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DIRECT-CONTACT-INTERMITTENT-SPRAY-COOLING FOR THERMAL MANAGEMENT OF A COMPUTER PROCESSOR

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ABSTRACT
The present paper reports on the assessment of a test bed built to assist computer product designers and manufacturers to optimize the design parameters of new developed cooling systems based on Direct-Contact-Intermittent-Spray-Cooling. A test bed was designed and built, which has the ability to reproduce programmed power profiles, as measured in benchmarks and desktop applications for a real processor. The results evidence that the duty cycle is the main operational parameter to consider in the control of the cooling system for dynamic boundary conditions, thus confirming the major conclusions reported in previous studies performed with a static test bed. There is an optimal range for the duty cycle, between 50% and 60%, above which there are no significant improvements in the cooling performance, due to the formation of a thick liquid film which mitigates an efficient heat removal by phase change. Based on the thermal behaviour of this test bed one should recommend that it can be more advantageous and safe, in a real system, to work with such mid term duty cycle, than trying to alter the operation conditions between smaller and higher duty cycles, for fluid management. The position of the test bed also has an important role: the system should work horizontally.

INTRODUCTION

Personal Computers' processors have registered, in the past years, 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 and technological advances in computer design [2] allowed to achieve faster processors, registering improvement rates of performance of the order of 35% per year [2], with the reduction of packaging size [3], bringing new challenges in terms of Thermal and Power Management. Power is an important issue for modern CMOS processors, since the energy required to function the transistor is proportional to a number of factors, including the frequency of switching [2]. But, as the working frequency increases and the dimensions of the chip decreases, the transistor leakage current increases, leading to excess power consumption and heat generation [4]. Hennessy and Patterson [2] referred that thermal management would be, in the short term, one of the majors limitations to the development of faster processors. 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/cm^2 and the emergence of on-chip hot spots, with heat fluxes approaching 1 kW/cm^2, can degrade the processor performance and reliability. As an example, Paik et al. [5] argue that an increase of just 15ºC in the temperature can affect timing at the same time that the on-chip thermal variation reduces reliability. Given this scenario and taking into account that according to *International Technology Roadmap for Semiconductors* (ITRS) [5], the power consumption of high-performance desktops will jump from 147W to 288W in 2016, the development of new and more effective cooling methods is an emergent need. As stated by Cader et al. [6], conventional air-cooling solutions are struggling to cope with the increase in clock frequency and in the number of gates, which reinforces the call for alternative cooling technologies. In line with this, Shedd [7] refers that spray cooling allows reaching heat transfer coefficients of about 10000 Wm^{-2}K^{-1} with the use of refrigerants. In this context, spray impingement has the potential for further miniaturization of 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. Also, one can expect significant enhancements in the performance of the cooling device with the use of two-phase boiling flows.

However, fluid management is the main limitation to the development of this technology (e.g., Shedd [7]). 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 [8, 9]. One of the advantages of using an intermittent spray is the ability to control the amount of liquid injected by proper matching the frequency of injection and pulse duration through the duty cycle. Nevertheless, most of those studies addressed the physical fundamentals behind heat, the heat transfer process and, although experimental, were performed at static boundary conditions, which do not entirely reproduce the dynamic behaviour of real processors. Only a few studies are based on dynamic arrangements. For instance, Cader et al. [6] addressed the ability of spray cooling to handle transient die power dissipation and its effects on device reliability using a bare die thermal system and a dual Opteron CompactPCI single board computer.

In this context, the present paper reports on 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. With this objective in mind, the test bed was designed to reproduce the dynamic behaviour of a real processor so to allow to characterize the design parameters of

Direct-Contact-Intermittent-Spray-Cooling systems applied to a computer processor.

EXPERIMENTAL APPARATUS

In a real processor, power dissipation varies considerably at a rate which depends on the programs currently being executed. A variation of 50W on an application-by-application basis is usual in today's processors, so that power dissipation of real running systems has become crucial for hardware and software system research and design [10]. Given that, the present work focuses on the analysis of the application of cooling systems to real case studies. 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 test bed developed in this work 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 [11]. 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 (AKASA AK-460 Thermal Compound), similar to that used in most common commercial personal computers, to guarantee 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 mm^2) in accordance with [11]. The components are assembled in a support base which is designed to allow the accommodation of different cooling systems and is made to resist to the temperature of the heat source. The main component of the heat source is a transistor, which was chosen, in opposition to an electrical resistance system, because it allows fulfilling the three 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 achieve power dissipations of the same order of magnitude as those in the commercial processor, with response times allowing to fulfil the required time response rates, as assured in preliminary tests using a commercial air cooling system. The transistor used in the present system is based on a Darlington scheme which allows obtaining higher power dissipation and a more accurate control on power dissipation.

The temperature of the system is monitored by three K type thermocouples: two in direct contact with the heat spreader and a third in direct contact with the heat source. This arrangement allows controlling the effects of cooling on both elements of the test bed.

