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MONODISPERSE SPRAY COOLING OF SMALL SURFACE AREAS AT HIGH HEAT FLUX

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ABSTRACT

Spray cooling is an effective method to remove high heat fluxes from electronic components. To understand the physical mechanisms, the current work studies heat transfer rates from single and dual nozzle sprays on a small heated surface (1.3 mm x 2 mm). Thermal Ink Jet (TIJ) atomizers generate small droplets, 33 μm dia. at known frequencies leading to controlled spray conditions with a monodisperse stream of droplets interacting with the hot surface. Particular interest in this work is the dissipated heat flux and its relation to the liquid film thickness, the surface superheat, the cooling mass flow rate. Experimental results show the heat flux scales to the cooling mass flow rate. The limit of droplet spreading-splashing deposition has been reported to be K=57.7 ($K=We^{1/2}*Re^{1/4}$) for an ambient temperature of 25 ºC at the surface. Current experimental results at K= 47.9 and K=27.2 for the surface temperatures of 140 ºC and 120 ºC indicating that a stable droplet spreading regime is achieved with little splashing. In addition, the liquid film thickness is investigated in relation to the heater superheat and a stable thin film is seen at superheats beyond 20 ºC. The efficiency of the spray system is inversely related to the film thickness and may be due to ejection of liquid from the surface due to bursting of vapor bubbles.

INTRODUCTION

Two phase spray cooling has the potential for high heat flux removal and control of surface temperature. In two-phase spray cooling, drops are jetted onto a surface and heat is removed through evaporation and boiling. The latent heat of the phase change leads to high heat flux removal at relatively small surface superheats, surface temperature above fluid saturation temperature. In addition, the delivery of liquid through a spray is an efficient way to apply liquid to the surface and allow space for the removal of the vapour leaving the surface. There exist two types of spray systems: pressure or co-flow atomized nozzles and drop on demand systems. Large nozzle based systems of the first type produce conical or two dimensional polydisperse sprays where there can be a large variation in droplet size and in spatial spray distribution on the surface [1, 2]. The drop on demand systems produce monodisperse drop jets through Thermal Ink Jet (TIJ) nozzles or piezo-electric actuators [3]. The advantage of a monodisperse spray is the uniformity of the spray over the area covered and the control of the spray characteristics, frequency, velocity, and drop size. These systems consist of an array of actuators manufactured using MEMS technology and are adapted from Ink-Jet printing technology.

To effectively design a system that provides controllable heat flux and uniform surface temperature, the physical mechanisms of the heat transfer on the surface need to be studied. Drop on demand spray systems have shown the ability to support extremely high heat flux rates, 300 W/cm^2, and the primary mode of heat transfer needs to be understood [3]. With the variety of spray systems, there may be multiple heat transfer mechanisms that are present and/or dominant under different conditions. The efficiency of spray cooling macro systems may depend on variables such as the surface roughness, droplet momentum, liquid properties, liquid film thickness, cooling fluid mass flux, and substrate temperature. In nucleate pool boiling, the number of activated sites in heterogeneous boiling correlates to the cavity sizes and substrate temperature [4]. In spray cooling, droplet penetration on a liquid film enhances the heat transfer by convection [5]; however, there may be a minimum liquid film thickness optimum for the heat transfer enhancement depending on the system characteristics [6]. In general, the Critical Heat Flux (CHF), local peak in heat flux before surface dryout, shows a steady scaling with mass flux [1, 3, 6, 7] with the potential for further increases in heat transfer [8]. In addition, spray cooling will be affected by the spray parameters such as droplet size, distribution, and velocity [9].

