EXPERIMENTAL STUDY OF HEAT TRANSFER IN A HEAT EXCHANGER WITH RECTANGULAR MINI CHANNELS

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ABSTRACT.
This paper presents the results of an experimental study related to characterisation of a mini channel heat exchanger. Such heat exchanger may be used in water cooling of electronic components.
The results obtained show the efficiency of this exchanger even with very low water flow rates. Indeed, in spite of the importance of the extracted heat fluxes which can reach about 50Kw/m^2, the temperature of the cooled Aluminium bloc remained always lower than the tolerated threshold of 80°C in electronic cooling. Moreover, several thermal characteristics such as equivalent thermal resistance of the exchanger, the average internal convective heat transfer coefficient and the increase in the temperature of the cooling water have been measured. The results presented have been obtained with in "quinconce" rectangular mini-channel heat exchanger, with a hydraulic diameter D_h = 2mm.

NOMENCLATURE

D_h Hydraulic diameter (mm).
$\hbar_{\text{int}}$ Internal average heat transfer coefficient ($W.m^{-2}.K^{-1}$)
$\dot{M}$ Mass flow of the liquid ($Kg.s^{-1}$)
$\dot{V}$ Volume flow of the liquid ($l.h^{-1}$)
A_{int} Wet surface (m^2)
T_a Ambient temperature (°C)
T_p Average temperature of the heated bloc (°C)
$T_{w,i}$ Inlet temperature of water (°C)
$T_{w,o}$ Outlet temperature of water (°C)
$T_{w,m}$ Average water temperature (°C)
$\dot{Q}_e$ Heat flux supplied electrically (W)
$\dot{Q}_{\text{int}}$ Internal convective heat flux (W)
$\dot{Q}_{out}$ Convective heat flux outside the system (W)
$\dot{Q}_{cd}$ Heat flux losses by conduction (W)

$\dot{q}_e$ Heat flux supplied to the unit area ($KW.m^{-2}$)

C_p Mass heat capacity at constant pressure of water ($J.Kg^{-1}.K^{-1}$)

ρ Density of aluminium ($Kg.m^{-3}$)

INTRODUCTION

In the last few years, high-power electronic components underwent a spectacular development and particularly in terms of technology of miniaturization. But this development runs up against the needs of components cooling necessary to dissipate highest heat fluxes from smaller surfaces. The first integrated circuit and microprocessors were cooled simply by natural air convection with finned heat sink. Then, as that became inefficient, fans have been integrated to these heat sinkswhich generate airflow directly on the fins with speeds which can reach $5 m.s^{-1}$. But these last years, due the the increase of the frequency of functioning of the integrated circuits and the microprocessor, heat flux to be extracted from these components are becoming extremely large, and approaching in some applications the values of about 10^5 W/m². For such components, liquid cooling in single phase or two-phases flows is becoming significantly most used in several domains: cooling of racks for servers, cooling of microprocessor and integrated circuit, current converter, IGBF….

Indeed, conventional cooling owes its efficiency to two parameters: the surface contributed in heat transfer by convection and the heat capacity of the cooling fluid. Air has low heat capacity and the surface cannot be increased indefinitely - even by the installation of fins - without encumbering the system, which is narrowing. Crucial acoustic problems related to the use of funs can appeared for high flow rates of air in air-cooling systems. So, the problem may be resolved in part by changing the fluid. Use of water is one of the most promoted ways, considering its high heat capacity. But in this case, several constraints can occur. First, the coolant must elapse in an exchanger which should provide a perfect sealing. Second, the exchanger must have very reduced dimensions to not encumber the system to be cooled, while offering the maximum of wet-surface. Consequently, the use of heat exchanger constituted by mini or micro-channels has been pointed out by several researches as an excellent alternative for conventional heat exchangers or heat sinks. Such exchangers, commonly called water-blocks, have been widely marketed the last years, particularly in the field of computer equipment, automotive, aerospace and telecommunication servers. However, different geometries of the microchannels and entry configurations of the cooling fluid have been designed without effective study of their performances.