Figure 2 shows a photo of the test bed assemblage. The facility can accommodate different cooling systems and allows to perform three different types of tests, namely: at constant power dissipation (from 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 entire control system for this test bed has been developed by the authors. It includes a microcontroller (Microchip® PIC18F8722) which, in association with a specific board, also from Microchip®, and by means of auxiliary circuits specifically developed for this purpose, has the ability to control the power variation and to monitor and collect the measured data. The signal of the thermocouples is monitored and collected by the microcontroller. A program was then created 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 by means of a communication protocol via an RS-232 interface. The various tests configuration can be selected by the means of a computer interface, also developed for this particular application. All the measured data return to the personal computer and are automatically saved in a file with a format chosen by the user. The power control and necessary variations are made automatically in real time, 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.

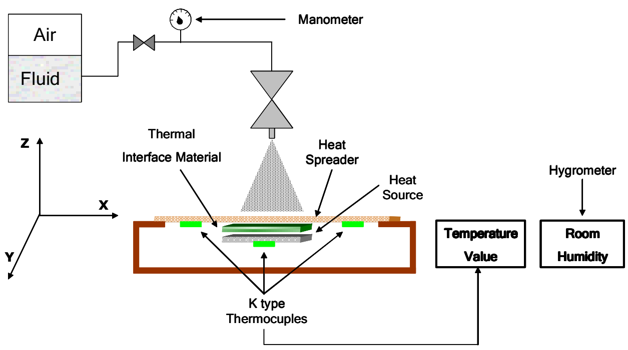

Figure 1 – Schematic of the test facility.

Figure 2 – Assemblage.

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 [10], who obtained live power measurements for benchmarks as well as some desktop applications for an Intel® Pentium® 4 processor, by combining real total power measurement with performance-counter-based per-unit power estimation.

To study the design parameters of Direct-Contact-Intermittent-Spray-Cooling, a cooling system was built which sprays a dielectric fluid directly onto the heat spreader. Two fluids are used, methoxy-nonafluorobutane (HFE7100 - $C_4F_9OCH_3$) manufactured by 3M and methanol (CH_3OH). The thermo-physical properties of the working liquids are presented in Table 1. The information provided here is based on that supplied by 3M for the HFE7100 and by CRC Handbook of Chemistry and Physics [12] for the 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, as depicted in Figure 1. An electronic circuit was developed, combined with a function generator, to control the frequency and the duty cycle of the valve signal.

Table 1 – Working fluids Thermo-physical properties.

Fluid	HFE 7100	Methanol
ρ [kg m^{-3}]	1488	788
$\mu \times 10^{04}$ [kg m^{-1} s^{-1}]	5.7	5.6
$\sigma \times 10^{03}$ [kg s^{-2}]	13.6	22.3
$\alpha \times 10^{08}$ [m^2 s^{-1}]	3.9	10.4
k x 10^{03} [W m^{-1} K^{-1}]	68.8	203.3
c_p [J kg^{-1} ºC^{-1}]	1177	2481
Temp.$_b$ [ºC]	61	65
h_{fg} [kJ kg^{-1}]	126	1158

The values of pressure reported in the present paper are measured by a manometer placed just before the electronic valve (Figure 1).

The spray 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 (*x*=0, *y*=0 corresponds to the position where the spray is centred with the IHS). The impact angle of the spray onto the surface of the test bed can also be varied from 0 deg to 90 deg.

RESULTS AND DISCUSSION

The present paper aims to provide the guidelines to optimize the design parameters of Direct-Contact-Intermittent-Spray-Cooling systems applied under dynamic behaviour conditions. Cader et al. [6] have already investigated the ability of spray cooling to handle transient die power dissipation and it effects on device reliability, but they evaluated the transient condition by switching on and off the power supply, so that transient responses during processor's operation were not investigated. On the other hand, Panão and Moreira [8, 9] studied the effects of injection parameters (such as frequency, pulse duration, pressure and impingement distance) on the performance of intermittent cooling systems under static boundary conditions.

The study reported here make use of the ability of 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 with the intention of verifying, for real conditions, the choice of the most important parameters to enhance the system cooling performance and to establish guidelines values for the design of a practical cooling system. Here, the duty cycle is defined as the ratio of the pulse duration to the pulse period, considering a signal made of rectangular pulses, as by the Alliance for Telecommunications Industry Solutions [13].

The effect of the distance from the nozzle to the test bed was considered, for the spray at various conditions, when the test bed dissipates 60W (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, for large distances, the temperature of the processor is globally higher and evidences a trend of continuous increase, thus indicating a deterioration of the potential of the spray cooling capability. This is illustrated in figure 3, where the temporal evolution of the temperature registered by the thermocouple in direct contact with the heat source is shown for several conditions. In particular, it is worth noting the results obtained at the larger distance (d_{noz} = 78 mm), which suggest that the thermal equilibrium of the system is no longer attained, even using a large duty cycle. Further increasing d_{noz}, the cooling performance of the spray continues to degrade down to a point where the test bed cannot be cooled below its maximum working temperature. At this point the tests had to be interrupted in order to avoid permanent damages of the test bed. A similar behaviour is observed when the nozzle is very close to the test surface (d_{noz} < 10 mm) and can be explained as in Mudawar and Estes [14]: as the IHS is square, the cooling performance depends weather the spray impact area covers, or not, the entire surface of the heater. Hence, when d_{noz} is increased past the point of heated area inscription, the cooling performance decreases due to the fact that a fraction of the liquid leaving the nozzle does not meet the surface and is wasted. On the other hand, when the d_{noz} is very small, the spray impact area decreases and only a small fraction of the heated area is directly impacted by the spray drops (in the present study only a small portion on the centre of the IHS) which is insufficient to achieve the thermal equilibrium for high power peaks, such as those considered here. In line with this, the optimal d_{noz} obtained with the injector used in the present study lays between 20 and 30 mm, which is the minimal distance ensuring that the impact area just inscribes the heat spreader area.

