Applied Energy Symposium 2021: Low carbon cities and urban energy systems
September 4-8, 2021, Matsue, Japan
Paper ID: 57

A comparative study on fluid flow and temperature distributions in microchannel heat sink with different I-type header shapes for high TDP CPUs

Xiyuan Chen[1], Zhao Lu[1,2*], Liyu Zhang[1], Rongjie Duan[1], Yi Che[1], Liwen Jin[1*]

1 School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an, 710049, China.

2 Shenzhen Envicool Technology Co., Ltd., Shenzhen, 518129, China.

E-mail: luzhao@xjtu.edu.cn; lwjin@xjtu.edu.cn;

ABSTRACT

Great thermal management challenges have to be considered that the thermal design power (TDP) of central processing unit (CPU) in the high-performance computer cluster has reached 400 W with package heat flux of 25 W/cm². In this study, the three-dimensional numerical model of I-type microchannel heat sink (MCHS) with uniform heat source (400W) applied to the fin area was established to explore its fluid flow and temperature distribution. Three dimensionless parameters, φ_C (0.111, 0.148, 0.167, 0.185, 0.222), φ_W (0, 0.5, 1) and φ_L (0, 0.5, 1) were employed to comprehensively analyze the effects of the header shapes on the flow distribution in MCHS based on the Mal-distribution Factor (MF).

The numerical results showed that the variation of flow rate in MCHS behaves an overall trend of gradually decreasing from the middle channels to the channels on both sides due to the I-type inlet/outlet arrangement. Besides, the difference of flow rate among the microchannels in MCHS becomes relatively gentle because of φ_C increasing. It is found that rectangular header (φ_W=1, φ_L=1) performs best in flow distribution but triangular header (φ_W=0, φ_L=0) performs worst. These results indicate that the strategy to improve the flow distribution in the microchannels is to increase the value of the three dimensionless parameters. Summarizing the results of fluid flow distribution, temperature maximum and pressure drop obtained from all simulation calculations, the optimal I-type MCHS header design is with φ_C=0.185, φ_W=1 and φ_L=1. This study could provide a specific instruction for the design of the practical I-type MCHS for high TDP CPUs liquid cooling.

Keywords: CPUs liquid cooling, I-type microchannel heat sink, dimensionless parameters, flow distribution, temperature distribution

NOMENCLATURE

Abbreviations	
CPU	central processing unit
MCHS	microchannel heat sink
MF	Mal-distribution Factor
TDP	thermal Design Power
Symbols	
C_p	special heat capacity
D	(hydraulic) diameter
E	relative deviation
k	thermal conductivity
L	length
m	mass flow rate
N	number of fins
P	pressure
P_{atm}	standard atmospheric pressure
T	temperature
V	velocity
W	width
ΔP	pressure drop
μ	viscosity
ρ	density
Subscripts	
avg	average
c	microchannel
in	inlet
max	maximum
min	minimum
s & f	solid & fluid

1. INTRODUCTION

Since the 1960s, the integrated circuit and chip industry has continued to develop in accordance with Moore's Law, which describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years [1]. That is, the density of transistors and chip performance have increased exponentially. Thus, higher performance means smaller size and lighter weight but more heat generation, which causes higher temperature and non-uniform temperature distribution. In 2020, the thermal design power (TDP) of central processing unit (CPU) in the high-performance computer cluster has already reached 400 W with package heat flux of 25 W/cm² [2]. Great thermal management challenges occur because more than 50% of failure causes are temperature-related [3] and the failure rate increases exponentially with temperature based on the failure rate of 348K [4].

Due to excellent heat transfer performance, mild pressure loss and convenient manufacturing, the microchannel heat sink (MCHS) has been recognized as an effective and efficient cooling method to remove heat and control the temperature in electronic devices since Tuckerman and Pease pioneered this investigation in 1983 [5]. The geometrical structure of MCHS has a significant influence on fluid flow characteristics and thermal performance. The foundation of fully using the advantages of a parallel microchannels system is proper flow distribution. The flow maldistribution is immediately reflected in the non-uniform temperature distribution, resulting in the formation of a hotspot area.

