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Experimental analysis of flow and heat transfer in a miniature porous heat sink for high heat flux application

Z.M. Wan [a,*], G.Q. Guo [a], K.L. Su [a], Z.K. Tu [b,*], W. Liu [b]

[a] Department of Physics, Hunan Institute of Science and Technology, Yueyang, Hunan 414006, PR China
[b] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China

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ABSTRACT

A novel miniature porous heat sink system was presented for dissipating high heat fluxes of electronic device, and its operational principle and characteristics were analyzed. The flow and heat transfer of miniature porous heat sink was experimentally investigated at high heat fluxes. It was observed that the heat load of up to 280 W (heat flux of 140 W/cm^2) was removed by the heat sink with the coolant pressure drop of about 34 kPa across the heat sink system and the heater junction temperature of 62.9 °C at the coolant flow rate of 6.2 cm^3/s. Nu number of heat sink increased with the increase of Re number, and maximum value of 323 for Nu was achieved at highest Re of 518. The overall heat transfer coefficient of heat sink increased with the increase of coolant flow rate and heat load, and the maximal heat transfer coefficient was 36.8 kW(m^2 °C)$^{-1}$ in the experiment. The minimum value of 0.16 °C/W for the whole thermal resistance of heat sink was achieved at flow rate of 6.2 cm^3/s, and increasing coolant flow rate and heat fluxes could lead to the decrease in thermal resistance. The micro heat sink has good performance for electronics cooling at high heat fluxes, and it can improve the reliability and lifetime of electronic device.

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1. Introduction

With rapid developments of semiconductor engineering and micro electronic technique, the trend of electronic devices is towards miniaturization, high power density and high performance quality. The conventional heat transfer method of forced air convection is reaching its thermal limit. Therefore there is a challenge to develop efficient methods for cooling of these high flux devices. Typically, the waste heat output by multi-core can be as high as 100–200 W with the chip area of only 1 cm^2 so that its heat flux can achieve more than 100 W/cm^2 and the trend of heat flux is still in constant growth [1–3]. Every electronic device has a working limit temperature range, 85–100 °C in general, above which the reliability of the device will deteriorate sharply [4–7]. Research results have shown that, once temperature arises every 1 °C above the limit temperature, reliability of chip will drop 5% and life span will be significantly reduced. Therefore, if the high heat flux generated by the electronic device can not be discharged in time, it is a huge threaten to chip reliability and service lifetime [8–12]. Thus, it is necessary to research and develop the effective cooling technology to meet the demand of the high heat fluxes electronic device.

Many researchers have investigated the electronic cooling technology for high heat flux applications. Darabi and Ekula [13] presented a new type of cooling device for chips, using film evaporation principle. The results showed that the maximum cooling capacity of the micro device is 65 W/cm^2 at the highest temperature less than 100 °C, with R-134a as coolant, and the pressure drop was 250pa. Leonid et al. [14] adopted loop heat pipe (LHP) for cooling of semiconductor chip. The circular evaporator with external diameter of 16 mm and effective length of 280 mm was used in the experiment. The results showed the maximum heat transfer was 1100 W (heat flux of 7.8 W/cm^2) at the highest junction temperature less than 100 °C. Mark et al. [15] designed a compact two phase cooler for high-performance CPU, and studied the flow and heat transfer in the cooler. It showed that the temperature of the chip surface was less than 70 °C at air flow rate of 0.98 m^3/min, the total thermal resistance of the cooler was 0.26 K/W, and heat flux was 24 W/cm^2. Wong and Saeid [16] investigated the mixed convection on jet impingement cooling in a horizontal porous layer using Brinkman-extended Darcy model, and analyzed the effect of different Da, Pe, Ra number on flow and heat transfer. Myung et al. [17] proposed a new type of single-phase micro-channel/micro jet impingement technology and analyzed the heat transfer characteristic of the system with numerical method. The experimental results showed that when using HEF 7100 as the coolant at jet temperature of −40 °C, heat flux of 300 W/cm^2 can be removed, but the heated surface temperature is above

* Corresponding authors. Tel.: +86 730 8713099; fax: +86 730 8648870.
E-mail addresses: zhongminwan@hotmail.com (Z.M. Wan), tzklq@whut.edu.cn (Z.K. Tu).