The use of microchannels coolers for electronic components was first proposed by Tuckerman et al. [1982]. They analyzed the laminar regime established channels with rectangular section made of silicon. For that purpose, they made a $1\times1\,cm^2$ silicon exchanger, consisting of 50 channels and fins of 0.05 mm in width, 0.3 mm in height,. Using water as coolant, the heat exchanger was able of dissipating $790\,W.cm^{-2}$ with a maximum temperature of 71 °C. Regarding the used low flow rate (about 500 $ml.\min^{-1}$) this exchanger was considered as a small feat.
Alain Bricard et al [2001] have studied the cooling of power semiconductors IGBT with micro-heat exchanger. The heat exchanger used is composed of four basic modules, each comprising two chips soldered on a copper block of 51 X 18 mm^2 in which the microchannels are machined. The coolant is water to 40% of glycol; the laminar flow regime is thermally and hydraulically established. The released heat under these conditions can reach flux densities up to 350 $W.cm^{-2}$; the found heat transfer

coefficient varies from $10398 W.m^{-2}.K^{-1}$ to $12430 W.m^{-2}.K^{-1}$ for flow rates varied from $0.136 l.s^{-1}$ to $0.26\ l.s^{-1}$. The measured thermal resistance is around $0.1\ K.W^{-1}$.

Wang et al [2008] have manufactured a heat exchanger to cool electronic components which consists of ten units of parallel cells, each composed of 33 parallel channels of 400 µm length. The de-ionized water was used as coolant. With water rate flows ranging between 0.64 and 6.79 $ml.\min^{-1}$ and heat flux between 10.4 and 20.3 $W.cm^{-2}$, this exchanger was able to dissipate a heat flux of about 18.9 $W.cm^{-2}$. (The temperature of the electronic component has not exceeded 85 °C during the series of experiments) for a flow rate of 6.79 $ml.\min^{-1}$. However, the authors recognized that such heat exchanger is very complicated to achieve.

The aim of this paper is to study experimentally a water-bloc constituted by one mini-channel in "quinconce". For that, we have carried out an experimental study by measuring the performances of the heat exchanger to evacuate heat generated by Joule effect in an aluminium rectangular bloc, simulating therefore the heat dissipated by a microprocessor during its operation. The heating system, which is mainly constituted with a heating resistance, is inserted between two identical mini-channel heat exchangers (figures1 and 2). This configuration allows obtaining symmetrical problem and therefore permits easy calculation of the heat flux generated in each one of the heat exchanger by assuming that electric power is divided equally between them. In this way, the heat generated by electrical resistance will be evacuated in the same way by each mini-exchanger. Each mini-exchanger is formed of a channel in quinconce having a rectangular section with a hydraulic diameter about 2 mm. Such geometry has been classified by Kandlikar [2003] as mini-channels heat exchanger. The coolant used is distilled water containing 10% of glycol, pumped through the exchanger using a small pump with a maximum water rate of 750 l/h.

EXPERIMENTAL SET-UP

The experimental setup we have designed and performed is composed of a heat source sandwiched between two mini-channel heat exchangers, a water tank, a thermostat, a data measurement and a pump.

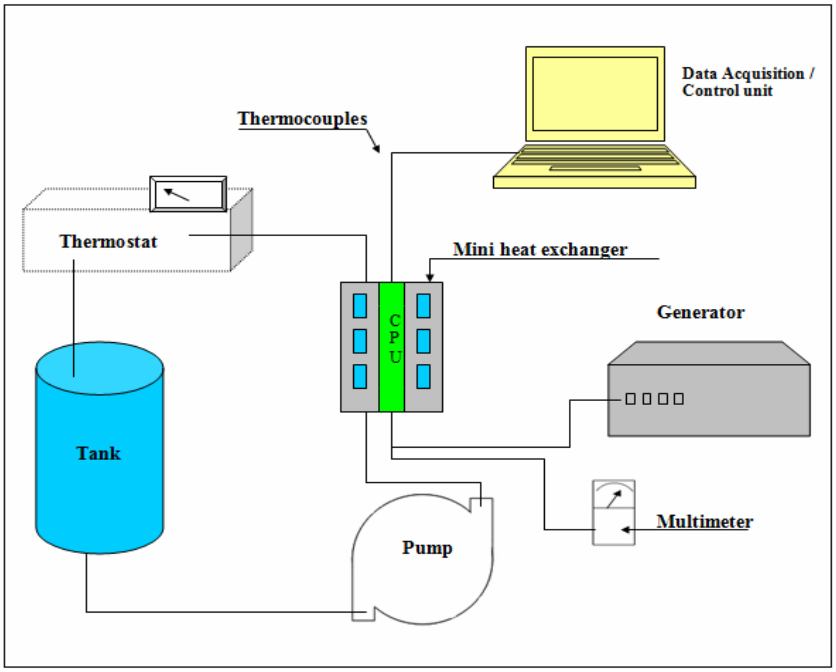

Figure 1. Experimental set-up

The heater is constituted by a thin film resistance powered by an electric current supply and electrically insulated. The heater is sandwiched between two identical heat exchangers tight back to back with 4 small screws. The heating element is threaded on a sheet of Samicanite with a thickness 2 mm, having a length L = 58 mm and a width W = 52 mm.

