Evaluation and Development of Advanced Cooling Systems for Microelectronics

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ABSTRACT

The work reported here aims the development of advanced cooling systems for computer processors. It includes the design and construction of a test bed which reproduces the dynamic behaviour of a real processor. The test bed can operate under diverse thermal boundary conditions, namely constant power dissipation, constant temperature and a time varying heat flux typical of real operating conditions. The experiments encompass the quantification of the thermal performance of air and indirect water-cooling systems currently available in the market. The results show that, although by a small margin, the water system performs better. A direct cooling apparatus was then applied to the test bed, which considers a recently technology of Intermittent Spray Cooling. The work includes a comprehensive study of the influence of the injection signal (frequency and duty cycle) and pressure, distance from the nozzle to the processor surface, orientation of the processor (horizontal versus vertical) and thermal properties of the coolant. The experiments clearly show that the technology has the ability to operate as a cooling system, given proper optimization, and the results show that: i) there is an optimal distance to place the nozzle above the processor (20 – 30mm) and ii) an optimal duty cycle range (50%-60%) that allows a correct fluid management; iii) small duty cycles with high frequencies should be avoided as they cannot manage accurately the system temperature; iv) processors should work horizontally. The present work was accepted for oral presentation at the 22nd European Conference on Liquid Atomization and Spray Systems (ISBN 978-88-903712-0-2).

Keywords: Cooling – Innovation – Processor – Test Bed – Spray – Intermittent

INTRODUCTION

Personal Computers’ processors have registered a considerable evolution. In 1965, the Intel® co-founder Gordon Moore predicted that the number of transistors on a chip would double about every two years and, in fact, the evolution of Intel’s® processors, over the past 40 years, respected this prevision [1]. The innovations in computer design [2] allowed to achieve faster processors, with the reduction of packaging size [3], bringing new challenges in terms of Thermal and Power Management. Bar-Cohen et al. [3] refer that the rise in chip power dissipation and heat fluxes, with roadmap projections of average chip heat fluxes exceeding 150 W/cm² and the emergence of on-chip hot spots, with heat fluxes approaching 1 kW/cm², can degrade the processor performance and reliability. Given this scenario, the development of new and more effective cooling methods is an emergent need.

In this context, spray impingement has the potential to further miniaturize the packed device, since spraying directly onto the processor die with a dielectric coolant allows removing the contact resistance between the die and the thermal dissipater. However, fluid management is the main limitation to the development of this technology (e.g., Shedd [4]). In this context, Intermittent Spray Cooling System (ISCS) appears as a new technological concept for two-phase cooling, which provides better performance and control over heat transfer mechanisms such as thin film boiling, e.g., Panão
and Moreira [5, 6]. Nevertheless, most of those studies addressed the physical fundamentals behind the heat transfer process and were performed at static boundary conditions, which do not entirely reproduce the dynamic behaviour of real processors. In this context, the work reported aims the assessment of a test bed built to assist computer product designers and manufacturers to develop new cooling systems and compare diverse cooling technologies based on real dynamic conditions.

EXPERIMENTAL APPARATUS

In order to reproduce a real processor behaviour, three main features must be taken into account: i) the power of the test bed must be controlled to vary at the same rate as in a real processor; ii) the temperatures achieved must be realistic and iii) the response to power changes must occur in a practical time frame. The developed test bed is based on a commercial processor, the Intel® Pentium® 4 processor in the 423-pin package and was designed in accordance with the specifications given in the manual of the processor [7]. As in the commercial processor, the heat source is in contact with an Integrated Heat Spreader (IHS). The contact between the heat source and the IHS is made through the use of a thermal interface material, similar to that used in most common commercial personal computers to ensure a good thermal contact between the processor and the cooling system (Figure 1). The IHS is made of the same material of that used in practice and has similar dimensions (27.5 x 27.5 mm²) in accordance with [7]. The components are assembled in a support base which is designed to allow the accommodation of different cooling systems. The main component of the heat source is a transistor (BD645), which was chosen, in opposition to an electrical resistance system, because it allows fulfilling the aforementioned design characteristics. A heat source based on electrical resistances was tested first, but the results showed that, although the temperatures achieved were realistic, the time response was not in accordance to those expected for a real processor. Nevertheless, the transistor must be selected in order to fulfil the required features, as assured in preliminary tests using a commercial air cooling system. The transistor used is based on a Darlington scheme which allows to reproduce a power dissipation similar to that found on a real processor. The transistor behaves as a Controlled Current Source. The facility allows to perform different types of tests, namely: at constant power dissipation (0 to 60 W), at a constant temperature for one of the thermocouples or it may introduce power variations during a test, to simulate the dynamic boundary conditions of a real processor. The temperature of the system is monitored by 3 K type thermocouples: 2 in direct contact with the heat spreader and 1 in direct contact with the heat source.

