THE ADVANTAGES OF EVAPORATION IN MICRO-SCALE CHANNELS TO COOL MICROELETRONIC DEVICES

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ABSTRACT

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

Δ	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/cm^2 (according to the units in the microelectronic industry) to 100 W/cm^2 and has the perspective of achieving values near to 300 W/cm^2 in some few years. Such a huge value corresponds to a heat flux of 3 MW/m^2. This is much higher than the values observed in conventional heat exchangers, generally lower than 0.02 MW/m^2 (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^{o}C, and optimally at a temperature bellow 60^{o}C. Assuming the cooling fluid at 40^{o}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/m^{2}K. 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.

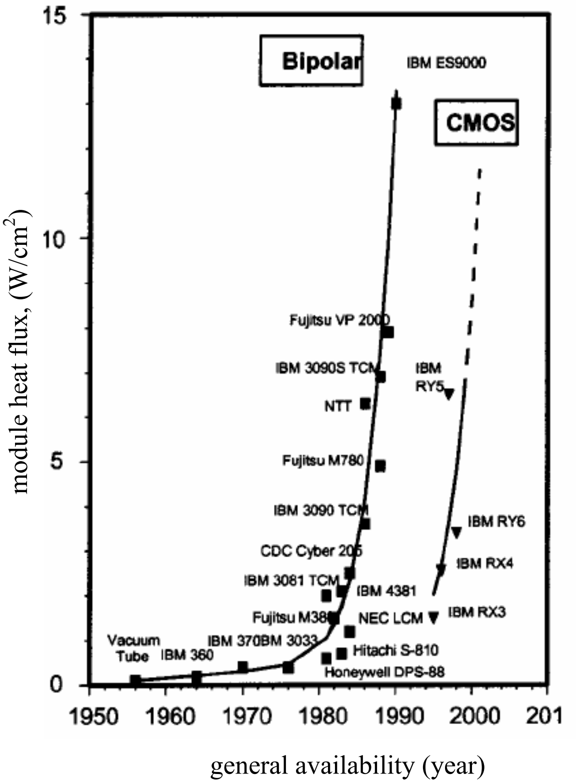

Figure 1. The chronological evolution of module level heat flux in mainframe computers, Chu (2004).

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.

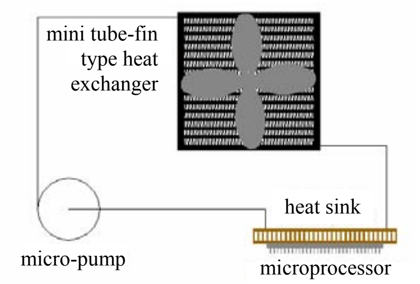

Figure 2. Schematic diagram showing a single-phase cooling system.

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_l for water and water+propylene glycol, and T_{sat} for R134a) and the wall surface, T_w, along a micro-scale channel within a heat sink. It was adopted a dissipated power and microprocessor foot print dimensions typical of a Pentium 4 made by Intel. Several simplifying assumptions were adopted, viz. uniform heat flux distribution, uniform mass velocities through the channels, developed flow, and a non-existence of dryout conditions.

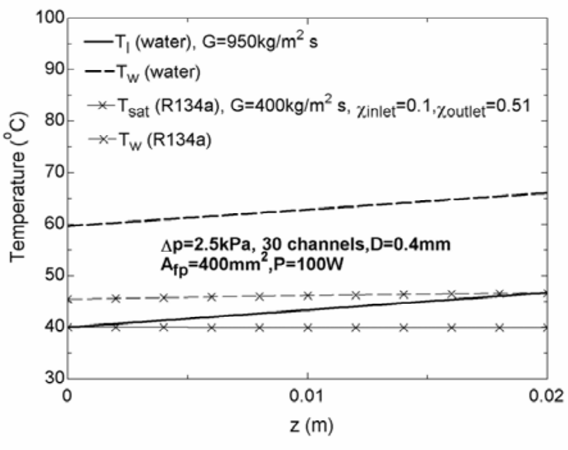

Figure 3. Cooling fluid and wall temperature profiles for a single-phase and a two-phase based heat sinks.

For two-phase flow, the pressure drop was estimated according to the separate-phases flow model, using the correlation proposed by Muller-Steinhagen and Heck (1986) to obtain the frictional pressure drop. To obtain the evaporating heat transfer coefficient, the 3-zone model recently proposed by Thome *et al*. (2004b) was used. Detailed descriptions of these models are found in a web book recently published by Thome (2004c), which can be downloaded freely. For turbulent single-phase flow the heat transfer coefficient and the pressure drop were estimated according to the correlation proposed by Gnielinski (1976), and the friction given by the Blasius equation, respectively. For laminar flow, a constant Nusselt number of 4.36 (circular channel) and a Fanning friction factor given by 16/*Re* were used to calculate the heat transfer coefficient and the pressure drop, respectively.