Noting that the parameters of the inlet and outlet are crucial to the overall performance of MCHS. Specifically, the flow maldistribution of MCHS is impacted by the inlet/outlet parameters in three aspects: the form of inflow/outflow (horizontal or vertical), the arrangement of inlet/outlet (U-type, I-type or Z-type) and the header shape (rectangle, trapezoid or triangle). Through the experiment data, Anbumeenakshi and Thansekhar [6] discovered that the rectangular header improves flow maldistribution at high flow rate and the vertical inflow/outflow configuration causes lower flow maldistribution than horizontal inflow/outflow configuration in all cases studied. Xia et al. [7] also discovered that I-type arrangement with rectangular header is more likely to acheieve uniform distribution. Manikanda Kumaran et al. [8] used Mal-distribution Factor (MF) to evaluate flow maldistribution and the results clearly illustrated that flow separation and recirculation bubbles occurring in the inlet header are main reasons for the flow maldistribution between channels.

Recently, Some authors [9,10] summarized the current researches and concluded that I-type header shapes (vertical inlet/outlet) are preferred by most of researchers due to relatively uniform flow distribution. However, there is no benchmark for comparing various studies so that the standard design and analysis method can not be obtained to guide the layout of I-type MCHS with better flow distribution and relatively uniform temperature distribution. Most importantly, the correlation between fluid flow and temperature distributions is rarely explored in the lots of references. In this study, therefore, the three-dimensional numerical model of I-type MCHS with different header shapes was established to comprehensively explore the flow distribution and analyze the correlation between fluid flow and temperature distributions, which could provide a specific instruction for the design of the practical I-type MCHS for high TDP CPUs liquid cooling.

2. NUMERICAL ANALYSIS

2.1 Numerical model of microchannel heat sink

Based on the practical application of the I-type MCHS design for CPU liquid cooling, the copper and water are choosen for the material of MCHS and the coolant. It consists of 86 rectangular microchannels and 85 rectangular fins with 0.4 mm/0.2 mm in width respectively, 68 mm in length and 3 mm in height commonly. The thicknesses of MCHS in top, base and side are 2 mm, 2.5 mm and 3 mm respectively.

The design in both inlet and outlet header is symmetrical and identical. Circular inlet/outlet with 4.5 mm in diameter is positioned in the geometric center of header’s length/width direction. The max length of header is 51.4 mm constantly and the max width of header is changed from 1.5 to 3 times diameter of inlet/outlet. The header shapes(rectangle, trapezoid and triangle) would be characterized by changes in the ratio of the min width to the max width and the ratio of the min length to the max length. Some specific geometric details are presented in **Fig 1**.

2.2 Governing equations and boundary conditions

Some assumptions are made for the current numerical study. Fluid flow and heat transfer are steady and three-dimensional. In microchannel, fluid flow is laminar and incompressible. Effects of gravity (or other body forces), radiation heat transfer and viscous heat generation are negligible. Due to the symmetry of