![Figure 1 – Test bed: (a) Schematic of the test facility; (b) Assemblage.](image-url)
The control system has been developed by the author. It includes a microcontroller (Microchip® PIC18F8722) which, in association with a specific board, also from Microchip®, and by means of auxiliary circuits has the ability to control the power variation and to monitor and collect the measured data. A Digital-to-Analog converter (DAC) was developed to act as an interface between the microcontroller and the test bed control circuit. To control the dissipated power, the system uses an 8 bit control system with 256 power levels that correspond to a 0.2 W resolution. The DAC created is based on a Binary Weighted DAC and it was tested and adjusted in order to compensate any offset.

The signal of the thermocouples is monitored and collected by the microcontroller after amplified by a circuit with an instrumentation amplifier (INA128). A program was then developed to receive the test parameters from a personal computer and monitor and collect the measured data, online, while a test is being performed. All the communications are made using a communication protocol, designed for this purpose, via an RS-232 interface. All the measured data return to the personal computer and are automatically saved in a file with a format chosen by the user. At the same time, the user has available in the computer monitor, in real time, all the information about the test. The power control and necessary variations are made automatically, eliminating the need for the user to perform any type of manual control or verification during the tests. The control program also ensures a continuous monitoring of the system temperature in order to ensure that its maximum limit is not reached.

Using the ability of the system to introduce power variations during a test, the experiments conducted here were based on the power profiles reported by Isci and Martonosi [8], who obtained live power measurements for benchmarks as well as some desktop applications for an Intel® Pentium® 4 processor, by combining real total power measurements with performance-counter-based per-unit power estimation. The work includes the study of two commercial systems, an air-cooling (Intel® C25704-002) and a water-cooling system (supplied by AquaPC), and also the development and study of a cooling system based on ISCS. The ISCS built sprays a dielectric fluid directly onto the IHS. Two fluids are used, methoxy-nonafluorobutane (HFE7100 - C₄F₉OCH₃) manufactured by 3M and methanol (CH₃OH). The thermo-physical properties of the working fluids are depicted in Table 1.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>HFE 7100</th>
<th>Methanol</th>
</tr>
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<tbody>
<tr>
<td>Density [kg m⁻³]</td>
<td>1488</td>
<td>788</td>
</tr>
<tr>
<td>Dynamic viscosity (µ x 10⁶) [kg m⁻¹ s⁻¹]</td>
<td>5.7</td>
<td>5.6</td>
</tr>
<tr>
<td>Surface Tension (σ x 10⁵) [kg m⁻²]</td>
<td>13.6</td>
<td>22.3</td>
</tr>
<tr>
<td>Thermal diffusivity (α x 10⁶) [m² s⁻¹]</td>
<td>3.9</td>
<td>10.4</td>
</tr>
<tr>
<td>Thermal conductivity (k x 10⁵) [W m⁻¹ K⁻¹]</td>
<td>68.8</td>
<td>203.3</td>
</tr>
<tr>
<td>Specific heat capacity at constant pressure [J kg⁻¹ sC⁻¹]</td>
<td>1177</td>
<td>2481</td>
</tr>
<tr>
<td>Boiling Temperature [°C]</td>
<td>61</td>
<td>65</td>
</tr>
<tr>
<td>Latent heat of evaporation (hₘ) [kJ kg⁻¹]</td>
<td>126</td>
<td>1158</td>
</tr>
</tbody>
</table>

