In this paper, the importance of the development of new high power density thermal management systems for electronic devices is assessed. It is described the new heat sink technologies under development to be used in the cooling of microprocessors. The main difficulties to be overcome before the spreading of one specific heat sink configuration are identified. At the end, it is concluded that a heat sink based on flow boiling in micro-scale channels is the most promising approach.

**Keywords:** micro-channel, heat exchanger, micro-refrigeration

**NOMENCLATURE**

- $D$: tube diameter, m
- $G$: refrigerant mass flow, kg/(m$^2$.s)
- $h$: convective heat transfer coefficient, W/(m$^2$.K)
- $k$: thermal conductivity, W/(m.K)
- $Nu$: Nusselt number
- $p$: pressure, Pa
- $P$: power, W
- $Re$: Reynolds number
- $T$: Temperature, K
- $z$: length, m

**Greek symbols**

- $\Delta$: difference

**Subscripts**

- $l$: single-phase fluid
- $sat$: saturation
- $w$: wall surface

**INTRODUCTION**

Compact heat exchangers with micro-scale channels (arbitrary denomination adopted in the literature for channels diameters smaller than 3.0 mm) possess clear advantages over those with macro-scale channels, also referred to as conventional channels. Micro-scale channels can provide a much larger contact area with the cooling fluid per unit of volume than conventional channels. Furthermore, due to the heat exchanger structural characteristics, they can endure a higher operating pressure. In addition, micro-scale channels are also distinguished for providing much higher heat transfer coefficients than conventional channels in similar conditions, allowing, according to preliminary studies, the removal of heat fluxes as larger as 10 MW/m$^2$. These characteristics permit minimizing the heat exchanger size and, therefore, the amount of material used in their manufacture. Additionally, the refrigerant inventory can be also reduced. All these aspects have not only impact on cost but also on environmental aspects.

The high degree of compactness yields new application areas for such devices, which increase as they advance to smaller sizes. At present, compact heat exchangers with micro-scale channels are found in an extensive number of applications such as automobile air conditioning systems, cooling of electronic devices, fuel cells, high-power laser cooling systems, fuel cells, micro-chemical reactors and offshore applications. In addition, they have a high potential for many other applications, viz. spacecraft radiator panels, thermal control of spacecraft payloads, residential air conditioning...
systems and cooling of fuel elements in nuclear energy production industry.

However, despite the interest of the industry and academy, evaporators (and condensers) with micro-channels are being developed in a heuristic way without the benefit of proven thermal design methods for predicting their heat transfer and pressure drops. In fact, as highlighted by Thome (2004a) the technologies available for miniaturization of micro-cooling devices have vastly outpaced what can be hydraulically and thermally modeled. Only recently, predictive methods for heat transfer coefficient and pressure drop were developed. However, unbelievable discrepancies are observed when comparing independent experimental data against these predictive methods as well as when comparing experimental data from different laboratories. Such a scenario is well illustrated in a recent work published by Ribatski et al. (2006).

Such a status quo has attracted the interest of many researchers from academy and industry and this topic became one of most important subjects of research in the heat transfer area. There has been a notable growth in the number of studies on two-phase flow and evaporation heat transfer in micro-scale channels in recent years, similar to that which occurred during the 1960s on flow boiling evaporation in macro-scale channels that was pushed mainly by the nuclear industry. These studies having been carried mainly in China and developed countries as United States, Germany, Switzerland, Sweden, Japan and South Korea. In Brazil, studies on two-phase flow inside micro-scale channels are been carried out in the LEPTEN at the UFSC by Prof. Passos and also in the Dept. of Mechanical Engineering at EESC-USP by Prof. Ribatski. At EESC-USP, a meticulous experimental study on pressure drop, flow patterns and heat transfer flow boiling inside single micro-scale channels using the most modern experimental techniques is been realized under support of FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo). Besides the coordinator of the project, two Ph-D and an undergraduate student are engaged in this study.

