Experimental demonstration of a tailored-width microchannel heat exchanger configuration for uniform wall temperature

S Riera[1], J Barrau[1], J I Rosell[1], M Omri[2] and L G Fréchette[2]

1 University of Lleida, Solar Energy Group, Edifici CREA, C/Pere de Cabrera, s/n, 25001 Lleida, Spain
2 Université de Sherbrooke, Dépt génie mécanique, 2500 boul. Université, QC J1K 2R1, Canada

E-mail: sriera@macs.udl.cat

Abstract. In this work, an experimental study of a novel microfabricated heat sink configuration that tends to uniform the wall temperature, even with increasing flow temperature, is presented. The design consists of a series of microchannel sections with stepwise varying width. This scheme counteracts the flow temperature increase by reducing the local thermal resistance along the flow path. A test apparatus with uniform heat flux and distributed wall temperature measurements was developed for microchannel heat exchanger characterisation. The energy balance is checked and the temperature distribution is analysed for each test. The results show that the wall temperature decreases slightly along the flow path while the fluid temperature increases, highlighting the strong impact of this approach. For a flow rate of 16 ml/s, the mean thermal resistance of the heat sink is $2,35 \cdot 10^{-5}$ m^2·K/W which enhances the results compared to the millimeter scale channels nearly three-fold. For the same flow rate and a heat flux of 50 W/cm^2, the temperature uniformity, expressed as the standard deviation of the wall temperature, is around 6 °C.

1. Introduction

Solar cell arrays need to maintain acceptable operating temperatures and temperature uniformity to maintain the reliability, which implies dissipating high heat fluxes from small areas. That demands efficient and innovative cooling systems with high capacities for heat removal. Within the cooling technologies that have high heat flux removal capacities, microchannels are one of the most reliable and commonly used.

Microchannel heat sinks were first suggested by Tuckerman and Pease [1]. The improvement of the cooling performance is based on the fact that the convective heat transfer coefficient scales inversely with channel width. The major drawbacks of this cooling scheme are the temperature increase in the direction of the fluid flow and the relatively large pressure drop that they generate. In order to reduce the temperature non uniformity of the cooled object, Ryu et al. [2] proposed to alternate inlets and outlets along the microchannels, adding some manifolds dividers. Missagia and Walpole [3] reduce temperature non-uniformity by alternating flow directions through the channels in a single layer, while Vafai and Zhu [4] proposed a two-layered microchannel structure with opposite directions flows. Lee et al. [5] enhances the heat transfer performance by implementing oblique fins into a microchannel.

Along these lines, Barrau et al. [6] developed a new hybrid jet impingement/channel cooling scheme. In this design the fluid enters through the slot located in the symmetry plane of the heat sink

and travels along the channels to leaves the heat sink at its extremities. The fluid flows through a series of microchannels with variable width along the flow path. As the fluid heats up, the smaller channel diameter decreases to consequently decrease the convective thermal resistance. The authors demonstrated the capacity to achieve temperature profiles of the target object that remain constant or even decrease in the fluid flow direction of the coolant, maintaining the global high heat removal capability. The numerical study [7] showed that the temperature distribution provided by the heat sink can be tailored according to the needs of the system by varying the local heat removal capability.

Some subsequent studies, such as that conducted by Karathanassis et al. [8], studied experimentally and numerically a hybrid system based on the design of Barrau et al. [6], but with a radial disposition of the channels. They confirmed that the introduction of stepwise varying channels increases the thermal performance of this heat-sink configuration without introducing a severe pressure drop penalty. The ability of this design to provide a quite uniform temperature profile of the cooled object has been confirmed by Ji et al [9]. Those last investigations display the enhancement of implementing variable channel width.

Those previous studies were done at the millimeter scale. But more and more, heat flux densities tend to increase, suggesting the use of smaller scale channels to increase the convective heat transfer rate. The current design is therefore implemented at the micrometer scale in order to evaluate the impact of the channel scale on the performance of the device, looking for the same effect of thermal resistance reduction at small scale. This work presents an experimental analysis of such a novel microfabricated heat exchanger configuration that tends to make the wall temperature uniform even under lateral flow with increasing flow temperature. This is the first demonstration of this approach in a Si microchannel heat exchanger.

