Inkjet Assisted Micro-scale cooling of Electronics
Enabling device compaction by efficient thermal management

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ABSTRACT

Micro-scale cooling can enable compaction of microelectronic and MEMS devices. The use of thermal inkjet technology to precisely supply coolant onto the surface of a microprocessor has the potential to address this problem in a micro-scale form factor. By providing coolant when and where it is needed on the surface of a chip or package, very high critical heat fluxes can be obtained in an energy efficient manner in a minimum of physical space. Results from an experimental test bed provide valuable data to benchmark and develop understanding of inkjet assisted spray cooling. Analysis of these results also provides a window into future paths of research for efficient ink jet assisted spray cooling with jet impingement control.

Keywords: ink jet assisted spray cooling, thermal management, electronic cooling, micro-scale cooling

1 INTRODUCTION

Rise in the overall power dissipation of computer systems has posed a severe challenge for cooling microprocessors. Increases in microprocessor power dissipation and the resulting effect on the cost and complexity of thermal management solutions has been well documented in recent years. Accompanying this increase in overall power dissipation has been a reduction in feature size due to process improvements resulting in a steady decrease in the size of the processing core where most of the power on a die is generated. This trend is expected to continue into the near future and will likely lead to a power dense core covering a fraction of the total die surface area surrounded by areas of reduced power density cache[1]. Increases in microprocessor power density along with an accompanying spatial variation in power density pose a severe challenge for the provisioning of cooling resources at the microprocessor level. Moreover, it has been shown that the spreading resistance associated with this increase in heat flux is significant and will necessitate the cooling of the microprocessor with heat sinks operating at temperatures very near ambient room temperature. Indeed, recent major chip initiatives are a reflection of the high power density issue. Unfortunately, the current approach is to limit the total power dissipation from the chip, and even reduce the performance by limiting frequency of operation. Adequate thermal management of these device packages will enable manufacture denser systems that provide more computing power in a smaller volume than today’s systems.

Conventional technologies that rely on air cooling with physical contact have limitations when removing heat from non-uniform sources due to their inherent resistance to heat spreading [1]. Technologies like vapor-compression and solid state refrigeration have been investigated and show promise (notably vapor-compression in the near-term), but are limited in power density at heat sink operating temperatures above dew-point. Non-refrigeration phase change techniques like thermosyphons with enhanced evaporation structures are reaching their limit close to 100 W/cm² in passive configurations with uniform power density.

Spray cooling, alternatively, has been shown to be effective up to 1300 W/cm² for uniform heat sources with water as the working fluid and 300 W/cm² using dielectrics [2][3]. Most heat transfer studies have been conducted with pressure atomized nozzles with different patterns in varying configurations [4]. None of the spray delivery mechanisms used are capable of controllable, non-uniform spray patterns and would, therefore, be ill-suited to applications in which power dissipation is markedly non-uniform. Such limitations in the controllability of individual spray droplets has generally prevented its use in applications that contain marked variation in spatial power density. Since only a relatively uniform spray pattern is possible with existing spray delivery technologies, such as pressure assisted spray, sections of lower power density become susceptible to pool boiling and thereby place limitations on bulk flow rates, which accordingly limit thermal performance. Moreover, variations in heat transfer coefficients caused by uncontrolled pool boiling across devices can create thermal stresses.

In this paper, we demonstrate how thermal inkjet technology can be effectively utilized to spray cool a heat source with non-uniform power density [5]. The precise supply of coolant onto the surface of a microprocessor by use of an inkjet head has the potential to address this problem in a chip-scale form factor. By providing coolant
when and where it is needed on the surface of a chip or package, very high critical heat fluxes can be obtained in an energy efficient manner in a minimum of physical space.