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. This is illustrated in figure 4, which depicts the variation of temperature at the heat source for an injection frequency of 3.1 Hz and duty cycle of 25.0%, for which the cooling system is no longer capable of keeping the heat source temperature below its maximum working value and the test had to be aborted around 50 seconds after it started.

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 corresponding to the one of power profiles measured by Isci and Martonosi [10] in benchmarks and desktop applications for an Intel® Pentium® 4 processor. This particular power profile (see figure 5) was chosen because it gathers multiple operation conditions of a real processor under demanding situations, thus being a good case study to evaluate the behaviour of the ISCS. Moreover, the selected profile includes most of the thermal characteristics of benchmarks and desktop applications.

For all the tests, the spray cooling technique is applied to the test bed at the same time that the power profile starts. In this manner, instead of evaluating the temperature decay of the test bed when the cooling system is activated (as in previous works reported by Panão and Moreira [8, 9]), the experiments start at room temperature, so that the cooling performance is evaluated under more realistic conditions along the power profile duration.

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 study: 23.6% is close to the smallest duty cycle at which the ISCS can keep the heat source at a safe temperature, 57.7% represents an average test condition and 75.2% approaches a continuous spray application.

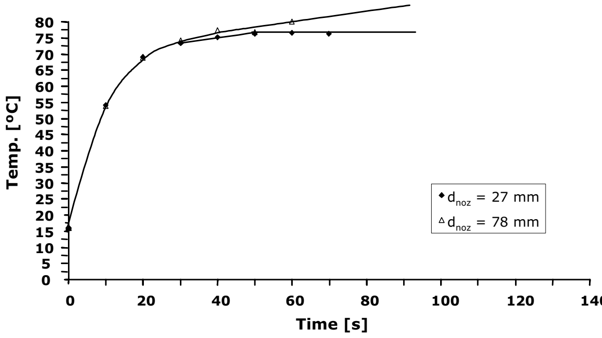

Figure 3 – Temporal evolution of the temperature of the heat source for a test performed with spray cooling, when the system dissipates 60W, for different d_{noz} using HFE7100 for an injection signal of 0.71 Hz with 72.9% duty cycle at 3.0 bar.

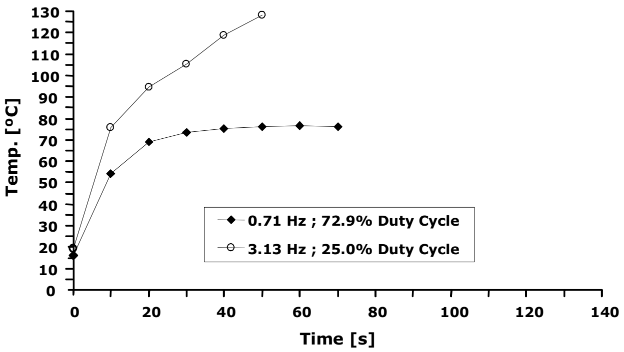

Figure 4 – Temporal evolution of the temperature of the heat source for a test performed with spray cooling, when the system dissipates 60W, using HFE7100 for d_{noz} = 27 mm and a 3.0 bar pressure.

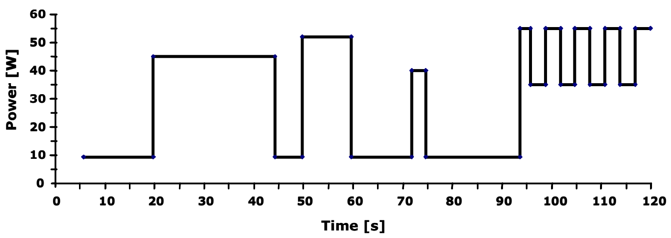

Figure 5 – Dynamic boundary conditions: power profile as measured and reported by Isci and Martosini [10].

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. Figure 6 depicts the temporal evolution of the temperatures measured at the surface of the IHS, registered by thermocouples 1 and 2 and the temperature measured at the thermocouple which is direct contact with the heat source. The large temperature gradients are associated with the peaks of the power supplied and represent the main challenge of practical processors to the performance of the intermittent spray cooling system. Without any cooling (or when the operating conditions are not adequate to assure the thermal equilibrium of the system, so that the tests had to be interrupted) the power peaks would lead to very high temperatures and the test bed would be damaged in just a few seconds. As shown in figure 6, the thermocouple in the heat source consistently registers the largest temperature (the difference to the temperature registered at the surface is larger than 10ºC along the entire power profile). 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 (maximum peak difference is smaller that 2.5ºC), thus confirming that for the test bed at the horizontal position, the heating and cooling processes are symmetric.