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Nomenclature

A_{ac}	effective area of porous heat sink, m^2
D_e	hydraulic diameter, m
h	average heat transfer coefficient, $W(m^2\ °C)^{-1}$
R	thermal resistance, $°CW^{-1}$
T	temperature, °C
T_a	average temperature, °C
T_c	junction temperature, °C
u	velocity, ms^{-1}
V	volume flow rate, $cm^3\ s^{-1}$

Greek symbols

λ	thermal conductivity, $W\ m^{-1}\ °C^{-1}$
φ	applied heat load, W
ρ	density, $kg\ m^{-3}$
μ	viscosity, Pa s

Subscripts

f	water
in	inlet
out	outlet

110 °C. Luo and Liu [18] proposed a high-power LED active cooling solution based on closed micro jet system, both numerical and experimental studies were carried out. Tadrist et al. [19]developed a compact aluminum foam heat exchanger for dissipation of high heat flux. Bogojevica et al. [20] designed a two-phase silicon micro-channel heat sink composed of 40 rectangle channels with length of 15 mm and hydraulic radius of 194 um. They experimentally studied the oscillation of flow and heat transfer due to the fluid boiling in the heat sink with the heat flux in the range of 20–50 W/cm^2. The results showed that this oscillation, in the case of high heat fluxes, can cause high temperature fluctuation and large friction and may lead to gas block. Jiang et al. [21] performed numerical simulation on forced convection heat transfer in sintered porous flat channel using porous media local thermal non-equilibrium model with consideration of wall effect and concluded that compared to the non-sintered packed beds, the sintered porous wicks with low porosity had a higher convection heat transfer capacity. Jiang et al. [22] experimentally analyzed the forced convection heat transfer in the sintered porous channel, the results showed that the capacity of sintered porous channel are 30 and 15 times higher than smooth channel when working fluid of air and water was applied, respectively.

In the present work, a micro heat sink based on porous media is proposed to cool the electronic devices with high heat fluxes. Experimental setup of miniature porous heat sink system is made to investigate the heat and mass transfer for the thermal management of high fluxes applications, and the present study will attempt to provide experimental results on the thermal and hydraulic performance of such system.

2. Operational principle of miniature porous heat sink system

Fig. 1 shows the schematic of the miniature porous heat sink system. As seen, the system is composed of porous heat sink, small heat exchanger with a fan, micro pump, and transport pipe. During the normal operational process, coolant in the closed system is driven into the porous heat sink through the inlet by micro pump. Because of high heat transfer coefficient of miniature porous heat sink, the heat created by electronic devices can be easily removed by the cycling coolant of system. The coolant is heated and its temperature increases after flowing out of heat sink, then the coolant flows into the heat exchanger with fan. The exchanger cools the coolant and the heat can be dissipated into the environment. The cooled coolant will enter the porous heat sink to cool the electronic devices again by the force of micro pump, completing the cycle.

There are some unique advantages when miniature porous heat sink is applied into cooling of electronic devices. Firstly, the miniature porous heat sink has large surface area in contact between the working fluid and the porous matrix as well as provides large heat transfer area. Meanwhile, there are lots of tortuous micro-channels inside the porous media, which can greatly enhance the internal flow velocity and turbulence intensity at the same coolant volume flow rate, leading to high heat transfer coefficient. Secondly, heat generated from electronic devices in a finite space can be effectively transported to heat sink over long distance by the flexible transport pipes [23], and the problem of the space limits in practical electronic device packaging can be solved by using the present system.

3. Experimental setup of miniature porous heat sink system

Fig. 2 shows the experimental setup of the miniature porous heat sink system, and the coolant is water in the experiment. The heater is fabricated from a copper block with embedded cartridge heating rods, which simulates the heat generation of electronic devices. The heater is covered by insulation material and the heat loss from the source is minimized. The heat applied to heater is controlled by a voltage regulator and voltage stabilizer is applied to avoid the heat fluctuation due to the voltage fluctuation. The effective area of heater is 20 × 10 mm^2, the maximum power is 280 W,

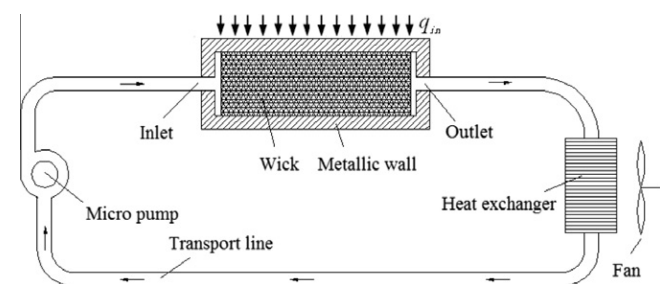

Fig. 1. Schematic of the miniature porous heat sink.