Although there are an extensive number of works in the open literature related to evaporation inside single micro-scale channels, papers concerning micro-cooling systems are rare. However, it is vastly know that there are a huge number of investigations on this topic being carried out mainly at research centers located in leading world companies from the microelectronics sector through partnerships between them and universities. Curiously, similar interest is not observed in Brazil, despite the existence of a vast market, academics personal know-how and the existence of several governmental programs that could provide founds.

Recently, at EESC-USP parallel to the experimental study abovementioned, the authors of the present paper have just started a careful study on micro-cooling systems, which concern numerical simulations focusing mainly on the transient temperature distribution on the surface of a cooled device. The present paper is the first result of this work. Here, it is presented the main advantages of the use of evaporation in micro-scale channels and the obstacles that have to be overcome on the development of a micro-evaporator prototype. A brief description of competing technologies is also presented.

**MICRO-SCALE CHANNELS APPLIED TO THE THERMAL-CONTROL OF ELECTRONIC COMPONENTS**

In 1965, Moore (1998) suggested that the number of transistors in a microprocessor would duplicate each period of about 18 to 24 months. Such affirmation has been confirmed in the last 40 years becoming known as the Moore’s law at the end of the 1970s. As the number of transistors increases, the energy consumption by the microprocessor, as well as the heat dissipation, also increases. Figure 1, elaborated by Chu (2004) and published in the Journal of Electronic Packaging of the ASME, illustrates the exponential increment in the amount of heat dissipated that was not observed only during a period in the 1980s due to a change in the technology of the circuit from bipolar to CMOS. Currently, the heat generated in microprocessors within PCs is dissipated initially through high-finned heat spreaders made in aluminum and further dissipated to the air through forced convection promoted by fans. Such systems can also incorporate heat pipes serving as intermediary cooling. However, the deadline date for this technologies are close not only due to a restricted cooling capacity, but also due to several other aspects as large sizes, high cost and by causing an excess of noise inherent to the use of fans. As an example, for an Intel Pentium IV processor the generated noise is already close to the limit accepted by consumer.

The heat flux dissipated by microprocessors increased in a short time from 30 W/cm² (according to the units in the microelectronic industry) to 100 W/cm² and has the perspective of achieving values near to 300 W/cm² in some few years. Such a huge value corresponds to a heat flux of 3 MW/m². This is much higher than the values observed in conventional heat exchangers, generally lower than 0.02 MW/m² (Bandarra Filho et al., 2004). Additional difficulties to be overcome are related to the fact that a microprocessor runs appropriately at a maximum temperature between 80 and 100°C, and optimally at a temperature bellow 60°C. Assuming the cooling fluid at 40°C what can be considered a reasonable operational condition, the achievement of such temperatures on the microprocessor surface would correspond at least to a heat transfer coefficient higher than 50kW/m²K. Based on these aspects, manufacturer of heat sinks for electronics industry.
have the task of designing devices that are not only able to dissipate huge amounts of heat but also that minimize temperatures differences between the microprocessor and the cooling fluid.

Currently there are in the market some cooling systems based on liquid circulation for desktop computers. They are used to keep under acceptable limits the temperatures in the central and graphical processing units (CPU and GPU, respectively). Basically these systems comprise a micro-pump and two heat exchangers. The first heat exchanger is in direct contact with the microprocessor and is based in micro-scale channels. The second is a mini tube-fin type heat exchanger placed on the external side of the cabinet that rejects the heat to the air through forced convection promoted by fans. This heat exchanger can be also based on micro-scale channels. The working fluid, when circulating through the first heat exchanger (heat sink) in contact with the microprocessor, absorbs heat, which is rejected to the environment from the warm liquid in the mini tube-fin type heat exchanger. A schematic diagram of this system is illustrated in Figure 2.

Somewhat similar is a cooling system comprising evaporation in the heat sink and condensation in the mini tube-fin type heat exchanger. The development of such a system has been subject of intense research. In most of the prototypes developed until now, the working fluid is also driven by a micro-pump placed between the condenser and the evaporator. The use of a compact vapor-compression system has also been speculated. Dissipation of higher heat fluxes and the reduction of the microprocessor overheating are achieved by using heat exchangers based on phase change processes. Moreover, this allows minimizing even more the size of the micro-cooling system when compared against those single-phase based. In addition, an increment of the refrigeration cycle efficiency is also achieved by diminishing temperature gradients along the heat exchangers.