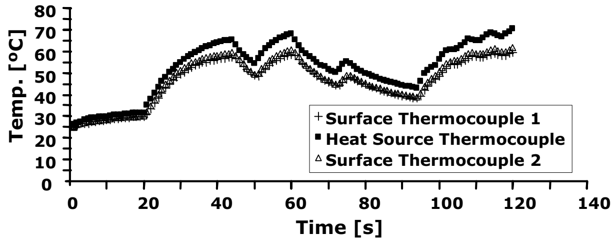

Figure 6 – Temporal evolution of the temperature registered by the three thermocouples for a test conducted for a 2.6 Hz, 23.6% duty cycle signal, with 5.0 bar in horizontal position using methanol.

Figure 7 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 the two frequencies, at the three prescribed pressures of injection (2.3, 3.3 and 5 bar). The coolant is methanol and the test bed is in the horizontal position, at a distance d_{noz} = 20 mm from the nozzle.

In general, the results highlight that there is an optimum duty cycle (between 50% and 60%) above which a further increase of the duty cycle does not significantly improves the cooling performance. In particular, for the case where the spray is injected at 0.8Hz and 2.3 bar test (figure 7a), it is clear that, not only the rising slopes (between 50 seconds and 60 seconds) are similar (1.61 for the 57.7% duty cycle versus 1.65 for the 75.2% duty cycle) but also the final temperatures (at 60 seconds) show only a 3.7ºC difference. Also, the slope of temperature associated with the power decay between 60 seconds and 72 seconds, measured at the 57.7% duty cycle condition is 1.73 against a 1.72 slope for that registered for the 75.2% duty cycle: again the difference between the temperatures achieved at 72 seconds is small (3.7ºC).

Similar trends are observed in the temporal evolution of the surface temperatures, as depicted in figure 8.

Moreover, the use of smaller duty cycles is evidenced in Figure 7 to alter the time response to the power changes: the temperature increases to larger values during power peaks and does not decrease so much during power valleys. This is clear in figure 7a: at the power peak between 50 and 60 seconds, although the temperature registered for the 23.6% duty cycle condition presents a similar rise slope (1.65) when compared to that of the 57.7% duty cycle condition (1.61), the final temperature (at 60 seconds) is considerably higher (there is a 11.5ºC difference between the two curves).

Also, during the power decay between 60 and 72 seconds, the temperature slope is 1.77ºC/s for the 23.6% duty cycle condition and 1.73ºC/s for the 57.7% duty cycle, but the difference between the minima temperatures achieved at each duty cycle is again 11.0ºC.

This aspect may appear redundant but it must not be disregarded when evaluating the performance of the cooling system because, although the system may seem apparently efficient in cooling the surface, it may not be able to keep temperature of the heat source within safety conditions.

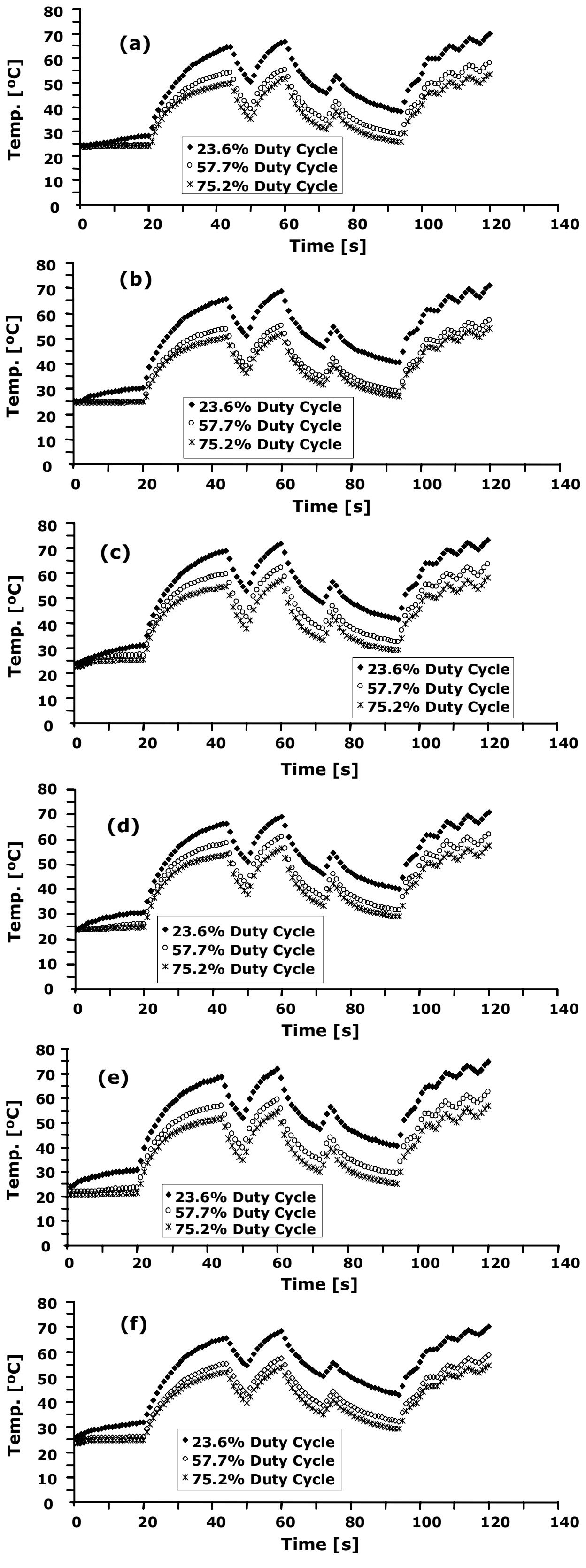

Figure 7 – The temporal evolution of the temperature registered by the thermocouple in direct contact with the heat source, when the test bed is in the horizontal position, using methanol, varying the duty cycle for different conditions: (a) 0.8 Hz for 2.3 bar; (b) 2.6 Hz for 2.3 bar; (c) 0.8 Hz for 3.3 bar; (d) 2.6 Hz for 3.3 bar; (e) 0.8 Hz for 5.0 bar; (f) 2.6 Hz for 5.0 bar.