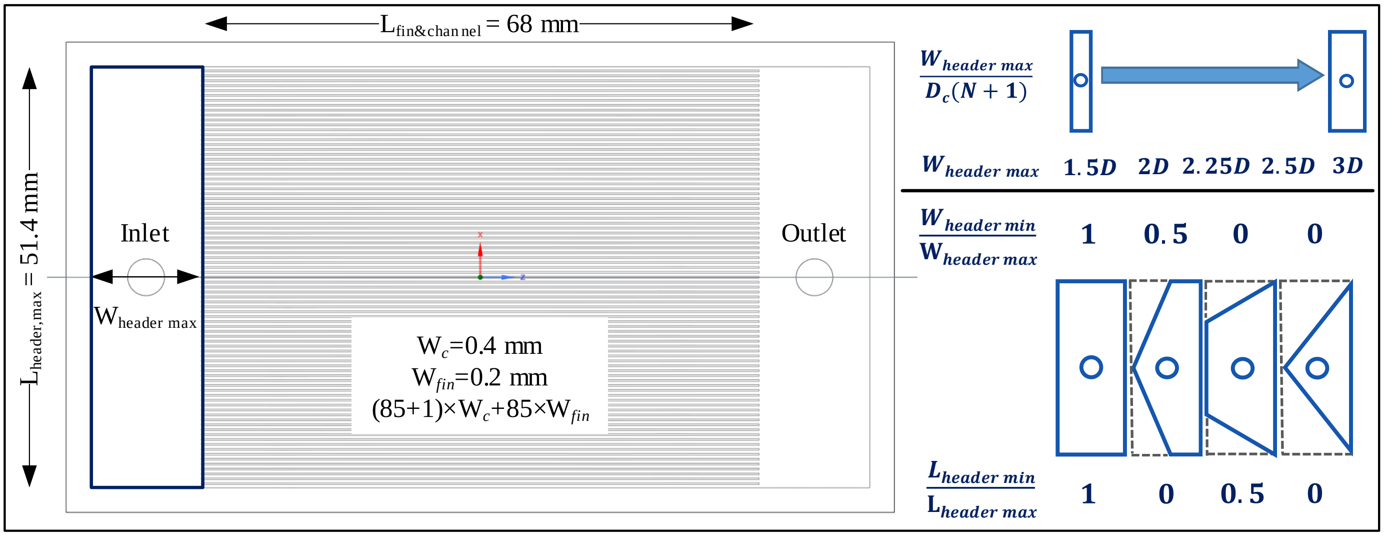


Fig 1 Geometry of the MCHS at top view and correlative change parameters.

geometric structure, half of MCHS is selected as the computational domain with symmetric boundary condition and the behavior of two parts is assumed to be identical.

Based on the above assumptions, the governing equations for fluid and solid are given as follows:

Continuity equation:

$$\nabla\vec{V}=0 \tag{1}$$

Momentum equation:

$$\rho_f\left(\vec{V}\cdot\nabla\vec{V}\right)=-\nabla P+\nabla\mu_f\cdot\left[\left(\nabla\vec{V}+\nabla\vec{V}^t\right)-{}^2\!/_3\nabla\vec{V}\right] \tag{2}$$

Energy equation in fluid flow:

$$\rho_f c_p\left(\vec{V}\cdot\nabla T\right)=k_f\nabla^2 T \tag{3}$$

Energy equation in solid:

$$k_s\nabla^2 T_s=0 \tag{4}$$

Equation in symmetry:

$$\frac{\partial\phi}{\partial\vec{n}}=0 \tag{5}$$

The boundary conditions for the governing equations are given as:

Inlet:

$$V=V_{in},T=T_{f,in} \tag{6}$$

Outlet:

$$P=P_{atm} \tag{7}$$

Fluid and solid interface:

$$V=0,T=T_s,-k_s\left(\partial T_s/\partial n\right)=-k_f\left(\partial T_f/\partial n\right) \tag{8}$$

Typical heat source of high TDP (400W) CPUs are simplified as surface heat source that ideal proformance of copper lid (68 mm × 51 mm, 400W) in CPU, corresponding to the entire fin and microchannel area, with uniform heat flux. Inlet temperature and the temperature difference between inlet and outlet are constantly 318K and 5K.The properties of copper and water (318K) used in the numerical simulation are tabulated in **Table 1**. Based on thermal balance equation, the uniform velocity (V_{in} = 1.217 m·s^{-1}) was applied at the inlet. The standard atmosphere pressure boundary condition was applied at the outlet. No-slip boundary condition was used in all wall boundaries. Outside surfaces of MCHS are adiabatic.

Table 1 Thermo-physical properties of water and copper (at T_{in} = 318K)

	ρ / kg·m^{-3}	C_p / J·(kg·K)$^{-1}$	k / W·(m·K)$^{-1}$	μ / Pa·s
Water	990.15	4174	0.6415	0.0006
Copper	8930	386	398	-

2.3 Numerical schemes

The simulation domains of fluid and solid were discretized by structure grids with grid-encrypted boundary layer in fluid flow particularly. SIMPLE algorithm was applied to coupling of pressure-velcity equations. Pressure items were discretized with Standard algorithm and the second-order upwind scheme was used to solve the momentum and energy equations.

2.4 Grid independence test

The representative case (rectangular header, $W_{header\ max}$ = 3D) is choosen for grid independence test. Three different grids are generated with total of 1.53 × 10^6, 5.47 × 10^6, 7.13 × 10^6 cells and finer grid are more refined in the direction of the length, width, height and boundary layer of microchannel. The relative deviation (*E*) in values of pressure drop, maximum and average temperature in MCHS base for fine grid (f_1) with other grids (f_2) are checked and the results are shown in **Table 2**, where $E=|f_1- f_2|/f_1\times100\%$. Regular gird ($5.47 \times 10^6$) with all diviations less than 1% is adopted for further simulations.