2. Test module description
The schematic design of the experimental setup used for this study is shown in figure 1.
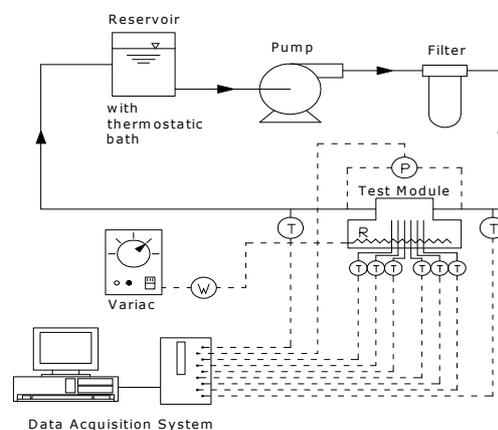

Figure 1. Test module setup.

The test module is cooled with water which is stored in a reservoir with a thermostatic bath to maintain a constant temperature. The water circulates in the loop with the aid of a variable speed peristaltic pump (JP Selecta PERCOM N-M), which can give a flow of 1 l/min. Then, the liquid passes through a 3-μm filter before entering the test module.

In the module, the heat flux needed to simulate the solar irradiation on a cell is generated by an advanced ceramic heater (Watlow Ultramic 600), which can give more than 100 W/cm^2.

This cooling scheme entails an optimized array of variable width microchannels (Fig. 2). The main objective of this optimized cooling scheme is to improve the temperature uniformity of the cooled object, while maintaining thermal resistance levels achieved in the previous works [6, 7] or less. The cooling scheme consists of a series of microchannel sections with stepwise varying width. The range

of width of the microchannel sections was designed from 1.53 mm to 140 μm to increase the convective heat transfer coefficient and surface to compensate the increase in flow temperature. The microchannel pattern is etched in silicon by lithography and DRIE, creating a constant depth (300 μm) microchannel array. In figure 2 is shown the microchannel heat exchanger scheme.
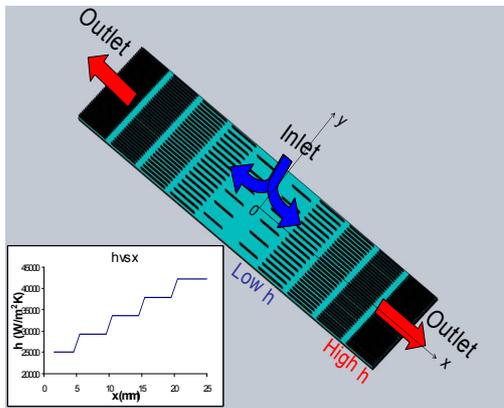

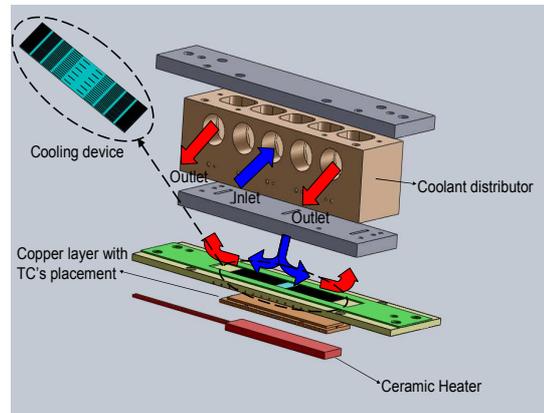**Figure 2.** Microchannel heat exchanger scheme.

Figure 3. Disassembled test module.

The microchannel heat exchanger is sealed on the copper layer of the test module through a thin layer of Thermal Interface Material (TIM). The thickness of the TIM layer has been measured with a microscope (50 μm, ±5 μm) and its thermal conductivity has been verified (λ_{TIM}=0,82 W/m·K).

The module has one cooling liquid inlet. Water is guided directly to the microchannel heat exchanger center through a slot in its bottom. The flow is then divided in two, following the microchannels path to both ends of the module. Two outlets collect the liquid leaving the extremities of the device after passing through the microchannels.

