EXPERIMENTAL CHARACTERIZATION OF SINGLE AND MULTIPLE DROPLET IMPINGEMENT ON SURFACES SUBJECT TO CONSTANT HEAT FLUX CONDITIONS

Guillermo Soriano  
Department of Mechanical Engineering  
Texas A&M University  
College Station, TX. 77843

Yen Po Lin  
Department of Mechanical Engineering  
Texas A&M University  
College Station, TX. 77843

Jorge L. Alvarado  
Department of Engineering Technology and Industrial Distribution  
Texas A&M University  
3367 TAMU  
College Station, TX. 77843-3367

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ABSTRACT

Spray cooling is one of the most promising technologies in applications which require large heat removal capacity in very small areas. Previous experimental studies have suggested that one of the main mechanisms of heat removal in spray cooling is forced convection with strong mixing due to droplet impingement. These mechanisms have not been completely understood mainly due to the large number of physical variables, and the inability to modulate and control variables such as droplet frequency and size. Our approach consists of minimizing the number of experimental variables by controlling variables such as droplet direction, velocity and diameter.

An experimental study of single and multiple droplet impingements using HFE 7100 as the cooling fluid under constant heat flux conditions is presented. A monosized droplet train is produced using a piezoelectric droplet generator with the ability to adjust droplet frequency, diameter and velocity. In this study, heaters consisting of a layer of Indium Tin Oxide (ITO) as heating element, and silicon substrates are used. Film morphology was characterized using a Laser Induced Fluorescence (LIF) technique with a focus on the droplet impact zone by measuring variables such as film thickness and diameter of the impact zone. Infrared Thermography was used to measure surface temperature at the liquid-solid interface. The IR thermography technique was also used to characterize temperature gradients at the droplet impact zone. The results and effects of droplet frequency, fluid flow rate, and fluid temperature on heat flux are also presented.

INTRODUCTION

Current development in electronic devices places a significant demand on thermal management systems to dissipate high heat flux densities in an economic manner in order to maintain adequate junction temperatures at the chip level. The high heat fluxes require a phase change cooling methodology instead of traditional single phase options. Among the phase-change cooling technologies, spray and jet impingement cooling are the most promising options [1-2]. Liquid droplet sprays and jet impingement cooling have been widely used in the metal manufacturing industry and have been shown capable of high heat removal rates. Spray cooling and droplet impingement cooling can achieve peak heat fluxes several times superior to critical heat flux in pool boiling [2-3]. Most research on spray cooling has been experimental in nature focusing on the boiling regime with limited ability to vary experimental parameters as shown in the work of Toda [4], Yang [5-6], Tilton [7], and Sodtke and Stephan [8]. A common agreement among researchers is that the physics of spray cooling are insufficiently understood due to complexity of the interplay between multiple drop impingement events and bubble nucleation, rendering the heat transfer processes in the thin liquid film extremely chaotic.

One promising avenue for uncovering the interplay between the dominant physical mechanisms in spray cooling is to remove the randomness in incident droplet size, frequency of arrival, and velocity at impingement. This can be achieved by carefully controlling the diameter and velocity of incident droplets, for instance, through the use of a piezoelectric droplet generator. Under this configuration, key non-dimensional quantities such as Weber and Reynolds numbers as well as the ratio of film height to droplet diameter, among others, can be manipulated at
will. This is the approach adopted in this work. The advantage is that mechanisms of heat transfer augmentation produced by drop impingement and bubble nucleation can be isolated in a much more controlled manner than in the common spray cooling studies.

In this article, experimental results of single and multiple droplet streams using HFE7100 as the cooling fluid are presented followed by conclusions and discussion of future work.

**EXPERIMENTAL SETUP**

The experimental setup consists of a fluid delivery system, a heater system and a data acquisition system as shown in Figure 1.