The advantage of the ISCS stems from the capacity to deal efficiently with this aspect: using an adequate fluid (dielectric) the heat source can be directly cooled eliminating the intermediate surface (IHS) which is required in other cooling systems (e.g. air cooling systems or indirect liquid cooling systems). Overall, it is now clear from figures 7 and 8 that the temperature of the surface is significantly lower than that of the heat source and the response to the transient power variations (e.g. in the last part of the profile which reproduces the 30W power swing) is almost unnoticed in the surface temperature.

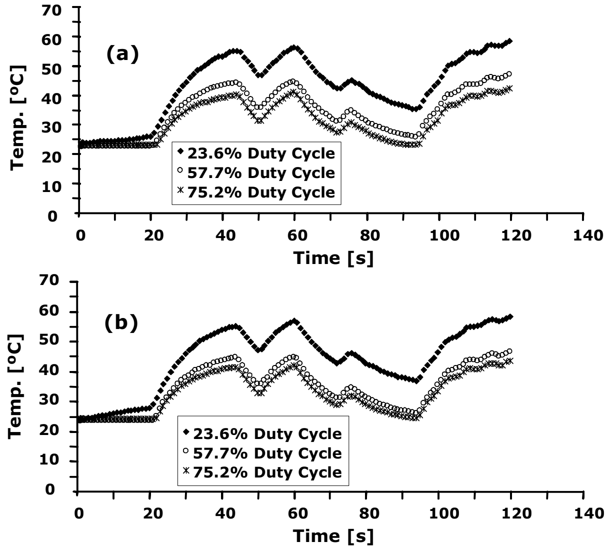

Figure 8 – The temporal evolution of the temperature registered by one of the surface thermocouple, when the test bed is in the horizontal position, using methanol, varying the duty cycle for different conditions: (a) 0.8 Hz for 2.3 bar; (b) 2.6 Hz for 2.3 bar.

Figures 9 and 10 further demonstrate that the effects of the frequency and pressure of injection are negligible compared with those of the duty cycle. Also, though not reported here due to lack of space, the surface temperature behaves similarly. It is worth noting, however, that the duty cycles considered so far were obtained varying simultaneously the frequency and the duration of injection in such a way to keep the liquid flow constant.

Given the negligible effect of pressure regardless the duty cycle, a practical system should use the lowest pressure capable of achieving a good atomization in order to keep hardware as simple 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 [8, 9], who reported detailed research of the effects of injection parameters, as previously refer, on the thermal response of a cooling system with stationary thermal boundary conditions. Also Shedd [7] refers that it is the droplet flux which controls the heat transfer performance and Bash et al. [15] 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 present study confirms an improvement of the cooling performance of the system as the duty cycle increases up to an optimum value, of the order of 60%, above which the cooling system cannot lower significantly the temperature of processor. This trend is associated by Panão and Moreira [9] with the formation of a liquid film at the surface, which mitigates heat removal by phase change. In this context, the value of the lowest temperature achievable by spraying the heated surface depends, not only on droplet flux at impact, but also on the thermo-physical properties of the coolant (namely its latent heat of vaporization and saturation temperature). However, it is worth noting that Panão and Moreira [8] achieved smaller duty cycles with similar coolant properties and much larger droplet fluxes. Careful analysis allows us to attribute this to the dynamic (instead of static) thermal boundary conditions of our experiments.

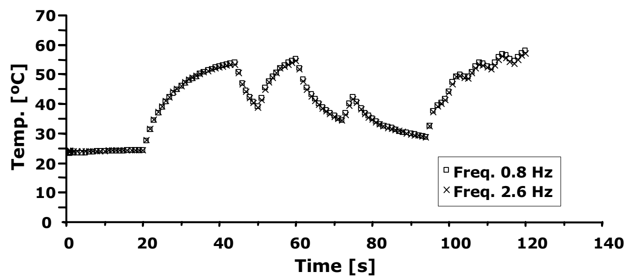

Figure 9 – The temporal evolution of the temperature registered by the thermocouple in direct contact with the heat source, when the test bed is in the horizontal position, using methanol, for a 2.3 bar test and a injection signal with 57.7% duty cycle for the two different frequencies.