Type-K thermocouples are used to measure the water temperature at the inlet and outlet of the microchannel heat exchanger and the temperature distribution of the copper layer along the flow path, at different positions (x) of the centerline (y=0 mm) of the microchannel heat exchanger. All this information is acquired by a datalogger Campbell CR23X and sent to a computer to be stored and analyzed. Finally the flow is channeled again to the reservoir with the thermostatic bath, closing the loop. Figure 3 shows a global scheme of the test module sited in the laboratory, disassembled.

3. Results and discussion

To study the temperature distribution and thermal resistance of the heat sink described previously, three experimental conditions are considered by varying the flow rate. Multiple tests were done in similar conditions to assure repeatability of the results, but only the conditions for three validated tests are listed in Table 1.

Table 1. Test conditions.

		TEST 1	TEST 2	TEST 3
Q	**(m³/s)**	8,80E-06	1,12E-05	1,60E-05
q"$_{eff}$	**(W/cm²)**	50,06	50,05	49,96
T$_{in}$	**(ºC)**	21,7	21,9	22,6

3.1. Temperature distribution and temperature uniformity

For each experiment, the energy balance is checked to validate the tests, and the temperature distribution is analyzed.

The temperature maps for the three tests in Table 1 are presented in Figure 4. As the distribution is symmetric with respect to the symmetry plane, the temperatures are displayed only for one side of the heat sink. It is clearly seen that even though the water temperature increases along the heat exchanger, the wall temperature is maintained nearly constant.
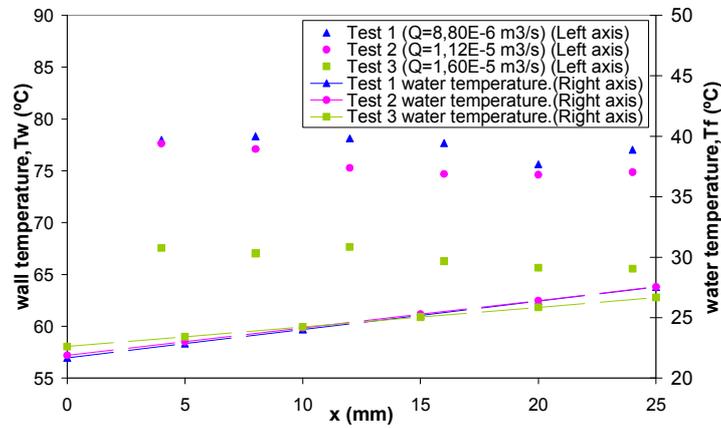

Figure 4. Temperature of the experimental microchannel heat exchanger for a heat flux of 50 W/cm², and several mass flow rates. The graph shows that near-uniform wall temperature (Tw) was achieved even though the water temperature (Tf) increases along the heat exchanger.

Table 2 presents the results of temperature uniformity at the height of the copper layer in the heat sink. To express the temperature uniformity, the standard deviation σ_T is calculated with respect to the average temperature and its difference to each data point. Included in the table, ΔT_{in-out} shows the difference between coolant temperature from inlet to outlet, $T_{i,m}$ the mean wall temperature at copper layer height and $\Delta T_{min-max}$ the maximum difference in the wall temperature.

Table 2. Temperature uniformity at copper layer height.

		TEST 1	TEST 2	TEST 3
ΔT_{in-out}	(ºC)	5,8	5,6	4,1
$T_{i,m}$	(ºC)	76,3	83,4	74,3
$\Delta T_{min-max}$	(ºC)	14,9	15,2	14,1
σ_T	(ºC)	5,8	5,9	5,4

The fact that there's a decreasing temperature distribution shows that it would be possible to shape a uniform one, or tailor the temperature distribution to the user's need depending of different applications. That shows the effectiveness of the proposed variable microchannel width scheme design procedure.

3.2. Thermal resistance coefficient
The thermal resistance is a way of showing and comparing the performance of the module in cooling the desired surface. Calculation of the global average thermal resistance coefficient of the system is carried out by applying the following equation:

$$R_{t\,m} = \frac{(T_{w,m} - T_{in})}{q''_{eff}} \qquad (1)$$

where q''_{eff} is the heat flux, T_{in} is the inlet water temperature and $T_{w,m}$ is the average temperature of the wall on which the heat flux is applied.