![Figure 1. Experimental Setup consists of 1) Frequency Generator; 2) Backlight Illuminator; 3) Droplet Generator Head; 4) High Speed Camera; 5) Syringe Pump; 6) Heat Exchanger; 7) Chiller; 8) Infrared Camera; 9) Power Supply; 10) PC and Data Acquisition System; and 11) Heater Assembly](image)

The production of a stream of mono-dispersed sized droplets is achieved using a piezoelectric droplet generator. The fluid is delivered by a syringe pump and is disturbed by high frequency vibrations taking place in the piezoelectric electric crystal attached to an orifice plate. In the case of a single stream, a plate with a 150 μm orifice is used. For multiple droplet streams, a plate with a 150 μm collinear array of orifices with a 500 μm distance between centers was used. Both plates were constructed of extra heavy substrate of BeCu with a thin layer of Ni where the orifices were etched. Vibrations cause the controlled breakup of liquid jets by the Rayleigh breakup mechanism. Square wave high frequencies were controlled and delivered by a frequency signal generator (BK Precision Model 4011A). The set up is able to generate a monodispersed stream of droplets ranging from 50 to 350 μm, with exit velocities ranging from 1 to 30 m/s. A view of the impinging droplets captured in flight is shown in Figure 2.

![Figure 2. Single and Multiple Droplet Trains](image)

The imaging system consists of a high speed Photron SA3 camera capable of recording images at 1,000 frames per second (fps) at a resolution of 1,024 x 1,024 pixels, and up to 60,000 fps at a reduced resolution of 128 x 16 pixels. High magnification zoom lenses (zoom 6000 series lens Navitar) were used with the system, when necessary. These lenses are capable to work with coaxial and backlight illumination, and attachments that can be used to provide the required magnification to be able to observe individual droplets at a magnification of 18X. A magnification of 0.35X was used to capture the total dimension of the film.

Images of the droplets were obtained with the high speed camera (see Figure 2) using backlight illumination at the proximity of the heater surface. The Image Analysis Tool from National Instruments was used to measure the projected vertical surface area of each droplet which in turn was used to compute droplet diameter. These values were compared to the theoretical values given by:

\[ d = \frac{A}{\pi} \]  

(1)

Initial droplet velocities were calculated using Equation 2 [10], which is based on energy balance taking place before and after the breakup of droplets in flight. Velocities obtained using Equation 2 were compared with the measured velocities obtained by measuring the distance between droplet and multiplying it by the input frequency as in Equation 3 [10]:

\[ v = \frac{d}{t} \]  

(2)

\[ v = f \cdot d \]  

(3)

The heater was made by coating the polished side of the 300 μm thick silicon wafer with a thin layer of ITO (Indium Tin Oxide) of approximately 200 nm in thickness to obtain a resistance of approximately 200 Ω/sq. The dimensions of the heater are 20 by 14 mm, but the usable part of the heater is 14 mm by 14 mm after being connected to power wires. Two wires were attached to the heater surface using a silver-based electrical conductive epoxy to provide electrical connectivity.
from the power supply to the heater. The assembly of the heater was attached to a Teflon® holder using an optical grade epoxy. The droplets always impinged the heater on the ITO coating side. Power was supplied by a 1500 W power supply (Lambda GEN600-2.6). The power supply was controlled by a PC through serial port communication using Microsoft® Hyper Terminal version 5.1. A schematic representation of the temperature measurement set up is depicted in Figure 3.

Temperature was measured using an infrared camera (FLIR A325) located below the heater. The infrared camera has a resolution of 320 x 240 pixels and is able to collect data at a frequency of 60 Hz. The temperature range of the camera is 0 to 350 °C. The camera has a close up lens (Model AT197215) with a spatial resolution of 100 µm, and FOV (field of view) of 32 x 24 mm. The IR camera is connected to a PC through an Ethernet connection, and controlled using ExaminIR package from FLIR. Figure 4 are sample infrared images of droplet impact with 1 and 3 streams respectively.

Droplet impact diameter and film thickness were measured using a laser induced fluorescence technique (LIF). A cross section of the impact zone of the impinging droplets was illuminated using a laser sheet which makes the free surface visible. The light source was a 10 mW laser (Lasiris®) emitting a green ray with wavelength of 532 nm. Line generators with fan angles of 1° and 5° were used to produce the laser sheet. The cooling fluid (HFE 7100) was mixed with a fluorescent red-nile dye in a concentration of 5 mg per 100 ml of fluid. The mixture was later filtered using a 20 µm membrane filter. The high speed imaging system was used to obtain images (see figure 5) of the illuminated section at a small inclination in order to optically observe inside the impact zone at a camera speed of 60 frames per second. Resolutions of 5.9 and 1.3 µm/pixel were used during the experiments. Impact diameter was measured directly from the images using a magnification of 5.9 µm/pixel. Film thickness was measured from the images with a magnification of 1.3 µm/pixel and taking into account the camera inclination.