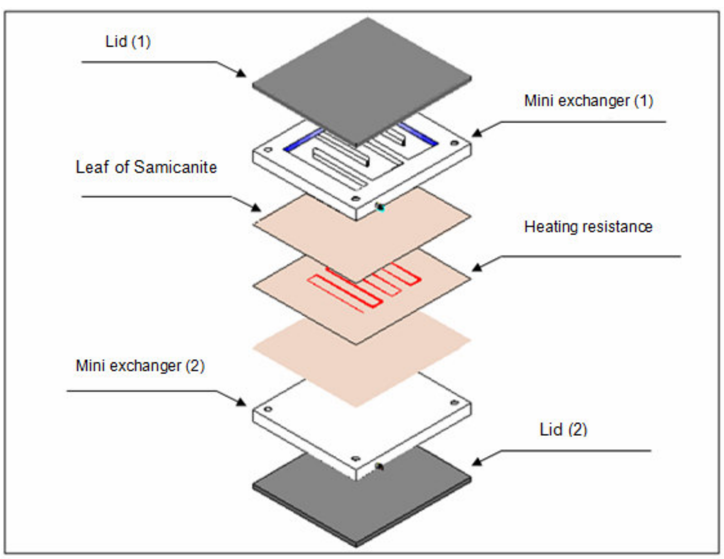

Figure2: Schematic representation of the heated bloc and the heat exchanger

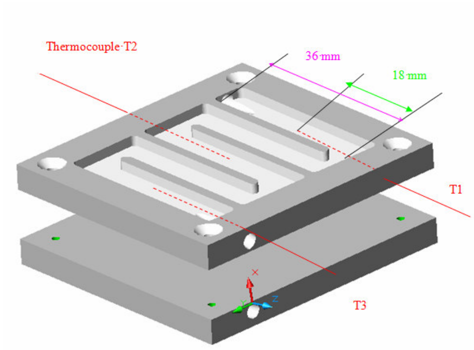

Figure 3. Details of the mini-channel heat exchanger

In the design of these exchangers, we took into account several considerations: the choice of conductive material, available techniques of machining and performing the channels, a minimum of congestion, etc…. The exchangers are machined in plates of aluminium 58x52 mm^2 and 5 mm thick. We have chosen mini-channels with rectangular cross flow section due to their easy performing as opposed to other forms (circular and trapezoidal). Both exchangers were thermally closed with two identical Plexiglas lids of 6 mm in depth, in order to be able to study the hydro-dynamical behaviours of the cooling fluid inside the heat exchanger by a visualisation of the flow patters. This is the task of incoming papers.

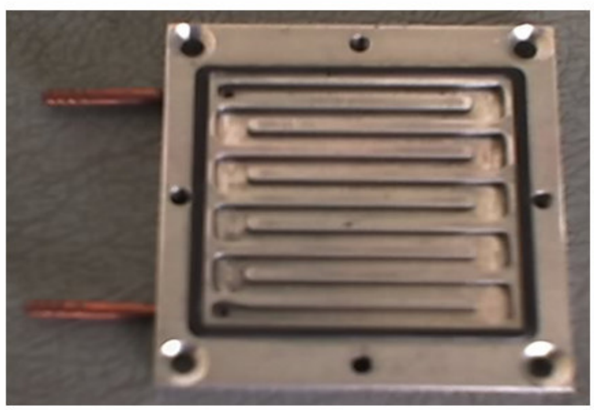

Figure 4. Photo of a mini-channel heat exchanger

MEASURING TECHNIQUES

To evaluate the efficiency of the cooling, which is the primary goal of this study, we measured temperatures in different locations of the cooled block. For that purpose we used nine K-type thermocouples, three of which are inserted into different positions of the base of each mini-exchanger on the side of the heating system. By this way, average surface temperature can be evaluated. Two other thermocouples are placed at the exit of the two mini-exchangers to measure the outlet temperature of the water. Another thermocouple allows measuring water temperature at the entrance of the exchangers. The ambient air temperature in the room handling is controlled.
The water flow rate is measured by collecting a volume of water at the outlet of each exchanger during a certain time. To ensure watertightness of heat exchangers, we used an O-ring resistant to high

temperatures in the range of 150 °C. Finally, the system is held vertically during the entire experiment where the pumped water is injected from the bottom.