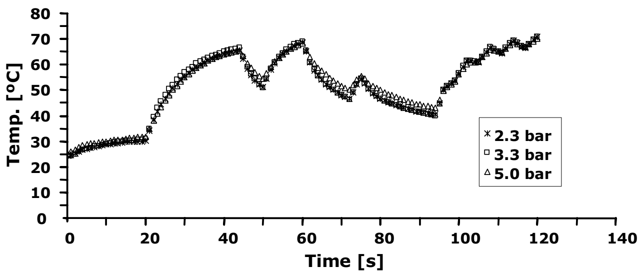

Figure 10 – The temporal evolution of the temperature registered by the thermocouple in direct contact with the heat source, varying the pressure, when the test bed is in the horizontal position, using methanol for a 23.6 % duty cycle and 2.6 Hz signal.

In the context of the discussion above, 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 conduced with the processor in the vertical position, which would preclude the formation of the liquid film over the IHS. The experiments were again performed with methanol, for d_{noz} = 20mm and followed the same methodology as for the processor in the horizontal position. Figure 11 depicts the thermal response for the three duty cycles (23.6%, 57.7%, 75.2%), the two frequencies of injection (0.8Hz and 2.6Hz) and for the lower injection pressure (2.3 bar). The results in the Figure show that, also in this case, the systems performs better when the duty cycle increases from 23.6% to 57.7%, although now with a lower gain than with the test bed in the horizontal position. Further increasing the duty cycle, one can still slightly cool down the heat source but the benefits of increasing the duty cycle over 60% are also reduced. For instance, for the power peaks occurring at 60 seconds the final temperature achieved at duty cycle of 23.6% is of the order of 6.5ºC to 8ºC larger than that achieved at a duty cycle of 57.7%. However, the difference between the temperatures achieved at duty cycles of 57.7% and the largest duty cycle of 75.2% is always smaller than 5ºC (for 0.8Hz) and 4ºC (for 2.6Hz).

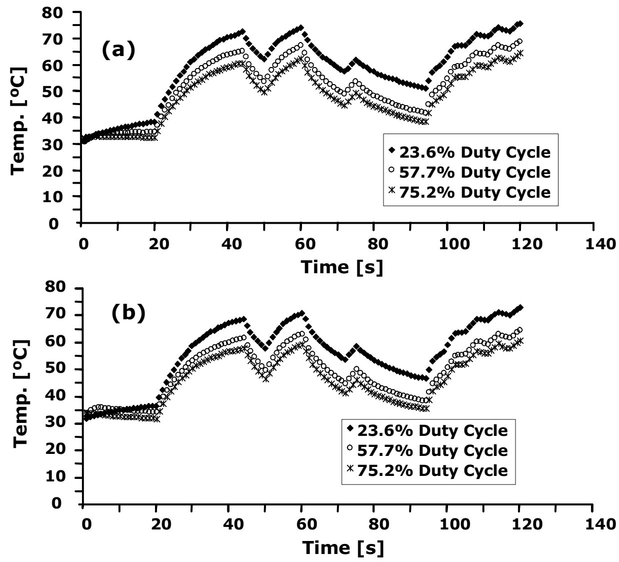

Figure 11 – The temporal evolution of the temperature registered by the thermocouple in direct contact with the heat source, varying the duty cycle, when the test bed is in the vertical position, using methanol for different conditions: (a) 0.8 Hz for 2.3 bar; (b) 2.6 Hz for 2.3 bar.

Figure 12 shows the distribution of the surface temperature compared with that measured at the heat source for an illustrative test condition. It is now noticeable a difference between the temperatures measured by the two surface thermocouples, which indicates that the surface cooling is no longer homogeneous when the test bed is in the vertical position. The difference is of the order of 5ºC, with smaller values measured at the region of the surface which is firstly impinged by the spray (thermocouple 1). Moreover, the values of surface temperature reported in Figure 12 are larger than those measured with the processor in the horizontal position and closer to the temperatures measured at the heat source.

This trend is a clear result of the influence of gravity on the dynamics of the liquid film. When the processor is in the horizontal position, the vaporization of the liquid film remaining at the surface between successive injections, guarantees a continuously removal of heat thus allowing to keep the surface temperature lower for the following power peaks (which during the test will also contribute to control the temperature of the heat source). This is observed, for instance in the last part of the power profiles where, in the short periods of power decrease the cooling is not enough to decrease the temperature which will subsequently be higher in the following power peaks. On the other hand, when the processor is in the vertical position, the spray is promptly swept away from the surface.

The main differences between the thermal behaviour of the system are better understood in figure 13, which compares the temperatures at the heat source when the ISCS operates at 2.3 bar, with a frequency of injection frequency of 0.8 Hz and a duty cycle of 57.7%. The Figure clearly shows that the temperature at the heat source is larger by almost 12ºC when the processor is in the vertical position, thus corroborating that the cooling system acts less efficiently when the test bed is in the vertical position, which contrasts with the recommendations given in Shedd [7].

Similar trends are observed for different frequencies and duty cycles, in the sense that the temperatures measured at both, the IHS and the heat source, are larger when the test bed is vertical, contrarily to what was expected considering that the film would lead to a less efficient heat extraction (e.g.

Shedd [7], Panão and Moreira [8]). It can be speculated that the differences may be due to a less efficient area subscription of the spray when the impacted surface is vertical, particularly because droplets swept away from the surface, thus reducing the time of thermal contact. The contact area is also altered (e.g. Moreira et al. [16]) which, again, precludes an efficient heat removal by phase change.