The information provided here is based on that supplied by 3M (HFE7100) and by CRC Handbook of Chemistry and Physics [9] (Methanol). The fluid is supplied from a tank pressurized with air and delivered by a fast response electronic valve, supplied by Candela, through a nozzle (Figure 1). An electronic circuit was developed, combined with a function generator, to control the frequency and
duty cycle of the valve signal. The reported values of pressure are measured by a manometer placed just before the electronic valve (Figure 1). The system is accommodated in a micrometer translation platform which provides a precise positioning of the nozzle in relation to the test bed, allowing displacements on the x axis, y axis and z axis. The impact angle of the spray onto the surface can be varied from 0º to 90º. In all the tests, the room temperature and humidity are measured and collected.

RESULTS AND DISCUSSION

The study reported here makes use of the ability of the test facility to introduce power variations during a test, as to reproduce power profiles of the processor during its normal use (e.g. opening an Internet site). This procedure was followed to quantify, for real conditions, the thermal performance of air-cooling and indirect water-cooling systems currently available in the market and to establish the main parameters and guidelines for the design of a practical Intermittent Spray Cooling System.

Regarding the study of the thermal performance of the air and indirect water-cooling systems, tests were conducted for constant power dissipation and under dynamic conditions. The constant power tests were conducted for 5 minutes for different power values: 15, 30, 45 and 60 W. The results for the constant power tests show that the tests with the water-cooling system register, although by a small margin, lower temperatures. For instance, for the heat source thermocouple there are average differences between the tests with air and water-cooling systems of 1.6ºC (15 W), 2.2ºC (30 W), 4.3ºC (45W) or 1.3ºC (60W). In all the cases, the results for the tests with the air cooling system show higher temperatures. Also, with water-cooling, the system can attain thermal equilibrium in a faster way. Similar trends are observed for the surface thermocouples.

In addition to the constant power tests, the cooling systems performance was further investigated under dynamic conditions. The tested thermal boundary conditions correspond to one of the power profiles measured by Isci and Martonosi [8]. This particular power profile (Figure 2) gathers multiple operation conditions of a real processor under demanding situations, thus being a good case study to evaluate the behaviour of the cooling systems.

Figure 2 shows the temperature of the thermocouple in direct contact with the heat source, for both cooling systems under the dynamic conditions of Figure 2. The results highlight that, as for the constant power tests, the water-cooling system allows to achieve lower temperatures (in Figure 3, there is an average temperature difference of 1.9ºC between curves with some points with differences of 3ºC). Although the water-cooling system allows to achieve lower temperatures, its response to power variations is similar to that of the air-cooling system (the curves present similar slopes for the different power peaks/decays). This behaviour is also observed in the surface thermocouples. The results also show that, for all the tests, the surface thermocouples present similar trend: the maximum
average difference between the two surface thermocouples is only 1°C for the tests with the air-cooling system and 0.28°C for the tests with the water-cooling system. These results are associated to homogeneous heating/cooling of the surface.

![Figure 3 – Temperature of the heat source for the commercial cooling systems under dynamic conditions.](image)

From this analysis, one cannot affirm a domain of one of the technologies, but the water-cooling system seems to have more potential to function as a cooling system for new computers processors. In this context, similar conclusions are reported by Zhang et al. [10], who also studied the cooling performance of an air and water-cooling systems, although using a different configuration.

The present work also aims to provide the guidelines to optimize the design parameters of an Intermittent Spray Cooling System (ISCS) applied under dynamic behaviour conditions. Panão and Moreira [5, 6] have already studied the effects of some of the injection parameters (e.g., frequency, pulse duration, pressure, impingement distance) on the performance of ISCS but under static boundary conditions. The term duty cycle is defined here as the ratio of the pulse duration to the pulse period, considering a signal made of rectangular pulses, in accordance with [11].