EXPERIMENTAL CASES

Four cases of single stream droplets were tested at an ambient temperature of 22° C with Weber numbers ranging from 190 to 460. Three cases of three-collinear droplet streams were tested at the same ambient temperature of 22°C. The cases are summarized in Table 1.

<table>
<thead>
<tr>
<th>Flow rate (ml/hr)</th>
<th>Input Freq. (Hz)</th>
<th>Diameter (µm)</th>
<th>Velocity Droplet (m/s)</th>
<th>We No.</th>
<th>Re No.</th>
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</thead>
<tbody>
<tr>
<td>180</td>
<td>2970</td>
<td>318</td>
<td>2.7</td>
<td>260</td>
<td>2286</td>
</tr>
<tr>
<td>180</td>
<td>7320</td>
<td>235</td>
<td>2.7</td>
<td>192</td>
<td>1690</td>
</tr>
<tr>
<td>250</td>
<td>6010</td>
<td>280</td>
<td>3.9</td>
<td>462</td>
<td>2866</td>
</tr>
<tr>
<td>250</td>
<td>12040</td>
<td>222</td>
<td>3.9</td>
<td>367</td>
<td>2273</td>
</tr>
<tr>
<td>540</td>
<td>2970</td>
<td>318</td>
<td>2.7</td>
<td>260</td>
<td>2286</td>
</tr>
<tr>
<td>540</td>
<td>7320</td>
<td>235</td>
<td>2.7</td>
<td>192</td>
<td>1690</td>
</tr>
<tr>
<td>750</td>
<td>7320</td>
<td>262</td>
<td>3.9</td>
<td>433</td>
<td>2684</td>
</tr>
</tbody>
</table>

Notes: (1) Single-stream, (2) Three-stream
EXPERIMENTAL PROCEDURE

The experimental procedure for heat transfer performance of the heater was as follows:

1. Start the droplet stream at the desired flow rate and frequency.
2. Check for uniformity of the stream of droplets using the high speed imaging system.
3. Apply voltage from the power supply to obtain the desired heat flux.
4. Check that the average temperature of the heater has reached steady state using the IR camera system.
5. Take measurements of voltage and current applied to the heater, and surface temperature using IR camera.

In order to estimate the heat losses due to conduction and natural convection, the same procedure was repeated without any liquid flowing onto the surface. Heat flux was calculated according to the following equation:

\[ Q'' = \frac{V_{in} I_{in} - Q'}{A_h} \quad (4) \]

Equation 4 accounts for heat losses when no droplet impingement takes place. The experimental procedure for the optical imaging experiments necessary to compute impact diameter and film thickness was as follows:

1. Start the droplet stream at the desired flow rate and frequency.
2. Apply voltage from the power supply to obtain the desired heat flux.
3. Check that the average temperature of the heater has reached steady state using IR camera.
4. Adjust the horizontal position of the droplet stream and laser angle to have the laser sheet illuminate directly the droplet impact zone.
5. Record the images using the high speed imaging system.
6. Shut down the power supply and fluid delivery system, and record the position of laser baseline so film thickness can be determined.

The following section shows and describes the experimental results obtained following the steps outlined above.

RESULTS

Figures 6 and 7 show the heat transfer results for heat flux versus minimum wall temperature for single and multiple streams cases.

Figures 8 shows close-up images of the single droplet impact zone at 180 ml/hr, 2970 Hz at their maximum heat flux values. Figure 9 consists of close-up images of the single droplet impact zone at 250 ml/hr, with an input frequency of 12,040 Hz. Both cases are for the maximum heat flux values obtained with a single stream at the given flow rates.
Figures 10 to 13 show the cross-sectional temperature profiles for the single stream cases at the droplet point of impact. Each profile was obtained from an average of 200 infrared images.
Figure 13. Radial temperature distribution HFE 7100, 250 ml/hr, 12040 Hz

Figure 14 to 16 show the cross-sectional temperature profiles for the triple stream cases at the droplet point of impact.