Monodisperse spray cooling systems present several fundamental challenges from the perspective of heat transfer and fluid dynamics. The droplet stream typically has a low mass flux and a low number density of droplets. In this case it is tempting to consider the stream as a series of individual drops impacting on a surface. The dynamics of the drops interacting on the surface will depend on the drop Reynolds number and Weber number, the temperature of the surface, and the thickness and dynamics of a liquid film if it exists on the surface. In the cases studied here, the droplets impinge normally to the surface. For the case without a liquid surface film and a surface at ambient temperature, Mundo *et al.* [10] determined a spreading/splashing threshold for droplets (60-150 μm diameter) based on a parameter, *K*, derived from the droplet Weber number and Reynolds number. Meanwhile, other researchers have characterized the boiling of droplets deposited on hot substrates without a clear determination of the threshold between spreading, splashing, and bouncing [11, 12].

The focus of the current work is testing a small heater surface comparable to the sprayed area, testing single and dual nozzle sprays, and measuring film thickness and heat transfer efficiency. Unlike previous experiments, the heater size is scaled to the spray area. In previous experiments, a relatively large heater was cooled by a small spray. The mismatch in spray area to heater area leads to difficulty in predicting the heat flux rate per unit area. A large heater suffers from two-dimensional heat transfer near the heater surface at the boundary of the spray. Therefore the heat flux should be based on an area that is larger than the wetted surface area and smaller than the heater area. In the current experiment, the heater area has been reduced to 1.2 mm by 2 mm which is still large but more comparable to the wetted area. In the experiments both single and dual nozzle experiments were performed. This allowed testing of the possible interaction of the sprays and the scaling of the results. The extension of the present work is the study of the liquid film thickness formed under spray conditions on a hot surface and its correlation to the spray efficiency.

Previous experiments showed high heat flux rates and scaling among nozzles [3, 8]. These experiments showed the potential of the TIJ spray system but were not able to show the mechanism of heat transfer and the film thickness. Following these experiments the smaller heater surface was constructed. In the current apparatus the losses to the insulation through conduction and convection become large. These losses may be comparable to the heat removed by droplet evaporation, therefore it is important to accurately determine the losses in the system and calculate the temperature and heat flux at the sruface. A methodology for calculating and calibrating the losses to determine the heat transfer from the heater surface was developed in Escobar-Vargas [13].

NOMENCLATURE

A_h	[m^2]	Heater area
L_C	[m]	Characteristic length scale
N	[-]	Number of activated nozzles
T_{surf}	[^{O}C]	Temperature at the heater surface
d	[m]	Drop diameter
K	[-]	Drop surface interaction parameter
$\dot{m}$	mg/sec	Mass flow rate
η	[-]	Spray efficiency
h_{fg}	kJ/kg K	Latent heat of evaporation
ρ_f	kg/m^3	Fluid density
V	m/s	Characteristic velocity
k	W/mK	Thermal conductivity
σ	kg/s^2	Coefficient of surface tension
q_s''	W/m^2	Heat flux per unit surface area

EXPERIMENT

The experiment consists of a TIJ spray impinging normally on a heated target. The TIJ spray head is placed at 5 or 10 mm from the heater target. In this work, the target is scaled down to a small size (1.3 mm x 2 mm) comparable to the spray scale which reduces convection losses and the two-dimensional conduction on the heater surface. A custom built circuit based on an SX28AC/DP integrated circuit and Darlingtons is used to drive the atomizer at a range of frequencies from 2 to 8 kHz and to activate one or two nozzles at a time. The signal from the driving circuit is monitored continuously with an oscilloscope (Tektronic TDS210). The circuit is powered by a system power supply (6033A, HP). The atomizer delivers monodisperse micron sized droplets of deionized water, and experiments are carried out with a mass flow rates from 40 to 320 mg/s. To control the surface roughness the copper surface is first polished with sand paper of 3 μm grit followed by another polishing with sand paper of 1 μm grit. The copper body is insulated by a custom built system composed of air and Ultem material (k_{ultem}=0.122 W/mK) as shown in Figure 1.

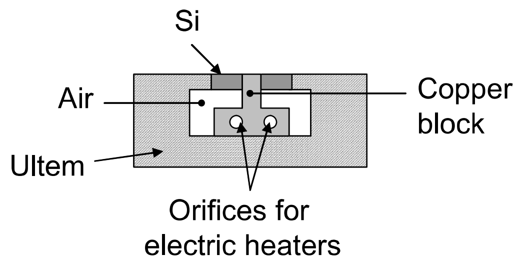

Figure 1 Cross-section of the heater target structure. The copper block has a 1.3 by 2 mm finger that extends to create the target surface. Along this finger 4 thermocouples are used to measure the temperature gradient and hence the heat flux.