The effect of the distance from the nozzle to the test bed was considered, for the spray at various conditions, when the test bed is in the horizontal position and dissipates 60 W (constant power tests). The absolute distance of the nozzle to the surface ($d_{noz}$) was varied from few millimetres ($\approx$ 5 mm) above the surface up to 80 mm and the results show that, both for large or very small ($d_{noz} < 10$ mm) distances, the temperature of the test bed is globally higher and evidences a trend of continuous increase, thus indicating a deterioration of the potential of the spray cooling capability. This trend can be explained as in Mudawar and Estes [12]: as the IHS is square, the cooling performance depends whether the spray impact area covers, or not, the entire surface of the heater. Outside this range, the cooling performance is degraded as the spray area does not cover the surface of the test bed. The optimal $d_{noz}$ obtained in the present study lies between 20 and 30 mm. Also Bash et al. [13] found that the critical heat flux presents a decrease when the height of the spray is increased. The results found for $d_{noz}$ are compatible with the use of this type of technology in a real desktop computer.

The signal applied to the electronic valve was also studied for constant power tests in order to select the range of frequencies and duty cycles to be considered in the experiments. Once again, thermal equilibrium is not attained at all conditions, particularly when higher frequencies are associated with small duty cycles.

Other design parameters were further investigated under dynamic conditions. Each was varied independently with the nozzle at the optimal distance from the surface ($d_{noz} = 20$ mm) and with thermal boundary conditions (Figure 2). Three different injection pressures were selected (2.3 bar, 3.3 bar and 5.0 bar) after a preliminary study, which revealed that 2.3 bar was sufficient to assure an adequate
atomization and with a good cooling performance. The frequency of injection was varied from 0.8 Hz up to 2.6 Hz, a 3.25 fold increase which was observed to be enough to conclude on the relative influence of this parameter. Three representative duty cycles were also chosen after preliminary studies: a low (23.6%), an average (57.7%) and a high duty cycle close to a continuous spray (75.2%).

The analysis focuses on the thermal behaviour of the test bed, as characterized by the temporal evolution of the temperature measured at the heat source and on the surface of the IHS. The heat source thermocouple consistently registers the largest temperature. Thus, the information provided by this thermocouple is the most relevant to assure the safety operation of the processor.

The temperatures registered by both surface thermocouples are similar, thus confirming that, for the test bed at the horizontal position, the heating and cooling processes are homogeneous (more information available in [14]).

Figure 4 shows the temporal evolution of the temperature of the thermocouple in direct contact with the heat source, measured at duty cycles of 23.6%, 57.7% and 75.2%, for 0.8 Hz at 2.3 bar. The coolant is methanol and the test bed is in the horizontal position ($d_{noz} = 20$ mm). In general, the results highlight that there is an optimum duty cycle (between 50% and 60%) above which a further increase does not significantly improves the cooling performance. Particularly, for the case in Figure 4, it is clear that the curves corresponding to the larger duty cycles are almost collapsing, e.g. at 60 seconds, they show only a 3.7ºC difference. This behaviour can be found in all the results and similar trends are also observed for the surface temperatures. Moreover, the use of smaller duty cycles alters the time response to the power changes: the temperature increases to larger values during power peaks but does not decrease so much during power valleys. This is clear in Figure 4: for instance, there is an 11.5ºC difference (at 60 seconds) between the curves with 23.6% and 57.7% duty cycle. This behaviour is observed for all tested pressures and frequencies in the horizontal position.

The results also show that, when compared with the effects of the duty cycle, the frequency and pressure of injection have a negligible effect. Also, the curves for the surface temperature behave similarly. For instance, for the heat source thermocouple for tests in the horizontal position ($d_{noz} = 20$ mm) using methanol with a 2.3 bar injection pressure, the average differences between the curves for the two tested frequencies can be as low as 0.4ºC (57.7% duty cycle, 2.3 bar). For the injection pressure one can, for instance, found for tests in the horizontal position, using methanol with $d_{noz}$ at 20 mm and an injection signal of 2.6 Hz with 23.6% duty cycle, at a demanding point (44 seconds), temperatures of 65.4ºC (2.3 bar), 66.4ºC (3.3 bar) and 65.5ºC (5.0 bar) which allows to observe that the maximum temperature difference for this case is only 1ºC. A more detailed analysis is reported in
Given the negligible effect of pressure, a practical system should use the lowest pressure capable of achieving a good atomization in order to keep hardware as simple and safe as possible.