Figure 14: Radial Temperature Distribution HFE 7100 540 ml/hr 3 Streams 2970 Hz

Figure 15. Radial temperature distribution HFE 7100, 540 ml/hr, 3 streams, 7320 Hz

Figure 16. Radial temperature distribution HFE 7100, 540 ml/hr, 3 streams, 7320 Hz

Table 3 shows the results of average crater diameter and average film thickness with its radial location relative to the point of impact. The film dynamics data shown in Table 3 was for 180 ml/hr, 2970 Hz with an approximate heat flux of 18 W/cm², and 250 ml/hr, 12040 Hz at an approximate heat flux of 24 W/cm².
Table 2. Spreading diameter and film thickness results

<table>
<thead>
<tr>
<th>Flow (ml/hr)</th>
<th>Frequency (Hz)</th>
<th>Spreading Diameter (μm)</th>
<th>Film Thickness (μm)</th>
<th>Radial Location (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>2970</td>
<td>1650</td>
<td>25</td>
<td>400</td>
</tr>
<tr>
<td>250</td>
<td>12040</td>
<td>2130</td>
<td>18</td>
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**DISCUSSION**

Figure 6 shows heat transfer results for the cases where an individual stream hit the surface. From Figure 6, it can be seen that maximum heat flux value depends on flow rate primarily. From Figure 6, it is evident that higher Weber number results in greater surface temperature at higher flow rate. Figure 7 shows heat transfer results for the cases where three collinear streams hit the surface. Figure 7 also shows that higher heat flux values and lower surface temperature can be achieved when using three identical droplet streams.

Figures 8 and 9 show that flow rate as well as droplet frequency can yield different spreading behavior. In Figure 8, a smooth spreading at the droplet impact can be seen, whereas in Figure 9 splashing is observed during droplet impact. The figures suggest a different regime in physics of droplet impact which have a direct effect on heat transfer.

Figures 10 to 13 show the cross-sectional temperature profiles in the case of one stream hitting the surface. Common features of all these cases include an increase of the temperature gradient with respect to the point of impact at higher heat fluxes. Also a significant reduction in the size of the thermal impact zone at higher heat fluxes is seen.

Figures 14 to 16 show the cross-sectional temperature profiles in the case of three collinear streams hitting the surface. In all the cases it is possible to identify the impact location of each individual stream. As in the case of one stream cases, it is possible to see an increase of temperature gradient with heat flux. No major changes were seen in the size of the thermal impact zone at higher heat fluxes.

Table 3 shows an increase of the diameter of the impact zone (spreading diameter) at higher flow rates. On the other hand, film thickness reduces with flow rate.

**CONCLUSIONS**

The following conclusions can be drawn from the results of the experimental study:

- Heat flux values of up to 25 W/cm² and 45 W/cm² were obtained for the case of single and three collinear streams, respectively.
- At Weber number below 260 (flow rate of 180 ml/hr), the spreading of the droplet is smooth.
- At Weber numbers above 380 (flow rate of 250 ml/hr), spreading of the droplets results in splashing, and it is more chaotic. In the cases tested, heat flux decreased with Weber number.
- Single stream cases shows an increase in slope in the heat flux vs. wall temperature graph with flow rate, while in the three stream cases slope variation was less pronounced.
- Temperature profiles at all cases exhibit an increase in temperature gradient with heat flux.
- Diameter of the impact zone increases with flow rate.

Future work will include finding the relationship between spreading diameter and cross-sectional temperature profile at different flow rates and heat flux values. Measurement of film thickness at different heat fluxes will also be undertaken. Also, the effect of multiple stream spacing on film morphology and heat transfer phenomena will be studied in more detail.

**ACKNOWLEDGEMENTS**

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**NOMENCLATURE**

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<tr>
<td>d</td>
<td>Diameter</td>
</tr>
<tr>
<td>A</td>
<td>Area</td>
</tr>
<tr>
<td>L</td>
<td>Distance between droplets</td>
</tr>
<tr>
<td>f</td>
<td>Input frequency</td>
</tr>
<tr>
<td>v</td>
<td>Velocity</td>
</tr>
<tr>
<td>V</td>
<td>Volumetric flowrate</td>
</tr>
<tr>
<td>I</td>
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</tr>
<tr>
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<td>Heat flux</td>
</tr>
<tr>
<td>Μ</td>
<td>Magnification</td>
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<tr>
<td>µ</td>
<td>Viscosity</td>
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<td>Surface Tension</td>
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Subscripts:

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<thead>
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<tr>
<td>h</td>
<td>heater</td>
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**REFERENCES**