2 THERMAL INKJET DYNAMICS

Figure 1 is a cross section of a thermal inkjet firing chamber. [6][7] The chamber consists of reservoir equipped with a resistive heating element and covered with an orifice plate. Electrical pulses energize the resistor and vaporize the working fluid in the chamber. As the vapor bubble rapidly expands, a jet of fluid is ejected from the reservoir through the orifice plate. The jet, subsequently, separates from the nozzle and disintegrates into a primary and several satellite drops due to capillary pinching caused by propagation of hydrodynamic instabilities. After jet ejection, the vapor bubble collapses and the fluid chamber is refilled through feed channels. The complete process takes tens of microseconds and can be repeated at different frequencies.

![Figure 1: Thermal Ink Jet Nozzle](image)

Figures 2(a-b) show spray jets from consecutive nozzles of a standard design-jet plotter pen at 10 kHz and 20 kHz, respectively.

![Figure 2 (a) Spray at 10 kHz](image)

![Figure 2 (b) Spray at 20 kHz](image)

Observe the steadiness in direction and uniformity in shape of the jet. Control of each jet can enable dissipation of heat from localized hot spots at micro-second time scales. For higher heat loads, a higher firing frequency can be used. Observe that the morphology and momentum of the spray changes. When employed as a thermal management tool, inkjet assisted spray cooling has a number of benefits:

- Local flow rates can be varied according to variations in power density distribution with micro-scale precision across a heated surface;
- Extreme variations in flow rate magnitudes are possible.
- Spray resolution is very high with drop volumes in the picoliters range and drop spacing on the order of tens of microns.
- Micro-scale spray pattern is flexible allowing for tracking of power density variations with time.

3 HEAT TRANSFER RESULTS

Figure 3 shows the spray of a TIJ device firing from a nozzle array over a small heat source (35mm²) at a device height of 6 mm [8]. Average heat fluxes of over 300W/cm² (110 W over 36mm² area) have been obtained with the off-the-shelf printer pen. Based on the actual footprint (<1mm) of the spray, these heat fluxes can be several times higher. The coefficient of performance of the spray system (ratio of cooling load to pen power input) was more than 8, several times that of other state-of-art cooling technologies.

The ink jet spray has high momentum and lacks recirculation zones. Splashing created by the impact of the jet and the boiling phenomena is clearly visible. Similar to jet impingement cooling, the spray momentum is high and focused on a small region of the heat source. Although the spray creates a train of drops generated has flow characteristics are generally similar to that of a jet.

![Figure 3: Inkjet-Assisted Spray cooling of small heat source (35 mm²) at h=6mm](image)

Prior to heat transfer experiments, the flow rate of the TIJ device was characterized against different firing frequencies. Fluid was fed into the TIJ device from a graduated external reservoir with 1/10th ml resolution and
the drop in volume was recorded over time. Table I lists the liquid flow rate corresponding to each firing frequency.

Table I: Typical flow rates at different firing frequencies

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Flow rate (µl/s)</th>
</tr>
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<tbody>
<tr>
<td>8.33</td>
<td>60</td>
</tr>
<tr>
<td>10.00</td>
<td>80</td>
</tr>
<tr>
<td>11.11</td>
<td>132</td>
</tr>
<tr>
<td>20.00</td>
<td>168</td>
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</tbody>
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Boiling experiments have been carried out on fabricated heat sources with cartridge heaters, recording the heat rate at the heater surface ($q$) and the surface temperature ($T_{sw}$) for given liquid flow rate ($Q$). Initially, heterogeneous nucleation boiling occurs at nucleation sites on the heat source. Critical heat flux (CHF) is reached when the thermocouple at the heater surface detected a sudden unsteady rise in temperature. Flow measurements during each experiment ensured that the volumetric flow estimates were accurate (±1%). Tests were conducted under identical conditions to ensure repeatability of results for any given flow rate. The CHF results were benchmarked against results from published literature [9]. For a typical spray configuration, CHF experiments were carried out at different device heights distances to investigate the effect of separation on spray pattern and thermal performance. Use of different nozzle patterns for cooling different heater blocks provided an understanding of interaction of spray jets[8]. Figures 4 (a, b, c) show various stages of boiling.

