicated sensors and devices. Although some works have been done to setup an apparatus integrated with arrays of temperature and pressure sensors, as well as micro-PIV system [19,34], the manufacturing process is complex, costly, and inaccessible at some degree. Therefore, it is convenient to use the computational fluid dynamics (CFD) procedure to simulate the flow process numerically and obtain a fair description of the local fluid flow and heat transfer phenomena together with some experimental measurements in the microchannel. In our previous work, the performances of fractal-like microchannel networks with two branching levels had been studied numerically as well as experimentally [32,33]. And the microchannel networks with aspect ratio of 0.333 were demonstrated to have the best hydrodynamic and thermal performance among all the other microchannels investigated. Thus, according to the mentioned above, in this paper, we focused mainly on the Secondary flow and recirculation flow behaviors inside the bifurcations and bends based on the three-dimensional numerical calculations. The dynamics of the vortices generated at the bifurcations and bends were investigated. The effects of the aspect ratios and Reynolds numbers on the evolution and vorticity were compared in detail. And the influences of the bifurcations and bends on the behavior of fluid flow and heat transfer were expounded further.

2. Numerical analysis method

In order to compare with the experimental results obtained in measurements, the numerical simulations were performed by using the commercial software package of CFD-ACE+2006 based on the finite volume method (FVM). The broadly used steady three-dimensional governing equations are listed respectively as follows.

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_j}{\partial x_i}\right) - \frac{\partial P}{\partial x_j} \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\left(\frac{\lambda}{C_p}\frac{\partial T}{\partial x_i}\right) + \frac{\mu}{C_p}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{3}$$

where i, and j are indices in the Einstein summation convention, u_i and u_j are the velocity components, P is the pressure, T is the temperature, ρ and μ are the fluid density and dynamic viscosity respectively, and C_p is the specific heat at constant pressure. In the flow field, the following assumptions were made [35]:

1. The fluid is Newtonian.
2. The transport processes are considered to be steady.
3. The fluid flow is incompressible and laminar.
4. All solid walls of the microchannel are no slip and impermeable.
5. The effect of gravity is negligible in the momentum equations.
6. Thermal radiation effect is ignored.
7. The viscous dissipation effect is ignored, since the Brinkman constant B_r is far less than unity. For our cases, $B_r \approx 0.001$.

In our study, the deionized water (DI water) is used as the working fluid with thermophysical properties shown in Table 1. Apart from the governing equations, the related boundary conditions are provided as follows:

(1) Inlet: The initial temperatures of the working fluid and the ambient air are maintained at 297 K. And a uniform velocity profile is applied to the fluid at the inlet.
(2) Outlet: The ambient pressure is used as the reference pressure of the fluid at the outlet.
(3) Interface: The interfacial condition at solid/liquid interface requires temperature continuity and relates to the temperature gradients.
(4) Wall: The upper wall of the microchannel is treated as adiabatic, while the other three sides of the channel walls are maintained at a constant wall temperature of 323 K.

Table 1
Thermophysical properties of DI water and silicon within the temperature range 283–373 K.

Signal	Unit	DI water	Silicon
μ	Pa s	$0.0194 - 1.065 \times 10^{-4}T + 1.489 \times 10^{-7}T^2$	
λ	W/m K	$-0.829 + 0.0079T - 1.04 \times 10^{-5}T^2$	$290 - 0.4T$
C_P	J/kg K	$5348 - 7.42T + 1.17 \times 10^{-2}T^2$	$390 + 0.9T$
ρ	kg/m^3	998.2	2330

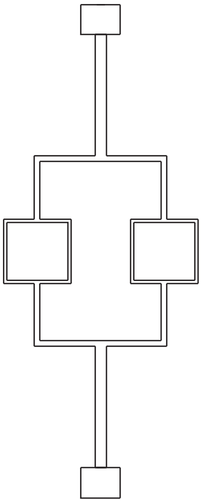

Fig. 1. Schematic diagram of the geometry of a fractal-like microchannel network.