The copper block is heated with two cartridge heaters controlled by a variable autotransformer (L21C, Powerstat) to reach measured temperatures up to 150 ^{o}C near the sprayed surface. The applied power is measured with an energy analyzer (PowerSight, Summit). The copper block temperature is monitored by means of T-type thermocouples attached to the copper fin at 4 positions along its length. The temperature was read with a data acquisition unit (34970A, Agilent). The heat flux at the surface is determined by calculating the temperature gradient in the copper block from the thermocouple measurements and accounting for the losses to the insulation. From this calculation the temperature at the surface is also extrapolated. A CCD camera (Pulnix TM-2200) and a 100x microscope (Mitutoyo) are used to collect video of the liquid film boiling on the copper substrate. A schematic diagram of the experimental set up is shown in Figure 2.

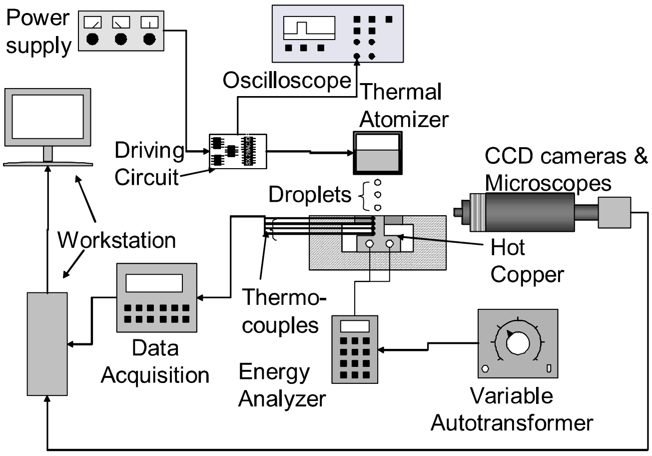

Figure 2 Schematic of the experiment. The spray conditions are electronically controlled and the heater temperature and power are monitored throughout the experiment. The surface film thickness is measured using a strobe, microscope, and CCD camera.

The liquid film is imaged from the side with the microscopic objective and the CCD camera. The imaging system has a resolution of 2 μm and the flash lamp strobe (Nanolite FX Xenon Flashlamp, High-Speed Photo-Systeme) captures the images with 150 nsec flash duration. Boiling videos are decompiled and each frame analyzed with an image processing algorithm to determine the liquid film thickness.

Experiments are performed using a single jet of droplets (33 μm diameter) or two jets of droplets activated simultaneously. The cooling mass flow rate is varied by driving the atomizer at different activation frequencies and the controlling the number of jets. The experiments are conducted in an open air environment at ambient pressure.

A series of experiments is performed by varying variables such as the mass flux, $\dot{m}$, droplet *Re*, and number of activated droplet jets, *N*. The drop mass flux is controlled by the number of activated jets and the activation frequency. The number of activated jets changes the surface wetted area while changing the nozzle frequency can change the film motion, evaporation, and boiling characteristics. The droplet Re is based on the drop diameter, velocity, and viscosity at ambient temperature. The Reynolds number can be varied be changing the distance between the spray head and the heater surface. Because of the small drop size, the drops experience significant drag and hence the impacting drop velocity changes as the distance between spray and surface increases. This allows variation of the drop Reynolds and Webber numbers. The drop size and velocity are measured relative to the distance between from the spray head in a separate calibration using the microscope system. Under the conditions tested the drops remain approximately the same size during their flight.

To accurately measure the heat flux, the system is run until quasi-steady temperatures are reached. To achieve stable temperatures thermal equilibrium needs to be reached between the heaters, copper block, and system insulation. The time constant required to achieve equilibrium is experimentally measured and is approximately 25 minutes. The time constant is determined by cooling time for the system without the spray.