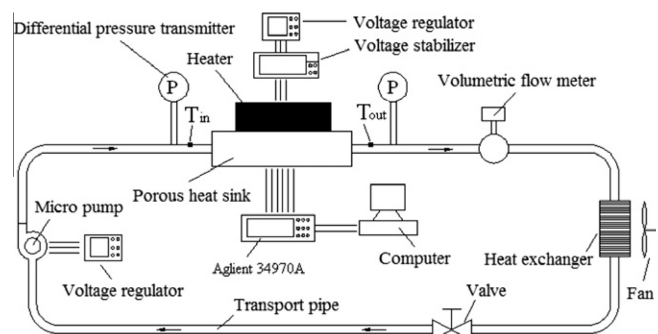

Fig. 2. Experimental setup of the miniature porous heat sink system.

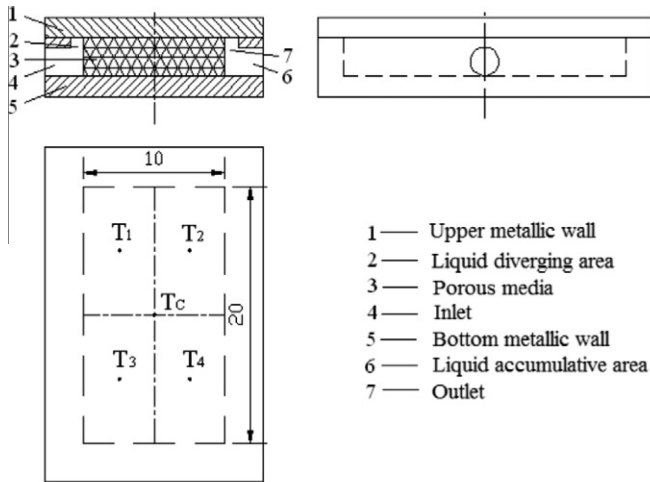

Fig. 3. Cross sectional views of miniature porous heat sink.

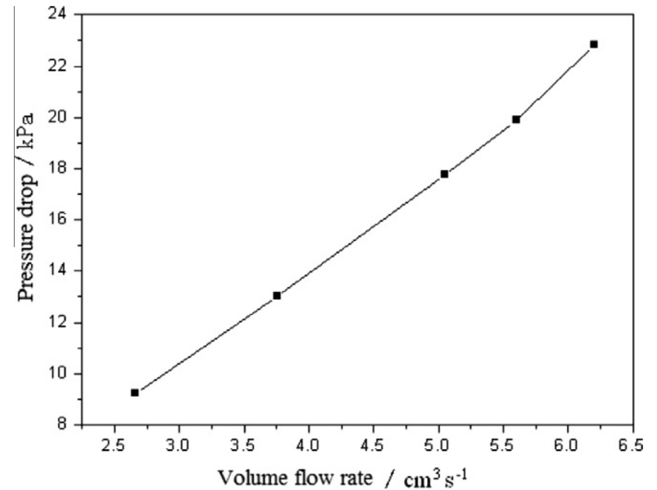

Fig. 4. Effect of volume flow rate on the system pressure drop.

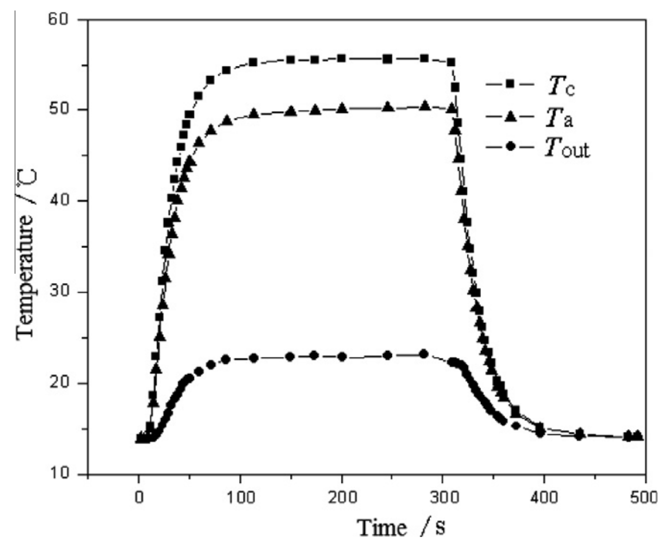

Fig. 5. T_c, T_a, T_{out} variation with time (φ = 200 W, V = 5.1 cm^3/s).

and the range of heat flux is 0–140 W/cm^2. T_{in}, T_{out} represent temperatures of inlet and outlet of porous heat sink, respectively.