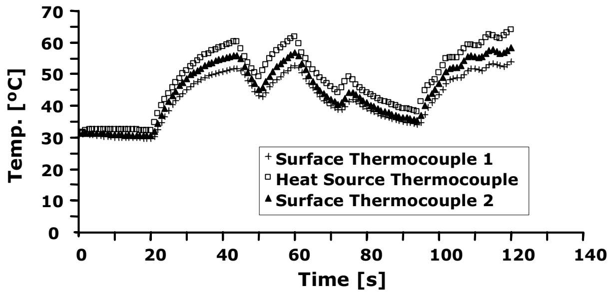

Figure 12 – The temporal evolution of the temperature registered by the three thermocouples, when the test bed is in the vertical position, using methanol for 2.3 bar with a 75.2% duty cycle and 0.8 Hz signal.

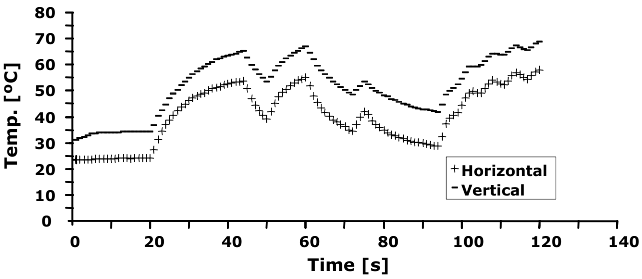

Figure 13 – The temporal evolution of the temperature registered by the thermocouple in direct contact with the heat source, varying the test bed position, for a 2.3 bar test with a 57.7% duty cycle and 0.8 Hz injection signal.

Although the experiments performed with the test bed in the vertical position show generally worse cooling performances than those obtained at the horizontal position, 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 performed to optimize the cooling performance of the processor in the vertical position, showed that the spray must operate with a duty cycle of 50%-60%.

In summary, based on the aforementioned role of the contact time of the impingement spray and of the benefit role of the liquid film in abrupt consecutive power peaks, one should recommend for the design and integration of practical systems a configuration considering the horizontal positioning of the processor. Moreover, it is more advantageous and safe, in a real system to work with a mid term duty cycle, of the order of 50%-60% (even if it may lead to a thin film formation during part of the working period), which provides good practical results in terms of the temperature of the processor, 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 and the thermal response of the system may not be fast enough to avoid damages, given that the temperature increase is very fast on the continuous power peaks. Duty cycles within the range between 50% and 60% still offer a much more effective working mode in terms of fluid management since it allows significant fluid consumption when compared to a continuous spray cooling system. Smaller duty cycles, promoting phase change, should be effective in less demanding conditions and in this case they should offer optimum fluid management performances.

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 [8]). In this context, further experiments were conducted using a dielectric fluid, the methoxy-nonafluorobutane (HFE7100).

Although not showed here due to paper 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 at the heat source using the HFE7100 are much larger, as expected, since the vaporization temperature is similar for both fluids but the latent heat of evaporation of the HFE7100 is much smaller ($h_{fgMethanol} \cong 9.h_{fgHFE7100}$). It is clear here, given the low latent heat of evaporation of the liquid which further reduces the heat flux removal, that small duty cycles, which are associated with smaller flows, are not sufficient to maintain the test bed surface at a low safe temperature, thus the tests were automatically stopped by the security routine to avoid damages in the test bed.

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 comparing 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_{fg}, which delays the formation of a liquid film thick enough to mitigate an effective heat removal by phase change. Nevertheless the difference in the temperature curves obtained for the duty cycle of 57.7.% and 75.2% is at the most of 9ºC, against 18.6ºC difference obtained when the duty cycle is increased from 23.6% to 57.7%. Therefore, although the exact optimum value of the duty cycle may be slightly adjusted depending on the properties of the working liquid, the results obtained for the whole conditions studied here suggest an optimum working range between 50% and 60%, which allows a significant fluid consumption, thus confirming the advantage of the ISCS in terms of fluid management potential, as strongly argued by previous authors (e.g. Bash et al. [15], Panão and Moreira [8, 9]) 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.

The properties of the working fluid are naturally important and major improvements can be achieved by combining the design of the cooling system with the development of an appropriate working fluid. However, as the selection of the working fluid for current systems can be much limited from the commercial point of view, to the cost and availability of the fluid, an adjustment of the system duty cycle can work as an alternative solution, when the choice of the most adequate fluid is restricted to commercial limitations. The control of this parameter should act based on the temperature of the heat source, which quickly responds to power variations (most of the existing commercial systems are based on temperature information also, although not always on the most critical points, which leads to additional costs to ensure the safety of the system) to avoid damages due to burnout of the system.