RESULTS AND DISCUSSION

Experimental conditions At the beginning of the experiments, we have used de-ionized pure water that allowed us to obtain good results in terms of cooling and avoiding oxidation and tartar depositing. But some problems of dirt and algae forming inside the heat exchangers have appeared during the tests, which led us to mix the de-ionized water with glycol to solve this problem. Thus, the coolant that we used throughout this work was a mixture of 90% de-ionised water and 10% glycol. The experimental determination of thermophysical properties of such a mixture has been conducted in our laboratoty, they shown that they are very close to those of pure water (C_p = 4157J.kg^{-1}.K^{-1} at 30 °C and ρ =1020 kg.m^{-3}). Ambient temperature was around 20 °C. Water flow rates were varied between 2 $l.h^{-1}$ and 9 $l.h^{-1}$. The heat flux fixed on the heating system was varied from 5 KW.m^{-2} to 40 KW.m^{-2}.

Results The results obtained in steady state are represented in Figures 5 to 8. It must be noted in figure 5 that the difference between the average temperature in the heated bloc (Tp) and ambient air temperature (Ta) evolves in linearly with the flow rate. The difference does not exceed 80 °C despite the importance of the imposed heat fluxes, which can reaches 50Kw/m$^{2.}$

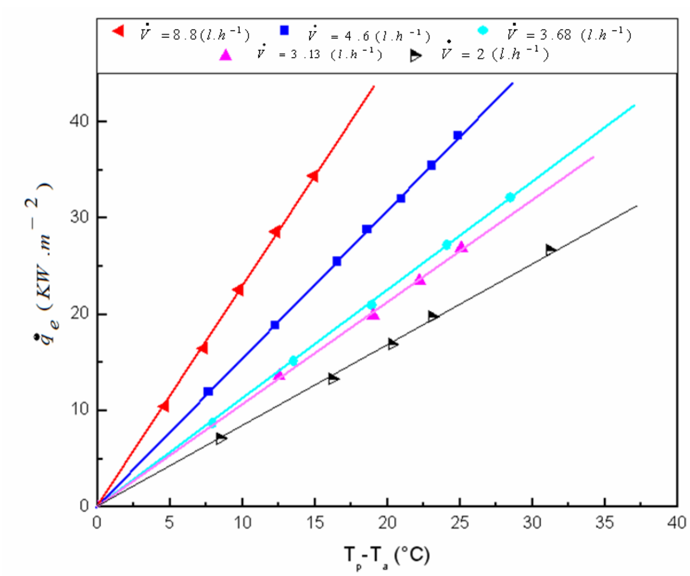

Figure 5. Heat flux density versus the difference temperature

In Figure 6, we represented the variation of equivalent thermal resistance as a function of volumetric flow rate. It is noted that, for low flow rates, this resistance decreases sharply, and then it decays less rapidly by increasing the water flow.

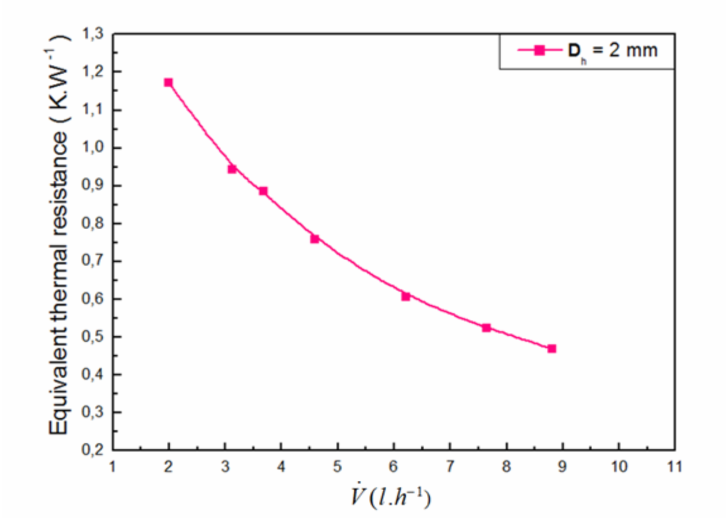

Figure 6. Thermal resistance evolutions of the heat exchangers with water flow rates

The variation of the difference temperature of water between the entry and the exit sections versus the flow rate is given in Figure 7. The curves confirm the previous findings of reduction of thermal resistance, and in particular the trend towards slight temperature difference when the flow rates go to high values.