Generally a thermal-paste is used in order to improve the contact between the microprocessor and the heat sink. This contact resistance is related to a significant parcel of the microprocessor overheating. Smaller temperature gradients along the heat sink, typical in phase-change based heat exchangers, may avoid significant variations with temperature of the properties of the thermo-paste viz. viscosity and thermal conductivity. Temperature variations along the microprocessor may affect drastically the properties of the thermal-paste favoring local overheating and a possible microprocessor damage. Actually, it is being object of intense research the development of new compounds based on nanoparticles. The objectives of these researches are obtaining a thermal-paste having physical properties that improve the thermal contact between the heat spreader and the microprocessor and also a material that keeps its optimum properties almost independent of the temperature within a larger temperature range. The improvement of the surface finishing on the heat spreader side in contact with the microprocessor is another way to decrease their contact resistance, however, is not used since can increase significantly the cost of the heat spreader. Prasher et al. (1986) described the main techniques that are being developed in order to improve the thermal contact between the microprocessor and the heat sink and, although their work was published sometime ago, is still actual today, and is suggested here for an overall overview on this subject.

Figures 3 and 4 illustrate the temperature profiles of the cooling fluid ($T_f$) for water and water+propylene glycol, and $T_{sat}$ for R134a and the wall surface, $T_{ws}$, along a micro-scale channel within a heat sink. It was adopted a dissipated power and
The advantages of evaporation in...
At the present, it is clear that several difficulties have to be overcome before the widespread use of heat sinks based on phase-change cooling. Initially, precise heat transfer and pressure drop predictive methods should be developed, so accurate designing tools for the project and improvement of these evaporators will become available. Moreover, it is fact that an extremely high bubble growing velocity (according to some authors "explosive") is observed in channels with reduced dimensions. Such a behavior, related to boiling in confined conditions, promotes reverse flows and wide pressure oscillations in the evaporator head, reaching values higher than 1 bar. A significant non-uniform flow distribution is observed under this scenario, which may favor the achievement of the critical heat flux (CHF). The achievement of the CHF can result not only in a complete damage of the heat sink, but also of the microprocessor. In addition, severe pressure fluctuations in the evaporator may propagate to the pump reducing significantly its life. Recently, instead of parallel channels, new multi-channels configurations aiming the confinement of the effects of the “explosive boiling” to restrict regions of the heat sink are under study. Cognata et al. (2006) performed experiments using a multi-channel heat sink machined in silicon consisting of 150-μm square fins separated by 50-μm square passages. The fins were staggered and oriented 45 degrees to the flow direction such that approximately 750 channel intersections occur within the volume of the heat exchanger. Cullion et al. (2006) performed experiments in a multi-channel structure having fractal-like branching micro-scale channels. Both studies obtained initial promising results.

Besides all these aspects, Thome (2006) enumerated the following targets to be pursued to the development of heat sinks based on evaporating fluids: (i) the definition of the most appropriate working fluid; (ii) a clear characterization of the conditions for the critical heat flux in order to guarantee a safe operation; (iii) the optimization of the format and dimensions of the channel taken into account effects of heat conduction through the heat sink structure, viz. Consolini and Thome (2005) pointed out that two consecutives rows of micro-scale channels presents certain advantages over single rows configurations; (iv) guarantee a safe operation in case of non-uniform heating; and (v) guarantee a safe operation also under transient conditions as the microprocessor and cooling system start up.

CONCLUSIONS

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The importance of the development of new high power density thermal management systems for electronic devices was assessed. New heat sink techniques under development to be used in the cooling of microprocessors were described. The main difficulties to be overcome before the spreading of one specific heat sink configuration were identified. Finally, a heat sink based on flow boiling in micro-scale channels was identified as the most promising approach.

REFERENCES


