Numerical investigation on the performance of a honeycomb-shaped channel

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Abstract. A certain number of researches have been implemented on the fluid flow and heat transfer in fractal-like channels for their excellent heat transfer performance, which can be attributed to the effects of the bifurcations causing diffusence flow and confluence flow on thinning thermal boundary layer and inducing secondary flow. In this paper, the three-dimensional numerical models of the honeycomb-shaped minichannels were established to research the effects of branching angles on the hydrodynamic and thermal characteristics in the case of laminar flow. A comparative study was carried out to evaluate the performance of the current structures with the straight minichannel based on approximately the same hydraulic diameter, heat flux density and convective heat transfer area. In the simulation results the superiority of overall performance of the honeycomb-shaped minichannels over the straight minichannel was discovered. In addition, the studies showed that the honeycomb-shaped minichannel with smaller branching angle attained the higher overall performance within the relatively high Reynolds number range. It was found that the honeycomb-shaped minichannel with branching angle of 60° yields the best overall performance at the Reynolds number of 400.

1. Introduction

The strong trend of miniaturization of devices has driven the rapid development of microelectronics and MEMS (micro-electro-mechanical system) technologies. The fast increase in heat generation rate of a variety of miniaturized devices such as multifarious electronic components poses severe challenges to the thermal management and control of these apparatuses. Therefore the microchannel heat sink technology proposed by Tacker man and Pease [1] has attracted extensive attention due to its promising heat transfer performance.

The micro-scale straight channel has been widely used because of its simple structure and easy processing. However, with the increase of the heat production rate of devices, the heat transfer capacity of the straight channel is limited and the temperature distribution is nonuniform, which is difficult to meet the application requirements. Therefore, many studies have proposed various structures to improve the heat transfer performance such as pin-fin structures [2] and zigzag grooves [3], the applications of a majority of which are still in the laboratory stage.
Many fractal structures in nature such as mammalian circulatory and respiratory systems have obvious advantages in heat and mass transfer. For this reason many researchers proposed various heat exchangers with fractal structures such as tree-like microchannel nets [4] and disk-shaped microchannel networks [5]. These researches indicate that the fractal-like structures have considerable advantages in achieving uniform temperature distribution and high thermal-fluid performance.

Inspired by the features of honeycomb structure in nature, the honeycomb-shaped minichannel heat sink was proposed in this paper with the purpose of attaining the high heat transfer performance and practical application value. The conjugate three dimensional numerical model of this structure was established to seek the effects of branching angles on the hydro-thermal characteristics.

2. Mathematical model of minichannel

The material of the honeycomb-shaped minichannel heat sink is aluminum and the working fluid is water. Figure 1 reveals the specific information about the computational domain where the gray section is solid and white section is fluid. To evaluate the performance of the proposed structures, a comparative study is conducted with the straight minichannel heat sink based on approximately the same hydraulic diameter, heat flux density and convective heat transfer area. Figure 2 demonstrates the computational domain with geometrical parameters of the corresponding straight minichannel heat sink. The overall dimensions of both the honeycomb-shaped minichannel and straight minichannel are tabulated in Table 1. It is seen that seven representative branching angles (60°, 70°, 80°, 90°, 100°, 110° and 120°) are selected to study the effects of branching angles on the hydrodynamic and thermal behaviour of the honeycomb-shaped minichannels. Noting that the total length \( L_t \) and width \( W_t \) of the tested minichannel heat sinks are different when the fin geometrical dimension \( a \) and the number of the hexagonal prism \( n \) remain fixed.

![Figure 1](image1.png)

**Figure 1.** (a) Three-dimensional schematic and (b) two-dimensional schematic of the honeycomb-shaped minichannel.

![Figure 2](image2.png)

**Figure 2.** (a) Three-dimensional schematic and (b) two-dimensional schematic of the straight minichannel.

| Dimension | \( a \) mm | \( n \) | \( W_c \) mm | \( H_c \) mm | \( t \) mm | \( L_t \) mm | \( W_t \) mm |
|-----------|------------|--------|--------------|-------------|----------|-------------|-------------|
| straight  | /          | /      | 2.0          | 3.0         | 1.0      | 78.5        | 4.8         |
| \( \theta = 120° \) | 3.0 | 9     | 2.0          | 3.0         | 1.0      | 52.9        | 7.2         |
| \( \theta = 110° \) | 3.0 | 9     | 2.0          | 3.0         | 1.0      | 54.7        | 6.9         |
| \( \theta = 100° \) | 3.0 | 9     | 2.0          | 3.0         | 1.0      | 56.6        | 6.6         |
| \( \theta = 90° \)  | 3.0 | 9     | 2.0          | 3.0         | 1.0      | 58.6        | 6.2         |
| \( \theta = 80° \)  | 3.0 | 9     | 2.0          | 3.0         | 1.0      | 60.7        | 5.9         |

**Table 1.** Dimensions of the minichannel heat sinks.
3. Numerical simulation

The fluid flow in the minichannel heat sinks was assumed to be laminar, incompressible and steady, and the solid and fluid have constant thermal properties in the present study. Meanwhile viscous dissipation, radioactive heat transfer and gravity are negligible. The CFD software FLUENT 15.0 was used to complete the numerical simulation.

The followings are the relevant boundary conditions:

1. Velocity-inlet: The inlet is given by velocity-inlet and initial water temperature is maintained at 300K.
2. Pressure-outlet: The outlet is set as pressure-outlet with reference to ambient pressure.
3. Interface: The temperatures and temperature gradients are continuous in solid/liquid interface.
4. Symmetry: The outer flank of the walls along the y direction (including the solid and the fluid surfaces) are set as the symmetrical plane.
5. Wall: The lower wall is maintained at a constant heat flux density of 50000W/m², and the other walls are treated as adiabatic.