RESULTS

Liquid film results

Visualization of the liquid on the surface shows a number of different stages in the interaction, Figure 3. The images are not taken consecutively nor at a specific phase relative to the spray. This is a result of the CCD camera operating at a substantially lower frequency. Figures 3 (a) and (d) show cases where there is a quasi-steady film at different heights on the surface. The mean high of the liquid film is calculated from the side view and is indicated by δ. As can be clearly seen, there are cases where there is a large film supported on the surface and cases with a small stable film. The drop size is substantially smaller than the film thickness in Fig. 3 (d) and an incoming drop can be seen in this image. Figures 3 (b) and (c) show different events where boiling phenomena is observed. In Fig. 3 (b) a bubble has formed that is substantially larger than the film thickness. The small scale of the film thickness relative to the bubble size differentiates this type of boiling behavior from nucleate pool boiling and can lead to a faster growth rate of the bubble. The vapor bubble increases the liquid/vapor surface area which enhances the evaporation rates. In Fig. 3 (c) the bubble has burst leading to expulsion of liquid contained in the film. Liquid volume lost from the film in this way leads to less mass available for evaporation and a reduction in the efficiency of the cooling.

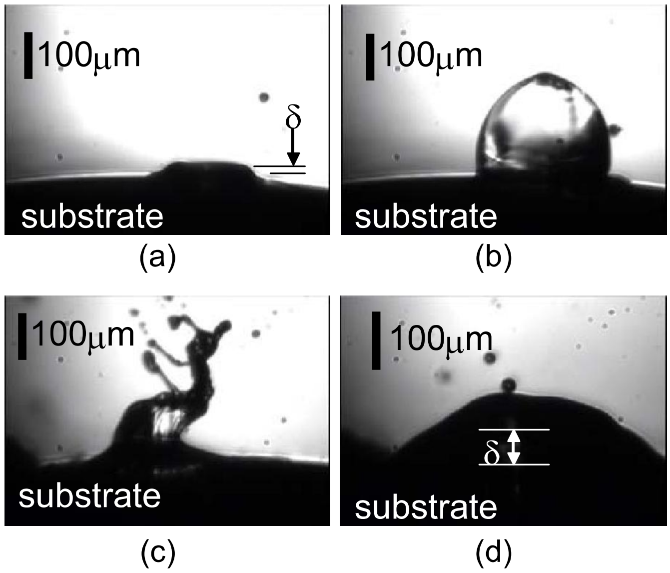

Figure 3 Individual frames indicating phenomena exhibited in the liquid film: (a) a stable thin liquid film at high temperature; (b) a bubble expanding within the liquid film; (c) a bubble bursting; (d) a thick liquid film at lower temperature.

Critical Heat Flux Results

The experimentally measured heat flux scaled by the heater size and the drop mass flow rate is shown in Figure 4. Scaling relative to the heater size provides an absolute comparison of the performance of a single and dual nozzle spray. In observation, the heat flux scales directly with the mass flow rate, and a difference between the single or dual nozzle spray is not seen. Again, the mass flow rate is controlled by adjusting the frequency of drop ejection. The inference is then that the film dynamics are stable or steady, *i.e.* the behavior of the boiling and evaporation in the film is not connected to the frequency of the arriving drops. This is determined by the near linear relationship between the heat flux and mass flow rate. Second, activating two nozzles increases the wetted area, effectively doubling it, but doesn't lead to a different trend in the heat flux. This indicates that the mechanism of the heat transfer scales with the mass flow rate and is not significantly influenced by thin film evaporation which would scale with the total film area.