Fig. 3 shows the schematic of miniature porous heat sink. As seen, the heat sink consists of seven parts: upper metallic wall, liquid diverging area, porous media, inlet, outlet, liquid accumulative area, and bottom metallic wall. The water enters from inlet. Due to the diversion of the diverging area, water can flow uniformly through the porous area, and make the heated surface temperature of the sink more uniform.

Parameters measured in the experiment include the mass flow rate of water, applied heat load, pressure drop along the heat sink system, and temperatures at the appropriate points. The flow rate, input power and inlet liquid temperature are fixed for each test. The K-type thermocouples are connected to a data acquisition system (Aglient 34970A) for temperature monitored, and all temperature measurements are recorded after steady-state condition is reached. The local temperatures of upper plate at different locations as shown in Fig. 3 were measured with five thermocouples, which were inserted into the upper plate of the test section (0.5 mm deep) using the thermally conductive epoxy resin. The inlet and outlet water temperatures were monitored by four thermocouples as shown in Fig. 2. The temperature accuracy was within ±0.1 °C. The water flow rate is measured by accurate volumetric flow meter with measuring range of 5–50 L/h and measured accuracy of ±0.5%. The pressure drop is measured by FCX-All series differential pressure transmitter with measuring accuracy of ±0.1%. The applied heat load is measured by taking the product of the voltage and the current readings from the wattmeter, and the maximum uncertainty is ±1.5%. The micro pump is electromagnetically driven and the flow rates can be adjusted by changing the input voltages of micro pump.

In the experiment, the wick is made of 200 mesh stainless wire mesh, and the length, width and thickness of wick is 20, 10 and 3 mm, respectively. The pore radius is about 0.055 mm, porosity is 0.61, and permeability is approximately 6.16×10^{-11} m^2. The dashed line in the top view represents the porous simple footprint (heater footprint) of 20 × 10 mm. T_1, T_2, T_3, T_4, T_c are the temperature measure points of thermocouple. T_c is the junction temperature, which means the highest temperature in the heat sink.

4. Results and discussion

Fig. 4 shows the pressure drop of the miniature porous heat sink system as a function of the volume flow rate of water. As seen, the total system pressure drop is relatively small. The pressure drop of water is 9.2 kPa at the flow rate of 2.6 cm^3/s. Even at the flow rate of 6.2 cm^3/s, the pressure drop is 22.8 kPa.

The average temperature of heat sink surface is defined as $T_a = (T_1 + T_2 + T_3 + T_4)/4$. Fig. 5 presents the variation of different points temperature with time at flow rate of 5.1 cm^3/s and heating power of 200 W (heat flux of 100 W/cm^2). After achieving steady state of the system, stop heating at time of 300 s. It can be seen that at high heat flux, system can return to steady state rapidly and the balance time is about 80 s. When system is balanced, the fluctuation of temperature is small and temperatures of the surface are maintained at a low level. As seen from the Fig. 5, at the steady state, T_c = 55.8 °C, T_a = 50.5 °C, T_{out} = 23.1 °C. After ceasing heating power, the heat sink system can return to the initial state very fast, so the sink responds quickly at high heat fluxes application. Temperature of inlet T_{in} is 13.9 °C and T_{out} is 23.1 °C, the heat removed by water is 197.1 W by calculation of conservation of energy, the total loss of heat conduction, convection, radiation is 2.9 W, and the ratio of heat loss to total heat power is 1.45%. Therefore, heat loss of porous heat sink is relatively small and the reliability of experimental data is convincing.