4. Results and discussion

4.1. The effects of branching angles

On the straight minichannel basis, the ratio of Nusselt number $Nu/Nu_0$ and the ratio of friction factor $f/f_0$ are selected as the criteria of performance evaluation to ascertain the thermal and hydrodynamic characteristics of proposed structures.

Figure 3 portrays the variation of ratio of average Nusselt number $Nu/Nu_0$ with Reynolds number $Re$ for the honeycomb-shaped minichannels with different branching angles. It can be observed that the honeycomb-shaped minichannels have much better thermal performance than that of the straight minichannel under the tested Reynolds number range, which achieves a maximum ratio of 3.0 times.

As for the honeycomb-shaped minichannels, $Nu/Nu_0$ increases basically with the increment of branching angle $\theta$. The growth of $Nu/Nu_0$ for the honeycomb-shaped minichannels with branching angle $\theta$ from 60° to 90° is relatively stable, however the growth fluctuations with $\theta$ from 100° to 120° are relatively large, even appearing descent stage.

The effects of branching angles on the hydrodynamic performance are shown in Figure 4. It is found that the frictional loss of the honeycomb-shaped minichannels is higher than that of the straight minichannel except the value when $Re = 50$. Meanwhile, the ratio of average friction factor $f/f_0$ increases when the branching angle $\theta$ increases. Unlike the variation of $Nu/Nu_0$, the growth of $f/f_0$ is observed to be steady with branching angle $\theta$ for all the simulated minichannels.

| $\theta$ (°) | $Nu/Nu_0$ | $f/f_0$ |
|-------------|-----------|---------|
| 70          | 3.0       | 9.0     |
| 60          | 3.0       | 9.0     |

Figure 3. Variation of $Nu/Nu_0$ with $Re$ for different branching angles.

Figure 4. Variation of $f/f_0$ with $Re$ for different branching angles.
The overall performance of the minichannels can be evaluated by performance factor, whose expression is as follows:

$$P_f = \frac{(Nu/Nu_0)}{(f/f_0)}$$

(1)

Figure 5 describes the variation of performance factor $P_f$ versus Reynolds number $Re$. It can be discovered that the values of $P_f$ distinctly exceed one for all the honeycomb-shaped minichannels, which indicate the superiority of overall performance for the proposed structures. Meanwhile, it is definitely heeded that $P_f$ of the honeycomb-shaped minichannel with the branching angle of 60° is superior over other types within relatively high Reynolds numbers which approaches its peak value of 1.65 when Reynolds number is 400.

Figure 5. Variation of performance factor $P_f$ with $Re$ for the honeycomb-shaped minichannels with different branching angles.

4.2. Characteristics of streamline and velocity distribution in the minichannels

To further analyze the effects of branching angles on the overall performance, the thermal and hydraulic characteristic of the honeycomb-shaped minichannels is studied detailedly and expressed in the light of streamline and velocity contour.

The streamline at the bifurcation is exhibited in Figure 6. It is seen that fluid in the bifurcation is diverted into two parts. Disturbance occurs when the two divided fluids meet in the confluence area, therefore creating a vortex in the backflow zone. In addition, the larger the branching angle, the greater the change in fluid flow path, and the larger the fluid vortex generated, causing the stronger fluid disturbance and the better heat transfer.

Figure 6. Streamline of the honeycomb-shaped minichannel with branching angle of 120° on x-y plane ($z = 1.5\text{mm}$) at $Re = 300$.

Figure 7 illustrates the velocity distributions for the honeycomb-shaped minichannels with branching angle of 60° and 120° at Reynolds number of 300. It is seen that the fluid velocity is relatively large in the main channel before diversion. The high flow velocity regions are closer to the sharp corner of the fin at the bifurcation with the reduction of the branching angle. After bifurcation the fluid is halved into the bifurcated channel, causing the fluid velocity reduction. In the bifurcated channel the high-speed fluid is mainly close to the side of the wall of the brushed fin, and the fluid velocity close to the side of the backflow zone is relatively low, which leads to a high heat transfer capacity near the brushed fin and a relatively low heat transfer capacity in the backflow zone. As the branching angle increases, the area of the backflow zone increases and the maximum speed is reduced accordingly due to the increased local flow resistance and larger fluid disturbance but the overall velocity uniformity is better.
5. Conclusion
This paper conducted a numerical simulation to study the convective heat transfer in the honeycomb-shaped minichannel heat sinks. By analyzing the effects of branching angles on the hydro-thermal performance, some conclusions can be delivered as follows:
1. Compared with the straight minichannel, the thermal performance of the honeycomb-shaped minichannel enhances at the cost of additional pressure drop. However, the overall performance of the honeycomb-shaped minichannel is higher than that of the straight minichannel.
2. The smaller the branching angle is, the higher the performance factor, namely, the higher the overall performance within the relatively high Reynolds number range.
3. The honeycomb-shaped minichannel with branching angle of 60° has the higher overall performance for all types within the relatively high Reynolds number range, which produces the best overall performance with maximum performance factor $P_f$ of 1.65 at $Re = 400$.

Judging from the above conclusions, the proposed structure is meaningful to acquire relatively high overall performance in electronic cooling and thermal management of small equipment. However, in order to achieve a promising overall performance and improve the applicability, the effects of other geometric parameters and experiment will be carried out in the further work.

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