Figure 5 shows measurements of the film thickness as a function of the substrate temperature. Since the Critical Heat Flux is associated with phase change at the surface a small level of superheat at the surface is required. Spray cooling shows similar or slightly higher levels superheat at CHF [14] to pool boiling [15]. The CHF is reached under steady operating conditions and generally corresponds to the highest surface temperatures reached and a thinner film, as visualized in Figure 3 (a). The film thickness measurement consists of frames where bubbles were not present and hence represent the quantity of fluid sitting on the surface. Although there is substantial scatter in the data, a transition seems to occur at 120 ^{o}C. At lower surface superheat, a thicker film stays at the surface and corresponds to a lower heat flux, while at higher superheats the film thickness drops to a relatively stable value of 8 μm which is higher than the 1.2 μm reported by Pais *et al.* [6]. At this film thickness the drop diameter is large relative to the film thickness and substantial motion is introduced with the impact of a drop. At very high superheat the film evaporates completely and temperature runaway starts to occur.

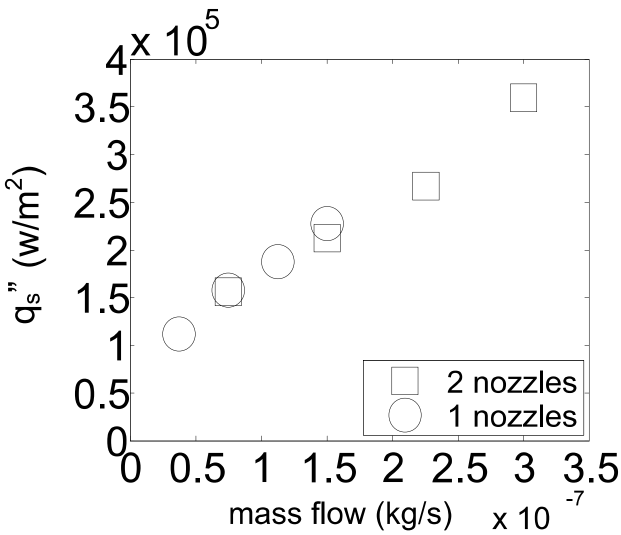

Figure 4 Critical heat flux, q_s" based on heater surface area, A_h, dependent on the spray mass flux, $\dot{m}$, under single and dual droplet streams and at different driving frequencies.

To measure the performance of the spray system, the efficiency is calculated from the heat flux and mass flow rate

$$\eta = \frac{q_s A_h}{\dot{m} h_{fg}},$$

where an efficiency of 1 indicates that all of the incoming fluid has been evaporated at the surface and produced cooling [2]. In this calculation the sensible heat is small relative to the latent heat and is not considered. In Figure 6, it can be seen that the highest spray efficiencies occur at the smallest values of film thickness. This is in agreement with Pais *et al.* [6] who indicated thinner film thickness results in enhancement of the heat dissipation. A thin film may be optimal since a larger thickness has the effect of damping the stirring effect of the droplets. The stirring caused by the droplets promotes heat dissipation by inducing a forced convection like state in the liquid film thickness. This forced convection mechanism is supported by modeling results for an individual drop impinging on a surface [5]. However, considerable small thickness may be difficult to attain thus causing a dryout state which in turn will decrease the heat dissipation efficiency. During boiling, a secondary mechanism for lowering in the spray efficiency is the ejection of liquid during bubble growth and rupture on the surface Figure 3 (c) [16]. Although we cannot draw a specific correlation from the data, a large film thickness can lead to more fluid being ejected through this mechanism.

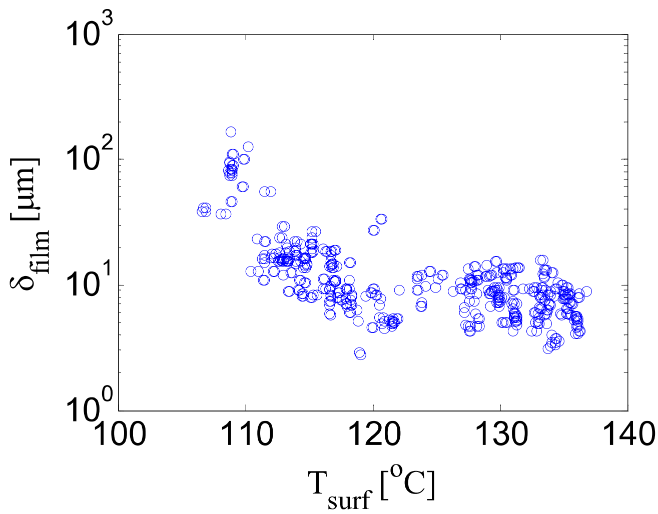

Figure 5 Mean liquid film thickness at different levels of heater temperature. The saturation temperature is 100 ^{o}C and CHF occurs at the peak temperature.