Fig. 6 shows junction temperatures at the different heat load and volume flow rates. The junction temperature T_c represents

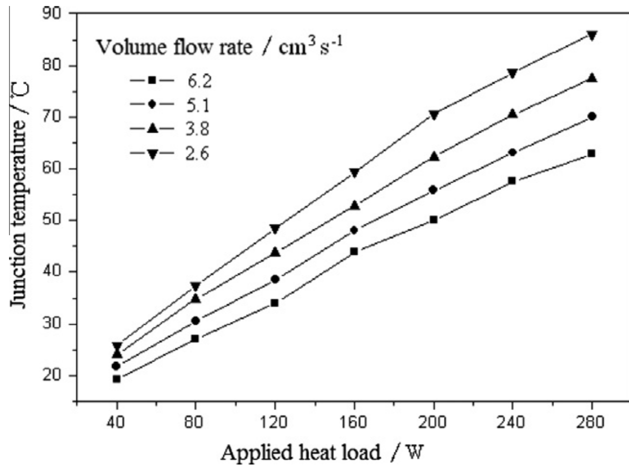

Fig. 6. Junction temperatures as a function of heat load for different volume flow rates.

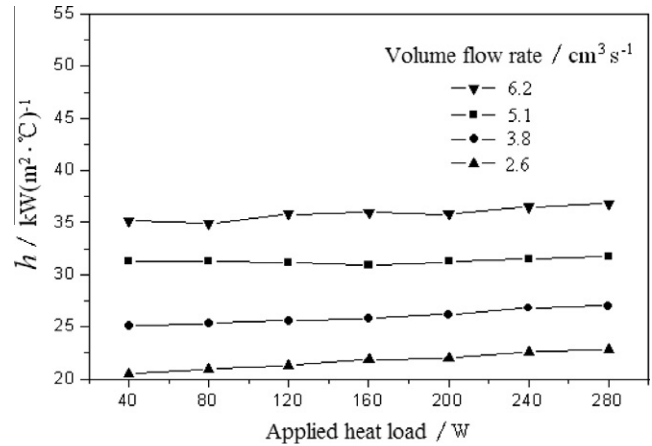

Fig. 7. Heat transfer coefficient variation with applied heat loads at different volume flow rates.

the highest temperature of the heated surface and the highest junction temperature must be lower than bearable temperature of electronic devices, otherwise, the reliability of devices will be decreased greatly or even be destroyed. During the experiment, the volume flow rate is in the range of 2.6–6.2 cm^3/s and the heating power is between 40–280 W (heat flux of 20–140 W/cm^2). As seen from Fig. 6, T_c is almost linear with applied heat load. At the same heat load, increasing the volume flow rate can lead to the decrease in the junction temperature T_c. At the volume flow rate of 2.6 cm^3/s and heat load of 280 W, the highest T_c is 86.1 °C. At the volume flow rate of 6.2 cm^3/s, the corresponding T_c is 62.9 °C, lower than bearable temperature range, which can guarantee the reliability of the electronic devices in a high heat flux condition.

The average heat transfer coefficient (h) of miniature porous heat sink is defined as follow:

$$h = \frac{\varphi}{A_{\text{ac}}(T_a - T_{\text{fa}})} \tag{1}$$

The Nusselt number (Nu) and Reynolds number (Re) of miniature porous heat sink are described as follow:

$$\text{Nu} = \frac{hD_e}{\lambda_f} \tag{2}$$

$$\text{Re} = \frac{\rho_f u_f D_e}{\mu_f} \tag{3}$$

where φ is applied heat load; A_{ac} is the effective area of porous heat sink; T_{fa} is the average temperature of the water, $T_{fa} = (T_{\text{in}} + T_{\text{out}})/2$ D_e is hydraulic diameter of heat sink section; λ is thermal conductivity; ρ is density; μ is viscosity. The subscript f stands for water.

Fig. 7 shows the relationship between the average heat transfer coefficient and heat loads at different volume flow rates. As seen, the average heat transfer coefficient is very large and it increases with the increasing of volume flow rate. At flow rate of 6.2 cm^3/s, the average heat transfer coefficient is beyond 3.5×10^4 W (m^2 °C)$^{-1}$ and the highest average heat transfer coefficient can achieve 3.68×10^4 W(m^2 °C)$^{-1}$. At the same volume flow rate, h is slightly enhanced with the increase of heat load. As a result, the miniature porous heat sink greatly increases the heat transfer coefficient for water compared with the empty plate channel and it is suitable for the cooling of electronic devices of the high heat fluxes.

Fig. 8 presents the Nu number variation with Re at heat load of 280 W (heat flux of 140 W/cm^2). As seen, Nu increased with rising of Re. At Re of 518, the maximum Nu number is 323.