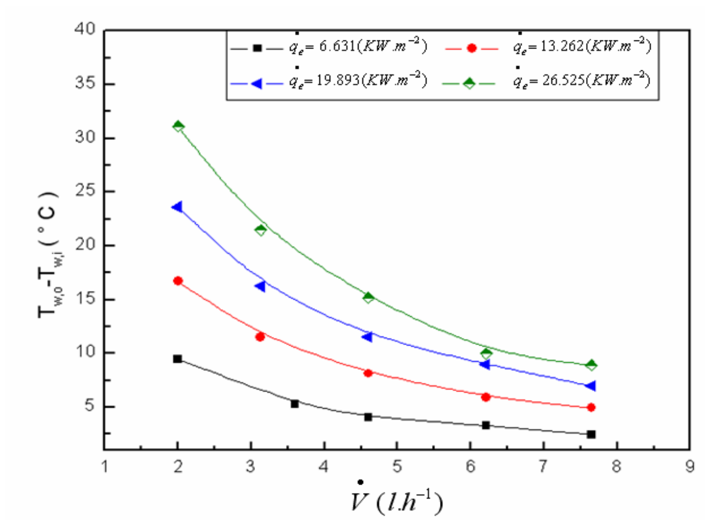

Figure 7. Outlet-inlet difference temperature evolutions for different heat flux

Average heat transfer coefficient The average heat transfer coefficient between the water flowing through the mini-channel and the walls is estimated by the use a heat balance in steady state :

$$\dot{Q}_e = \dot{Q}_{\text{int}} + \dot{Q}_{ext} + \dot{Q}_{cd} \tag{1}$$

We assume that the heat flux losses by conduction through the support of system ($\dot{Q}_{cd}$) and by natural convection in the ambient air ($\dot{Q}_{ext}$) are neglected compared to heat flux $\dot{Q}_{\text{int}}$ exchanged by internal convection.
The heat flux transferred to the cooling water is deduced from the following equation:

$$\dot{Q}_{\text{int}} = \dot{M}C_p\,(T_{w,o} - T_{w,i}) \tag{2}$$

Using $\hbar_{\text{int}}$ as the average convective heat transfer coefficient in the exchanger, we can write:

$$\dot{Q}_{\text{int}} = \hbar_{\text{int}}\, A_{\text{int}}\,(T_p - T_{w,m}) \tag{3}$$

where $T_{w,m}$ is the average water temperature defined as:

$$T_{w,m} = \frac{T_{w,o} + T_{w,i}}{2} \tag{4}$$

Thus, the coefficient $\hbar_{\text{int}}$ is given by:

$$\hbar_{\text{int}} = \frac{\dot{M}C_p\,(T_{w,o} - T_{w,i})}{A_{\text{int}}\,(T_p - T_{w,m})} \tag{5}$$

This coefficient was calculated for different imposed heat fluxes. Its evolution with the water cooling flow rates is given in figure 8. The curve shows a monotonous growth that tends to stabilize for high flow rates. One can note the importance of this coefficient which can reach 2500 $Wm^{-2}.K^{--1}$ for a flow rate of approximately $10\,l.h^{-1}$.

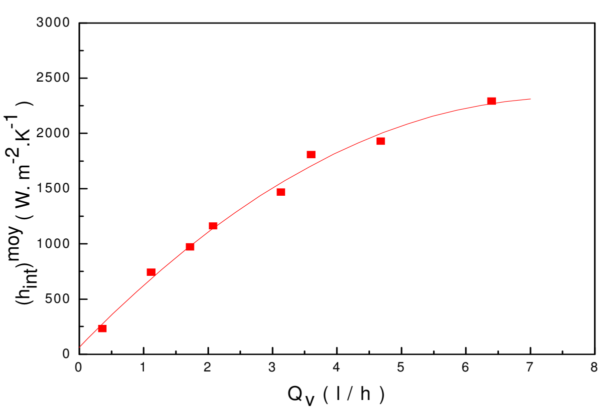

Figure 8. Evolution of the heat transfer coefficient with the flow rate

CONCLUSION

In this work, we experimentally determined the performances of mini-channels quinconce heat exchanger. The results show the efficiency of such exchanger even with low water flow rates. Despite

the importance of generated heat flux, the temperature of the heated bloc has not exceeded the allowed threshold of 80 °C for electronic components.
Considering the practical interest that represents the evaluation of the heat exchanger performance in transient state, such measurements have been recently conducted by the authors. Indeed, microprocessors and integrated circuits do not working in the constant conditions, the frequencies of their working, and therefore the dissipated heat flux are dependent on the manner they are solicited by the software. If the heat exchanger does not manage to lower the temperature elevation rapidly, failure or destruction of the microprocessor can occur. Performances are calculated under one minute thermal impulse duration from an initial non-isothermal state. The measurements have been done with different water flow rates. Experiments were also conducted for two minutes impulse duration. The analysis of the obtained results is in progress, and will be in the subject of incoming papers.

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