The analysis performed so far highlights that the duty cycle is the operational parameter of an ISCS that allows a more accurate control of the temperature of the processor. This is in accordance with previous studies by Panão and Moreira [5, 6]. Also Shedd [4] refers that it is the droplet flux which controls the heat transfer performance and Bash et al. [13] reported that, for heat fluxes of the order of those achieved in the present study, the critical heat flux is flow limited. In line with this, the existence of an optimum duty cycle value above which the cooling system cannot lower significantly the temperature of the test bed can be explained with the formation of a liquid film at the surface, which mitigates heat removal by phase change (e.g., Panão and Moreira [6]).

In this context, the angle of impact is expected to alter the dynamics of the liquid film and therefore, the thermal behaviour of the system. Several experiments were then conducted with the test bed in the vertical position, which would preclude the formation of the liquid film over the IHS. The experiments were again performed with methanol (d_{noz} = 20mm) and followed the same methodology as for the test bed in the horizontal position. Figure 5 depicts the thermal response for the heat source thermocouple for the three duty cycles, for 0.8 Hz, using the lower injection pressure (2.3 bar) in the vertical position.

![Figure 5](image_url)  
**Figure 5** – Effect of the duty cycle in the temperature of the heat source, when the test bed is in the vertical position. The coolant is methanol. Injection frequency = 0.8 Hz; Injection pressure = 2.3 bar.

The results evidence that the system performs better when the duty cycle increases from 23.6% to 57.7%, although now with a lower gain that when the test bed was in the horizontal position. The results obtained in the vertical position also show a difference between the temperatures measured by the two surface thermocouples, which indicates that the surface cooling is no longer homogeneous. The average difference between the surface thermocouples can be as high as, for instance, 2.6°C (0.8Hz, 75.2%, 2.3 bar) being the lower temperatures measured at the region of the surface which is firstly impinged by the spray. Moreover, the surface temperature measured in the vertical position is larger than that measured in the horizontal position. This trend is a clear result of the influence of gravity on the dynamics of the liquid film. When the test bed is in the horizontal position, the vaporization of the liquid film remaining at the surface between successive injections, assures a continuously removal of heat thus allowing to keep the surface temperature lower. Similar trends are observed for different frequencies and duty cycles, in the sense that the temperatures measured are larger when the test bed is at the vertical position, contrarily to what was expected considering that the film would lead to a less efficient heat extraction (e.g. Shedd [4], Panão and Moreira [5]). It can be speculated that these results may be due to a less efficient area subscription of the spray when the impacted surface is vertical, particularly because droplets are swept away from the surface, thus
reducing the time of thermal contact (e.g. Moreira et al. [15]). One possible solution could be to change the surface wettability, based on the work of Moita and Moreira [16]. For a real case system application and based on the aforementioned role of the contact time of the impingement spray, one should recommend the use of the horizontal position, which does not represent a limitation to the application of this technology.

Although the experiments performed with the test bed in the vertical position show generally worse cooling performances, the duty cycle is still the operational parameter which most affects the thermal behaviour of the system, when compared to the injection frequency. An exhaustive study showed that the spray must operate with a duty cycle of 50%-60%. Moreover, it is more advantageous and safe, in a real system, to work with a mid term duty cycle than trying to alter the operation conditions between smaller and higher duty cycles, since the use of very small duty cycles brings the system to dangerous high working temperatures. Smaller duty cycles, promoting phase change, should be effective in less demanding conditions. On the other hand, duty cycles within the optimum range still offer a significant improvement in terms of fluid consumption over continuous sprays.

Further improvements may be achieved by optimizing the properties of the working fluid, namely the temperature for phase change and the latent heat of evaporation (e.g., Panão and Moreira [5]). In this context, further experiments were conducted using a dielectric fluid (HFE7100). Although not shown here due to length constrains, the temporal evolution of the temperature was measured at different duty cycles, with two frequencies of injection at a pressure of injection of 2.3 bar. When compared with the results obtained with methanol, the temperatures measured using the HFE7100 are much higher, as expected, since the vaporization temperature is similar for both fluids but the latent heat of evaporation of the HFE7100 is much smaller ($h_{\text{fgMethanol}} \approx 9.1 h_{\text{fgHFE7100}}$). It is clear here that the fluid properties and in particular the latent heat of evaporation of the fluid are important parameters to consider. In fact, given the low latent heat of evaporation of HFE7100 which further reduces the heat flux removal, small duty cycles, which are associated with smaller flows, are not sufficient to maintain the test bed at a low safe temperature, thus the tests were automatically stopped by the security routine to avoid damages in the test bed. The average differences in the temperature curves, for the same test conditions, for methanol and HFE7100 can be as high as, for instance, 22.1°C (57.7% duty cycle, 0.8 Hz, 2.3 bar). Similar trends are observed for the surface thermocouples.