Related to the previous mechanism for the reduction of the spray efficiency, the drop, when it impacts the spray, can generate satellite droplets that are ejected from the film. In some sense a high momentum drop can lead high convection in the film increasing the heat flux but a drop with too high momentum can lead to fluid being ejected from the film decreasing heat flux and efficiency. In a simpler experiment, Mundo *et al.* [10] studied the dynamics and heat transfer of a single drop interacting on the hot dry surface. In their work they found that a product of the drop Reynolds number and

Weber number can lead to a prediction of whether the drop will lead to splashing at the surface, with fluid being ejected, or spreading on the surface, without fluid being ejected. It is informative to consider the current experiments based on this same parameter.

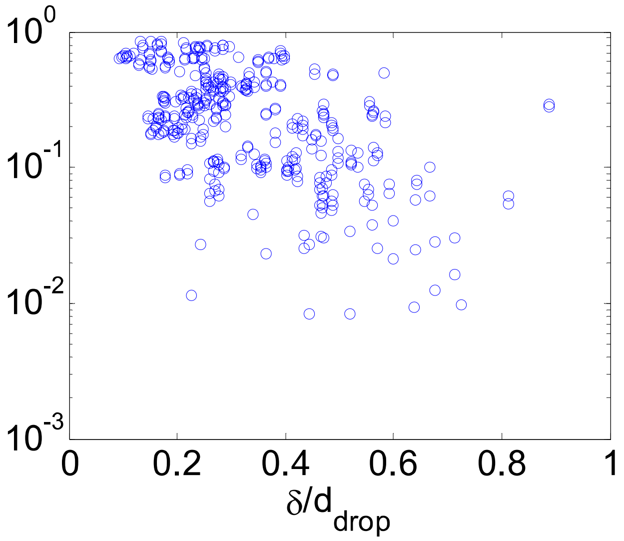

Figure 6 Spray efficiency relative to the liquid film thickness. The liquid film thickness is scaled by the drop diameter.

The current experiments varied the droplet velocity impacting the substrate and hence the Reynolds and Weber numbers. Previous experimental measurements determine impact velocities of 11 and 8 m/s for distances of 5 and 10 mm respectively. The droplet change in velocity resulted in two different values of the $K=We^{1/2}*Re^{1/4}$, 47 and 32, respectively. The Re number is defined by droplet velocity, diameter and fluid viscosity. The We number is defined in terms of the volumetric flux rate and the heater area and is given as

$$We = \frac{\rho_f V''^2 L_c}{\sigma}$$

where ρ_f is the liquid density, L_c the square root of the heater substrate area $A_h^{1/2}$, V the characteristic velocity, and σ the liquid surface tension. The superheat is estimated from the thermocouple measurements right under the substrate surface and considering the heat losses. In the current experiments, the value of K remained in the range where the incoming droplets spread on the film and did not introduce splashing. The heat flux measurements also confirm that the change in droplet velocity did not change the heat flux.

CONCLUSION

Spray cooling based on a TIJ spray system has been studied by measuring the critical heat flux and optically measuring the film thickness. It has been determined that the heat flux scales with the mass flow rate but not directly with the wetted area. In optical visualizations, it is seen that bubble growth in the film can lead to rupture and fluid ejection from the film. As the surface temperature is increased, a thinner film is established on the surface which in turn leads to a higher Critical Heat Flux and an efficient cooling process. It is speculated that the drop momentum leads to greater convection in the thin film and increased heat transfer, while fluid ejection leads to a reduction in efficiency.

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