Table 2 Results of grid independence test

	Coarse gird	*E*/%	Regular gird	*E*/%	Fine gird
ΔP/kPa	2017.24	1.96	2056.94	0.03	2057.57
T_{avg}/K	323.78	0.06	323.60	0	323.60
T_{max}/K	325.83	0.04	325.69	0	325.69

3. RESULTS AND DISCUSSIONS

In order to acquire the optimal MCHS geometric parameters of header design in fluid flow and temperature distributions, three dimensionless ratios which normalize the changing geometric parameters have been defined as basic parameters.

$$\varphi_W = \frac{W_{header\,\min}}{W_{header\,\max}} \tag{9}$$

$$\varphi_L = \frac{L_{header\,\min}}{L_{header\,\max}} \tag{10}$$

$$\varphi_C = \frac{W_{header\,\max}}{D_c(N+1)} \tag{11}$$

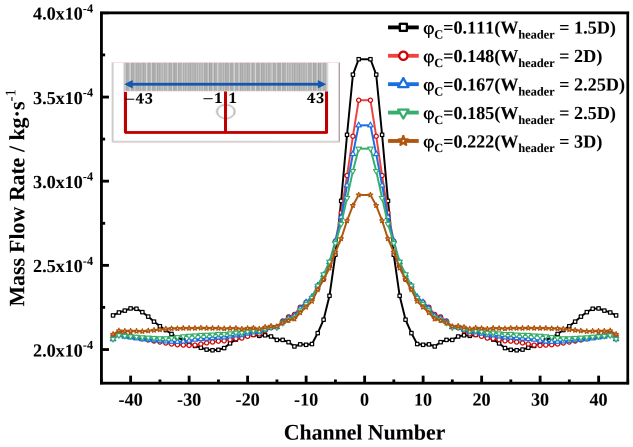
Evaluation factor of flow distribution is MF, which is defined that lower value has better performance in fluid flow distribution in microchannel. MF can be calculated as:

$$MF = \sqrt{\frac{1}{N+1}\sum_{i}^{N+1}\left(\frac{m_i - m_{avg}}{m_{avg}}\right)^2} \tag{12}$$

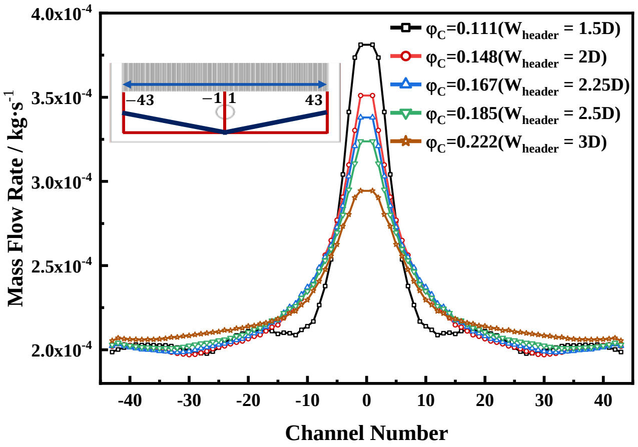
3.1 Influence of header design on flow distribution

Fig 2 presents the flow distribution in I-type MCHS with three kinds of header shapes, namely, rectangle, trapezoid and triangle, which are characterized by three dimensionless parameters of φ_C, φ_L and φ_W. As expected, the variation of flow rate in the MCHS shows an overall trend of gradually decreasing from the middle channels to the channels on both sides due to the I-type inlet/outlet arrangement. In all header shapes studied, there is a drastic flow rate difference between middle channels and its adjacent channels, which could be significantly improved by increasing φ_C value. That is to say, the difference of flow rate among minichannels in MCHS becomes relatively gentle because of φ_C increasing.

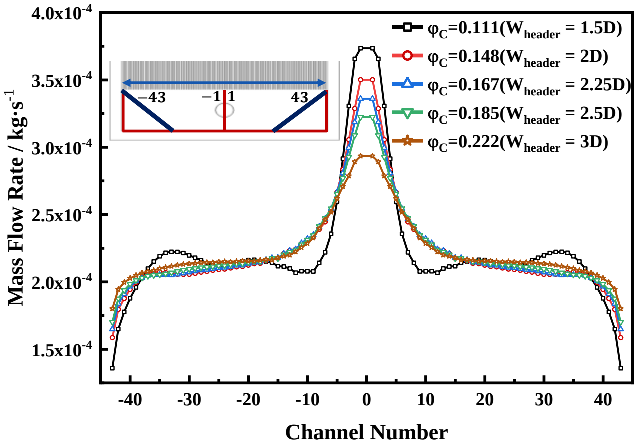
In the meantime, each header shape owns its unique flow distribution characteristics. The results of flow distribution of MCHS with rectangular (φ_W=1, φ_L=1, **Fig 2a**) and trapezoidal (φ_W=0.5, φ_L=0, **Fig 2b**) headers show more uniform flow distribution in microchannels on both sides. However, the flow rate in several microchannels on both sides is still decreasing gradually in the MCHS with the other trapezoidal (φ_W=0, φ_L=0.5, **Fig 2c**) and triangular (φ_W=0, φ_L=0, **Fig 2d**) headers.