There is an evident improvement of the cooling performance of the system when the duty cycle is increased from 23.6% to 57.7%. Further increasing the duty cycle, there is still some improvement, when compared to the experiments performed with methanol, as in this case the vaporization of the liquid over the surface of the IHS is faster, given the smaller $h_{\text{fg}}$. In fact, the latent heat of evaporation of the fluid can affect the optimum duty cycle range since this range will probably slightly increase when the latent heat of evaporation is lower. Nevertheless the difference in the temperature curves obtained for the duty cycle of 57.7% and 75.2% is considerably lower than that obtained when the duty cycle is increased from 23.6% to 57.7%. Therefore, although the exact optimum duty cycle range may be slightly adjusted depending on the properties of the working fluid, the results obtained for the whole conditions studied here still suggest an optimum range between 50% and 60%, which allows a
significant decrease in fluid consumption, thus confirming the advantage of the ISCS as strongly argued by previous authors (e.g. Panão and Moreira [5, 6]) while it assures the safety of the system.

Any significant changes are observed, also using a fluid with different properties, in changing the injection frequency. Also, as previously found for methanol at the horizontal position, the surface thermocouples present similar temperatures thus confirming that the cooling process is homogeneous.

**CONCLUSIONS**

The work reported here includes the design and construction of a test bed which reproduces the dynamic behaviour of a real processor. The results show that the cooling process on the surface for the air-cooling and indirect water-cooling systems currently available in the market is homogeneous. Also, for the constant power and power profiles tests, although by a small margin, the water-cooling system allows the test bed to achieve lower temperatures and, for the constant power tests, it attained thermal equilibrium in a faster way. Although one cannot affirm a domain of one of the technologies, the water-cooling system appears as a promising solution to the thermal management problem.

This study also intends to identify the main operational parameters of an ISCS. The results showed that the best performance of the system is achieved when the distance from the spray nozzle to the processor surface is within a definite range (20 and 30 mm).

The experiments confirm that the main conclusions drawn in previous studies under static boundary conditions, still apply under the dynamic boundary conditions: the duty cycle is the main operational parameter to consider; injection pressure and frequency have a negligible influence, so that small injection pressures can be used with advantages for the design of a simple and safe commercial system. In terms of the duty cycle range, there is an optimum range above which the cooling performance does not improve due to the formation of a thick liquid film over the IHS which will mitigate an efficient heat removal by phase change. For the current case, this value lays within 50-60%. Based on these results one should recommend the use of a mid term duty cycle (50%-60%), since it will still allows a significant reduction in the fluid consumption when compared to a continuous spray. The results also show that, for the horizontal position, the cooling process on the surface is homogeneous.

For the vertical position, the results show higher temperatures in all the cases which can lead one to say that the liquid film formed in the horizontal position helps to remove some heat from the system. The results also show that, in the vertical position, duty cycle continues to be an important parameter.

The higher temperatures founded in the vertical position can also be due to a less efficient area subscription of the spray. Based on these results, one should recommend the use of the computer processor in the horizontal position.

Finally, the results confirm that the properties of the working fluid are naturally important.

As in conclusion, one can affirm that the main parameters to consider in an ISCS are the distance between nozzle and processor surface, the duty cycle, the position of the processor and the properties of the working fluid and that the technology has the ability to operate as a cooling system, given proper optimization. As a final remark, the temperature control should be made at the heat source.

For future work, one should recommend the construction of a new test bed with the ability to introduce hot spots but maintain the ability to reproduce the dynamic behaviour of a real processor.
One should also recommend the study of the main parameters of the water-cooling system in order to optimize the cooling performance.

REFERENCES