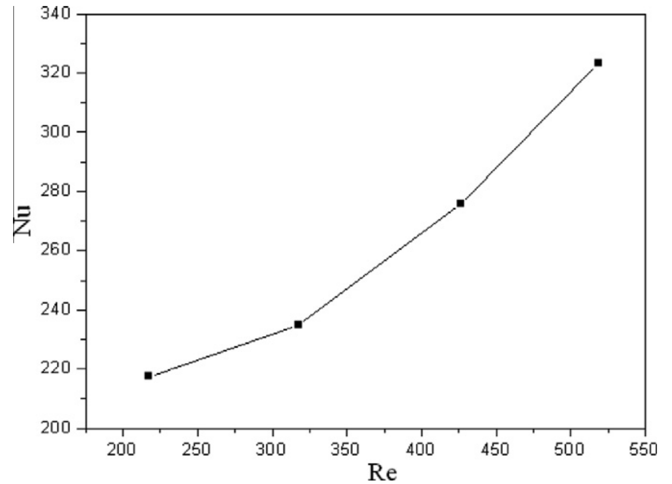

Fig. 8. Relation of Nu and Re.

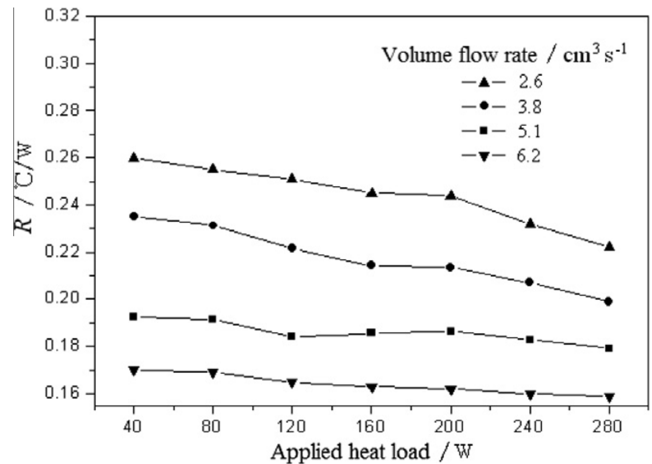

Fig. 9. Variation of whole thermal resistance with heat load at different volume flow rates.

The whole thermal resistance (R) is defined as follow:

$$R = \frac{(T_c - T_{\text{fa}})}{\varphi} \tag{4}$$

Fig. 9 shows the relation of whole thermal resistance of miniature porous heat sink with applied heat load (from 40 to 280 W) at different volume flow rates. As seen from the figure, at the same flow rate, the whole thermal resistance gradually reduces with the increase of heat load. The whole thermal resistance reduces with increasing the volume flow rate. At the rate of 2.6 cm3/s, the maximum of whole resistance is 0.26 °C/W. At maximum flow rate of 6.2 cm3/s, the whole resistance achieves the minimum of 6 °C/W. Therefore, the whole thermal resistance of heat sink is small, which means a lower junction temperature of devices can be gotten at the high heat fluxes and the present system is desirable for the cooling of electronic devices.

5. Conclusions

A high-efficient micro heat sink based on porous media is proposed to cool the electronic devices with high heat fluxes. The present heat sink system has high heat transfer capacity and coefficient. The wick of heat sink is made of 200 mesh stainless wire mesh, its porosity is 0.61, and the permeability is about 6.16×10^{-11} m^2. Experimental investigation about the miniature porous heat sink is carried out, and some conclusions can be drawn as follow:

(1) The junction temperature of heat sink decreases with the increase of volume flow rate and the micro heat sink has a strong heat transfer capacity. The applied heat load of up to 280 W (heat flux of 140 W/cm^2) was removed by the heat sink, and the coolant pressure drop across the heat sink system is about 34 kPa and the heater junction temperature is about 62.9 °C at the coolant flow rate of 6.2 cm^3/s.
(2) With increasing Re (or the volume flow rate), Nu is enhanced. At Re of 518, the Nu achieves the maximum of 323; the average heat transfer coefficient increases with the rising of volume flow rate and the highest average heat transfer coefficient can achieve 3.68×10^4 W(m^2 °C)$^{-1}$;
(3) The whole thermal resistance of system is very small. With increasing heat load and volume flow rate, the whole thermal resistance decreases. At flow rate of 2.6 cm^3/s, the maximum of thermal resistance is 0.26 °C/W. At maximum flow rate of 6.2 cm^3/s, the thermal resistance achieves the minimum of 0.16 °C/W.

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