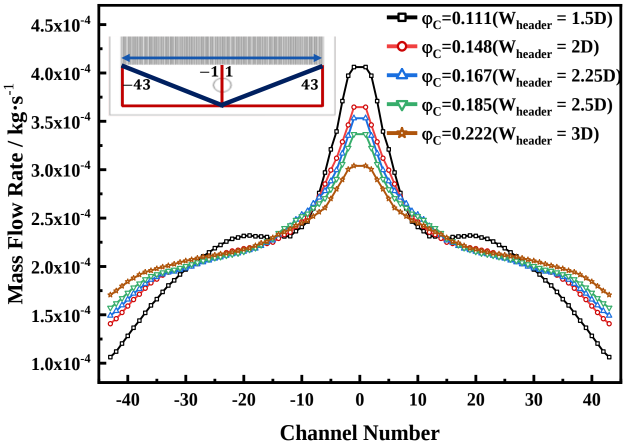
(a) φ_W=1, φ_L=1.



(b) φ_W=0.5, φ_L=0



(c) φ_W=0, φ_L=0.5



(d) $\varphi_W=0$, $\varphi_L=0$.

Fig 2 Flow distribution in each channel of MCHS with various width of header(φ_C) in specific shape(φ_W and φ_L).

In order to intuitively reflect the effects of three dimensionless factors (φ_C, φ_L and φ_W) on the flow characteristics in MCHS, the relationships between MF and φ_C under the all header shapes studied are illustrated in **Fig 3**. Interestingly but not surprisingly, rectangular header ($\varphi_W=1$, $\varphi_L=1$) performs best in flow distribution but triangular header ($\varphi_W=0$, $\varphi_L=0$) performs worst. As a result, the value of MF is smaller when the value of φ_C, φ_W and φ_L are higher. By modifying these dimensionless parameters in the design of header, the MF value can be reduced from the worst 0.306 to the best 0.095, which is optimized by 68.9 %. These findings indicate that the strategy to improve the flow distribution in the microchannels should be to increase the value of the three dimensionless parameters as soon as possible, that is to say, more volume is conductive to achieve better flow distribution in MCHS.

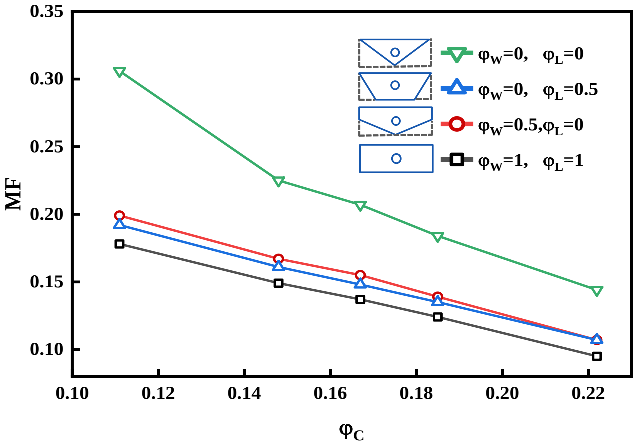


Fig 3 Flow Mal-distribution Factor in different dimensionless parameters of MCHS.

3.2 Influence of MF on maximum temperature and pressure drop

Fig 4 summarizes the effects of MF on the maximum temperature and pressure drop in MCHS. As expected, the maximum temperature and pressure drop almost increase with MF due to the poor flow distribution. Specifically, the maximum temperature increases less than 1K with MF ranging from 0.095 to 0.306, which seems to be a slight increase. However, the growth of pressure drop is up to 300 Pa at the same range of MF. Usually the header design sacrifices the pressure drop performance in order to pursue the uniform fluid flow and temperature distribution. In this study, surprisingly, under the cooperation of three dimensionless parameters, the optimal performance in flow distribution, thermal characteristics and pressure drop may be obtained at the I-type MCHS with $\varphi_C=0.185$, $\varphi_W=1$ and $\varphi_L=1$ header design.