CONCLUSIONS

This paper reports an experimental study conducted to identify the main operational parameters to be considered in the design of efficient Direct-Contact-Intermittent-Spray-Cooling systems. The final aim is to assist computer product designers and manufacturers to develop new cooling systems and compare diverse cooling technologies. For that purpose a test bed has been designed and build to reproduce pre-programmed power profiles during the tests, which replicate those measured in benchmarks and desktop applications for a real processor. The experiments were conduced to infer on the effect of several operation conditions (injection frequency and duty cycle, the distance between the nozzle and the test bed, the injection pressure, the position of the test bed and the properties of the working fluid). The results showed that the best performance of the system is achieved when the distance from the spray nozzle to the impacted is within a definite range. Outside this range, the cooling performance is degraded as the spray area does not cover the surface of the test bed: the minimum distance to surface distance is that assuring that the spray area just covers the surface of the heater. For the spray used in the current study this range is between 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 of real processors: the duty cycle is the main operational parameter to consider in the control of the cooling system; injection pressure and frequency have a negligible influence, so that small injection pressures and frequencies can be used with evident advantages for the design of a commercial system compatible with the hardware used in a personal computer. However, the analysis must take into account that a dynamic system brings a stringent constraint to the operation of the system, which is the need to keep the core temperature of the system below safety values. In this context, there is a range of duty cycles above which the cooling performance does not improves due to the formation of a thick liquid film over the IHS which will mitigate an efficient heat removal by phase change. The whole tests performed here point that, for the current ISCS, this value lies within 50-60%. Based on these results one should recommend that it can be more advantageous and safe to work with a mid term duty cycle, of the order of 50%-60% (even if it may lead to a thin film formation during part of the working period), which provides good practical results in terms of the temperature of the processor, 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 and the thermal response of the system may not be fast enough to avoid damages, given that the temperature increase is very fast on the continuous power peaks. Duty cycles within the range between 50% and 60% still offer a much more effective working mode in terms of fluid management since they allow significant fluid consumption when compared to a continuous spray.

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NOMENCLATURE

c_p	Specific heat capacity at constant pressure	$J\ kg^{-1}\ K^{-1}$
CPU	Central Processing Unit	
d	Distance	mm
h_{fg}	Latent heat of vaporization	$kJ\ kg^{-1}$
IHS	Integrated Heat Spreader	
ISCS	Intermittent Spray Cooling System	
ITRS	International Technology Roadmap for Semiconductors	
k	Thermal conductivity	$W\ m^{-1}\ K^{-1}$
Temp.	Temperature	ºC
Greek Symbols		
α	Thermal diffusivity	$m^2\ s^{-1}$
ρ	Density	$kg\ m^{-3}$
μ	Dynamic viscosity	$kg\ m^{-1}\ s^{-1}$
σ	Surface tension	$N\ m^{-1}$
Subscripts		
b	Boiling	
noz	Nozzle	

REFERENCES

[1] Moore’s Law – Made real by Intel® innovation, available at http://www.intel.com/technology/mooreslaw/
[2] J. Hennessy and D. A. Patterson, Computer Architecture: A Quantitative Approach, 3rd ed, Morgan Kaufmann, 2003.
[3] A. Bar-Cohen, M. Arik, M. Ohadi, Direct Liquid Cooling of High Flux Micro and Nano Electronic Components, *Proc. of the IEEE*, vol. 94, n. 8, pp 1549-1570, 2006.
[4] Evolution of Parallel Computing, available at http://www.intel.com/platforms/parallel.htm
[5] P. Y. Paik, K. Chakrabarty, V. K. Pamula, Adaptive Cooling of Integrated Circuits Using Digital Microfluidics, Artech House, 2007.
[6] T. Cader, L. J. Westra, R. C. Eden, Spray Cooling Thermal Management for Increased Device Reliability, *IEEE Transactions on Device and Materials Reliability*, vol. 4, n. 4, 2004.
[7] T. A. Shedd, Next Generation Spray Cooling: High Heat Flux Management in Compact Spaces, *Heat Transfer Engineering*, vol. 28, n. 2, pp 87-92, 2007.
[8] M. R. O. Panão and A. L. N. Moreira, , Intermittent Spray Cooling: towards a new technology concept, *6th International Conference on Multiphase Flow (ICMF 2007)*, Leipzig, Germany, 2007.
[9] M. R. O. Panão and A. L. N. Moreira, Intermittent Spray Cooling: a new technology for controlling surface temperature, Submitted to the International Journal of Heat and Fluid Flow, 2008.
[10] C. Isci and M. Martonosi, Runtime Power Monitoring in High-End Processors: Methodology and Empirical Data, *Proc. of 36th Annual IEEE/ACM International Symposium on Microarchitecture (MICRO-36)*, pp 93 – 104, 2003.
[11] Intel® Pentium® 4 Processor in the 423-pin Package at 1.30, 1.40, 1.50, 1.60, 1.70, 1.80, 1.90 and 2 GHz, Intel®, August 2001 (available at http://download.intel.com/design/Pentium4/datashts/24919805.pdf).
[12] D. R. Lide, CRC Handbook of Chemistry and Physics, 85th ed., 2004-2005.
[13] Information available at http://www.atis.org/glossary
[14] I. Mudawar, and K. A. Estes, Optimizing and Predicting CHF in Spray Cooling of a Square Surface, *Journal of Heat Transfer*, vol. 18, n. 3, pp 672-679, 1996.
[15] C. E. Bash, C. D. Patel, R. K. Sharma, Inkjet assisted spray cooling of electronics, *Proc. of International Electronic Packaging Technical Conference and Exhibition*, Hawaii, USA, 2003.
[16] A. L. N. Moreira, G. E. Cossali, M. Marengo, M. Santini, Secondary atomization of water and isooctane drops impinging onto tilted heated surfaces. Exp. Fluids, vol. 43, pp 297-313, 2007.