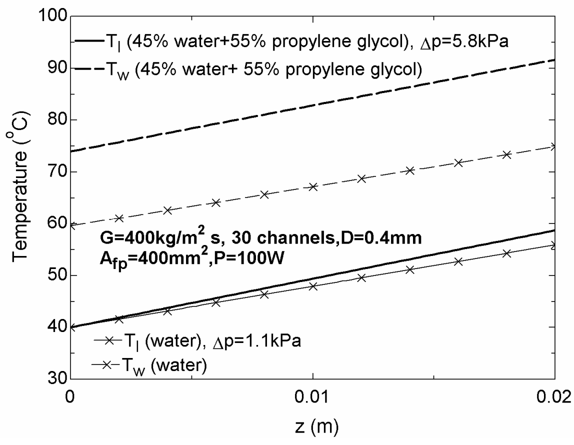

Figure 4. Fluid and wall temperature profiles for single-phase based heat sinks using as working fluids water and a solution of water and propylene glycol.

According to Figure 3, for a similar pressure drop of 2.5 kPa, a lower wall superheating and a wall temperature almost constant are observed when evaporating R134a. Water single-phase flow seems also a reasonable solution since the wall temperature was kept below 80°C and its variations was under 6°C. However, by imposing the maximum wall temperature and the heat dissipation as the limiting parameters of the heat sink project, it is important to highlight the fact that the pressure drop and also the heat sink size can be reduced. This can be done by decreasing the heat sink length in the flow direction due to the higher heat transfer coefficients achieved by evaporating R134a. The number of channels can also be reduced without compromising the maximum overheating. Both solutions result in a reduction of costs by decreasing the total machining process and also the amount of material in the case of minimizing the heat sink size.

Figure 4 shows a comparison between the performances of water and a solution of water and propylene glycol (antifreeze solution) as single-phase cooling fluids in a heat sink having dimensional characteristic similar to the one considered in Figure 3. A power dissipation of 100W and a mass velocity of 400kg/m^{2}s were adopted as input parameters. Propylene glycol instead of ethylene glycol was chosen due to its lower toxicity. A volumetric concentration of 55% of propylene glycol in water was assumed in order to fit the maximum freezing temperature recommended by the electronic industry of -40°C. According to Figure 4, the solution of water and propylene glycol gives a pressure drop five times higher than pure water and two times higher than the value shown in Figure 3 for evaporating R134a at similar flow rates and cooling capacity. Higher pressure drops are not suitable to mini cooling systems since they are related not only to a higher pumping power but also to an increase in the size of the pump. In addition, by using a solution of water and propylene glycol as working fluid, much higher wall temperatures and temperatures gradients along the heat sink are obtained as revealed in Figure 4. Such behaviors are related to the relative low thermal conductivity and high viscosity of the propylene.

It is important to highlight that the disadvantages of single-phase when comparing against two-phase cooling devices may be reduced in the future as result of the development of the nanofluid technology. However, it can be speculated that evaporating cooling is the most promising approach based on its advantages aforementioned and also in the increment in the rate of heat dissipated by a microprocessor that certainly will occur and difficultly will be handled by a single-phase solution.

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 became 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.

ALTERNATIVE COOLING TECHNOLOGIES TO MICRO-SCALE CHANNELS

In addition to micro-scale channels, techniques based on micro-jets and porous medium have also attracted the attention of industry and academy. The researches that were done on these topics involved single and two-phase flow as well. Porous medium heat sinks present a low cost and can be manufactured using conventional techniques as a brazing processes. The heat transfer enhancement achieved by using single-phase flowing in a porous medium is mainly related to the wide increment in the effective heat transfer area by the porous matrix. Capillary effects and the evaporation of a thin film are also important mechanisms in the heat transfer enhancement for flow boiling in a porous medium. The negative aspects in using porous mediums are the high pressure drops and the fact that the heat transfer coefficient decreases drastically when operating at conditions slightly different than the optimum one.

Cooling system configurations based on single and multi micro-jets are actually under development. Micro-jet cooling provides extremely high heat transfer coefficient (under some circumstances higher than micro-scale channels) and possess the possibility of direct contact between the refrigerant and the microprocessor. In addition, the jets can be displayed according to the heat generation distribution on the microprocessor surface. However, the use of micro-jet posse constructive and operational inconveniences which should be engineered, viz. keeping the jets stable and difficulties in removing the excess of cooling fluid. Moreover, surfaces under the impact of a jet during long periods tend to suffer an erosion process, which in case of direct contact can damage the microprocessor.

CONCLUSIONS

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.

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