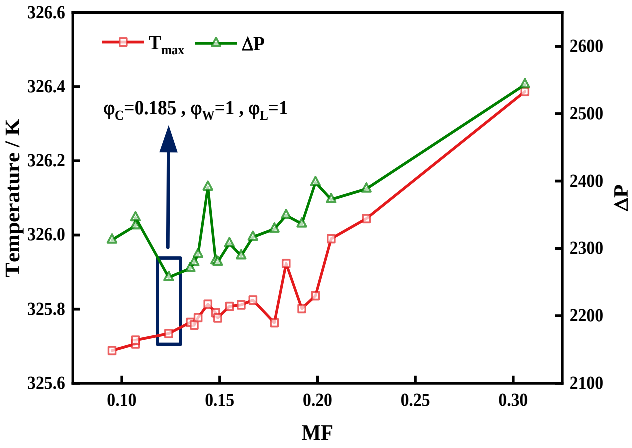


Fig 4 Variations of maximum temperature and pressure drop in MCHS with MF.

4. CONCLUSIONS

In this study, the three-dimensional numerical model of I-type MCHS design is established by practical application and defining dimensionless parameters of inlet/outlet header. Exploring the influence of three dimensionless parameters on the fluid flow and temperature distribution of MCHS through numerical simulation. The following conclusions might be drawn from the present study:

(a) The difference of flow rate among minichannels in MCHS with all header shapes studied becomes relatively gentle because of φ_C increasing.

(b) Rectangular header ($\varphi_W=1$, $\varphi_L=1$) performs best in flow distribution but triangular header ($\varphi_W=0$, $\varphi_L=0$) performs worst. The MF value can be reduced from the worst 0.306 to the best 0.095, which is optimized by 68.9 %.

(c) The optimal performance in flow distribution, thermal characteristics and pressure drop may be obtained at the I-type MCHS with reasonable header design in φ_C=0.185, φ_W=1 and φ_L=1.

ACKNOWLEDGEMENT

The authors are grateful for the support by the China Post-doctoral Science Foundation Funded Project (2021M692534).

REFERENCE

[1] MOORE G E. Cramming More Components Onto Integrated Circuits [J]. Proceedings of the IEEE, 2002, 86(1): 82-5.
[2] Guggari S I . Analysis of Thermal Performance Metrics-Application to CPU Cooling in HPC Servers[J]. IEEE Transactions on Components, Packaging, and Manufacturing Technology, 2020, PP(99):1-1.
[3] Pedram M , Nazarian S . Thermal Modeling, Analysis, and Management in VLSI Circuits: Principles and Methods[J]. Proceedings of the IEEE, 2006, 94(8):1487-1501.
[4] Handbook M S . Reliability Prediction of Electronic Equipment[J]. Mil Hdbkf, 1980.
[5] Tuckerman D B , Pease R . High-performance heat sinking for VLSI[J]. IEEE Electron Device Letters, 1981, 2(5):126-129.
[6] Anbumeenakshi C , Thansekhar M R . Experimental Investigation of Header Shape and Inlet Configuration on Flow Maldistribution in Microchannel[J]. Experimental Thermal and Fluid Science (EXP THERM FLUID SCI), 2016, 75:156-161.
[7] Xia G D , Jiang J , Wang J , et al. Effects of different geometric structures on fluid flow and heat transfer performance in microchannel heat sinks[J]. International Journal of Heat & Mass Transfer, 2015, 80(jan.):439-447.
[8] Kumaran R M , Kumaraguruparan G , Sornakumar T . Experimental and numerical studies of header design and inlet/outlet configurations on flow mal-distribution in parallel micro-channels[J]. Applied Thermal Engineering, 2013, 58(1-2):205-216.
[9] Alihosseini Y , Targhi M Z , Heyhat M M , et al. Effect of a micro heat sink geometric design on thermo-hydraulic performance: A Review[J]. Applied Thermal Engineering, 2020, 170:114974.
[10] Zha B , Yya B , Zz C . Thermal management and temperature uniformity enhancement of electronic devices by micro heat sinks: A review - ScienceDirect[J]. Energy, 2020.