Figure 4(a): Nucleate Boiling in sub-cooled drops

Figure 4(b): Mixed Boiling Regime

Figure 4(c): Critical Heat Flux Regime

Figure 5 shows the plot of CHF for different volumetric fluxes. The critical heat flux increases monotonically with volumetric flux. Since the values of G are very low, the CHF is gated by the delivery of fluid to the surface rather than by the hydrodynamics at the surface.

Data for the larger heater was collected with sprays from two parallel array of nozzles at device height of 14mm. The spray pattern is disturbed by the creation of recirculation cells between spray arrays, which entrain satellite droplets. Drop momentum is also retarded due to skin friction drag [10] between the fluid and ambient. The spray pattern is, therefore, susceptible to disturbance created by the rising vapor yielding low critical heat flux. Data for the smaller heat sources was obtained at lower device heights ranging from 4.5mm to 12.8mm with a single and smaller array of nozzles.

Figure 5: Variation of CHF with Volumetric heat flux

In order to account for the cumulative effect of multiple drops, volumetric flux is the appropriate scaling velocity in correlating CHF. Since the volumetric flux is based on the area of the heat source, the appropriate scaling length for correlating CHF is the characteristic length of the heat source. Increase in volumetric flux improves CHF while increase in heat source area decreases CHF. Further analysis based on dimensionless parameters have been described in [8].

Experiments indicate that the rise in device height reduces CHF for the case where parallel nozzle arrays were
used to cool the larger heat source (281 mm²). The device heights for this case ranged between 9 and 35 mm. The interaction between boundary layers of parallel spray jets and the resulting entrainment of air streams reduces volumetric flux.

Proper management of vapor and air flow is necessary to improve the effectiveness of the spray jets, at least above certain device heights. At high device heights the vapor flow affects the spray pattern and in turn the volumetric flux impinging the heat source. Recirculation cells between ink jet spray arrays trap satellite droplets and may account for major deterioration of heat transfer. Moreover close to the heat source, vapor flow deflects the flow of splashed droplets and diminishes heat transfer in the wall jet region. Experimental results, however, indicate that vapor removal has no perceptible impact on CHF at low device heights. Further investigation of hydrodynamics at the heat source is necessary to understand the interaction of spray jets and vapor removal close to heat source.

Drop ejection occurs as a jet filament from the nozzle. The leading end of the filament rapidly decelerates until the primary drop pinches off from the trailing filament. Thereafter, the interaction between the ambient and the jetted fluid leads to growth of instabilities in the filament and, subsequent, formation of satellite droplets followed by separation from the nozzle. The measured diameter is used to estimate the average jet Reynolds number (Rej) and Weber number (Wej). Rej (~10^3) and Wej (~10^3) values indicate that capillary pinching is the dominant mechanism of breakup for the jet. The jet is, therefore, unstable to axisymmetric modes whose wavelengths are of the order of the jet circumference [12][11].

4 CONCLUSIONS

Power dissipation in microprocessors is not only rising but also getting increasingly non-uniform. Moreover, power densities are approaching values that make investigation of high heat flux cooling technologies for electronics necessary. This scenario is further complicated by the need to miniaturize cooling solutions that are easily controllable. Thermal ink jet technology offers a cooling solution that combines the heat transfer performance of spray cooling and jet impingement cooling in a small factor that can be easily controlled and modulated.

Critical heat fluxes as high as 300W/cm² has been obtained with an off-the-shelf printer pen using water as working fluid. The independent control of micro-nozzles in an array makes the technology well-suited to non uniform heat removal. Nozzle distribution and device height, however, play an important role in determination of heat transfer performance of an ink jet cooling system. At lower device heights and using favorable spray pattern, performance of ink jet spray is closer to jet impingement cooling.

Further investigation is necessary into dynamics of stream of drops created by the TJ device and the propagation of the transients in the cooling system both at the device and at the heat source. Optimization of device design and development of control mechanisms will add tremendous value in improving the performance of this technology. Wide varieties of working fluids are compatible and are under investigation for use with the technology.

REFERENCES