This global thermal resistance is ascribed to the heat sink, but also to the thermal interface material and, with a minor impact, to copper. This result must be corrected by removing the effect of the TIM and the copper layer that exists between the base of the microchannel heat exchanger and the thermocouples location.

The average thermal resistance coefficients for the four different tests conditions listed in Table 1 are calculated, subtracting the effect of the copper layer and TIM. The value obtained for a flow rate of $1{,}6 \cdot 10^{-5}$ m^3/s is $2{,}35 \cdot 10^{-5}$ m$^2 \cdot$K/W. These values are in concordance with the existing reports and literature on microchannel cooling, enhancing most of the millimeter-scale results found. In effect, for the same flow rate, the thermal resistance coefficient was $7{,}2 \cdot 10^{-5}$ m^2.K /W [6,7].

4. Conclusions

Following the previous investigations done by Barrau et al. [6-7], this paper explores the viability of a variable-diameter microchannel heat exchanger in micrometer scale to achieve high heat fluxes and uniform wall temperature with only one fluid inlet. Experimental tests done with the test module in different conditions of flow rate are studied. The mean thermal resistance of the heat sink for a flow rate of 16 ml/s and a heat flux of 50 W/cm^2 is $2{,}35 \cdot 10^{-5}$ m$^2 \cdot$K/W, which enhances the results compared to the millimeter scale channels nearly three-fold. Another parameter evaluated is the temperature uniformity along the heat sink. The standard deviation σ_T is calculated and for the same flow rate and a heat flux of 50 W/cm^2, the temperature uniformity, expressed as the standard deviation of the wall temperature, is around 6 ºC. It can even be noticed that the wall temperature decreases slightly along the flow path, highlighting the effectiveness of the proposed variable microchannel width scheme. This shows that design optimization can lead to more uniform wall temperatures. Also, a specific profile of the microchannel width distribution could be fitted to the requirements of specific applications, such as adapting it to a non-uniform heat flux along the heated surface.

References

[1]   Tuckerman D B and Pease F W 1981 High-Performance Heat Sinking for VLSI *Electron. Dev. Lett.* EDL-2 pp 126–9.

[2]   Ryu J H, Choi D H and Kim S J 2003 Three-Dimensional Numerical Optimization of a Manifold Microchannel Heat Sink *International Journal of Heat and Mass Transfer* 46 pp 1553–62.

[3]   Missaggia L J and Walpole J N 1991 A Microchannel Heat Sink with Alternating Directions of Water Flow in Adjacent Channels *Integrated Optoelectronics for Communication and Processing* 1582 pp 106-11.

[4]   Vafai K and Zhu L 1999 Analysis of Two-Layered Micro-Channel Heat Sink Concept in Electronic Cooling *International Journal of Heat and Mass Transfer* 42 pp 2287-97.

[5]   Lee Y, Lee P and Chou S 2009 Enhanced Microchannel Heat Sinks Using Oblique Fins *Proceedings of ASME IPACK2009–89059,* San Francisco, CA(2009)

[6]   Barrau J, Chemisana D, Rosell J, Tadrist L and Ibañez M 2010 An Experimental Study of a New Hybrid Jet Impingement/micro-channel Cooling Scheme. *Applied Thermal Engineering* 30 pp 2058-66.

[7]   Barrau J, Omri M, Chemisana D, Rosell J, Ibañez M and Tadrist L 2012 Numerical Study of a Hybrid Jet Impingement/micro-channel Cooling Scheme. *Applied Thermal Engineering* 33-34 pp 237-45.

[8]   Karathanassis I K, Papanicolaou E, Belessiotis E V and Bergeles G C 2013 Three-Dimensional Flow Effects on Forced Convection Heat Transfer in a Channel with Stepwise-varying Width. *International Journal of Thermal Sciences* 67 pp 177-91.

[9]   Ji J, Wang Y, Chow T, Chen H and Pei G 2012 A Jet Impingement/channel Receiver for Cooling Densely Packed Photovoltaic Cells under a Paraboloidal Dish Solar Concentrator. *Heat Transfer Research* 43(8) pp 767-78.