Visualization of Electrohydrodynamic Effects and Time Scale Analysis for Impinging Spray Droplets of HFE-7000

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Abstract. Spray cooling is becoming a leading technique for removing excess heat from high heat flux electronics. Electrohydrodynamic effects have been found to result in significant variation in spray behavior once the applied voltage level is increased enough to reach the Rayleigh limit. In the present work the dielectric coolant HFE-7000 has been used to study spray cooling heat transfer across a thick film resistor heater mounted to a 16 mm diameter pedestal. Heater power levels have been varied from 0 to 80 Watts, with spray flow rates varied from 2 GPH to 6 GPH (2.1x10^{-6} m^3/s to 6.3x10^{-6} m^3/s). Applied voltage levels between 0 kV and 30 kV with both positive and negative polarity have been applied directly to the brass spray nozzle, resulting in contact charging of the spray. A high-speed video camera was used to study behavior of both the impinging spray and the liquid film that formed on the heater surface. Time scale estimates of the various physical processes within the spray and the liquid film have indicated the time between droplet impacts falling into a crater from a previous droplet to be the shortest time scale, which thus will limit the amount of heat transfer that may take place during spray cooling. However, the observed time between large droplet impacts onto the same heater surface location is comparable to the computed time to heat and vaporize a large drop, indicating a new explanation for the onset of spray cooling CHF: localized dryout of the original large droplet impact craters.

Keywords: Electrohydrodynamics (EHD), Spray Cooling, Boiling, Critical Heat Flux (CHF), Visualization.

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INTRODUCTION

Heat transfer enhancements are needed in the continually evolving world of high power electronics that generate large amounts of waste heat. Spray cooling has been identified as an efficient method for removing excess heat and has also documented higher heat transfer rates than jet impingement or pool boiling (Mudawar, 2000; Tilton, 1989; Chow et al., 1997). Previous work has achieved heat flux levels of 1000 W/cm^2 using spray cooling with water as the working fluid (Lin and Ponnappan, 2003). Applications of spray cooling include but are not limited to x-ray medical devices, supercomputer cooling, avionics, metal quenching, and material tempering. Typical heat flux values of common heat generating applications are found in Table 1 (Glassman, 2005).

Experimental studies have shown that many variables will affect the heat transfer rate of spray cooling. Air content, surface roughness, pressure, sub-cooling, droplet velocity and spray density have all been shown to influence the performance of spray cooling heat transfer (Chen et al., 2002; Rainey et al., 2003; You et al., 1995; Puterbaugh et al., 2007). Another increasingly popular method of enhancing heat transfer is by using electrohydrodynamics (EHD). Work in pool boiling has shown an increase in critical heat flux (CHF) of as much as 400 percent with the presence of an electric field (Cipriani et al., 2004). EHD is also beginning to be applied to spray cooling to enhance the heat transfer levels currently seen (Kreitzer, 2006; Kreitzer et al., 2007; Glaspell, 2006; Feng and Bryan, 2005).
TABLE 1. Typical Heat Flux Values for Common Heat Generating Components

<table>
<thead>
<tr>
<th>Heat Generating Device</th>
<th>Heat Flux (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Bulb (40-100W)</td>
<td>1</td>
</tr>
<tr>
<td>Intel Pentium 4 CPU</td>
<td>15-30</td>
</tr>
<tr>
<td>Car Engine</td>
<td>30-60</td>
</tr>
<tr>
<td>Cray Super Computer</td>
<td>70-120</td>
</tr>
<tr>
<td>Aircraft Electronics</td>
<td>150</td>
</tr>
<tr>
<td>Surface of the Sun</td>
<td>6,500</td>
</tr>
</tbody>
</table>

EHD effects have proven to significantly alter the spray behavior of spray cooling (Kreitzer et al., 2007). Therefore, it is important to visually study the interaction of the spray droplets with a heated surface with and without the effects of EHD. Visualization using a high speed video camera was able to capture the motion of the spray. Use of a laser light sheet with camera settings of up to 9,600 frames per second (fps), at a 10 μs exposure time slowed down the motion of the spray impingement to observe individual events. Figure 1(a) shows a single image from a data set taken at 3 GPH (3.16x10⁻⁶ m³/s), zero heater power, and no applied voltage. Figure 1(b and c) show similar images taken at the same flow conditions with applied voltages of 7.5 kV and 15 kV respectively. From these images it is possible to see a variation in spray behavior as the voltage level applied to the electrode increases.

FIGURE 1. Voltage Transition from 0 kV to 15 kV at a Flow Rate of 3 GPH

Variation in the spray behavior with the charging voltage applied to the spray nozzle has been attributed to the breakup of the spray droplets due to exceeding the Rayleigh limit (Kreitzer et al., 2007). The Rayleigh limit is the theoretical maximum charge that a droplet can hold before the repulsive forces overcome the surface tension, resulting in the breakup and formation of smaller droplets. Under stable conditions a single droplet can form as many as 40 smaller droplets. However, once the Rayleigh limit has been exceeded the number of droplets formed can increase to several hundred smaller droplets (Bologa and Bologa, 2000). However, the Rayleigh limit was derived assuming a static droplet in a vacuum, and in practice droplets are observed to break up when the charge on the droplet reaches 70–80 % of the calculated Rayleigh limit (Shrimpton, 2005). Equation 1 represents how to calculate the Rayleigh limit associated with a spherical droplet.

$$ q_{ray} = 8\pi \varepsilon_0 \sigma (r_d)^{3/2} $$  \hspace{1cm} (1)

Equation 2 represents the electrical force applied to a fluorinert fluid without the presence of magnetic fields. The right hand side of the equation is broken down into three terms. The first term represents the Coulomb force which for spray cooling can be used to manage the spray droplets. The second term is the permittivity gradient force, and
the third term is the electrostrictive force. In cases where the liquid is conductive the Coulomb force usually
dominates the other electrical forces (Di Marco and Grassi, 2002).

\[
F_e = \rho_e E - \frac{1}{2} E^2 \nabla (\varepsilon \varepsilon_0) + \frac{1}{2} \nabla \rho T \left[ E^2 \rho \left( \frac{\partial (\varepsilon_0 \varepsilon)}{\partial \rho} \right) \right].
\]  

(2)

EXPERIMENT

The current experimental apparatus is a single nozzle, closed loop spray cooling experiment with contact charging
capabilities (Kreitzer, 2006; Kreitzer et al., 2007). HFE-7000, a dielectric coolant, has been used during
experimental testing due to its lower resistivity and higher dielectric constant relative to FC-72, while the other fluid
properties are similar to the more traditionally used FC-72 (Mudawar, 2000; Rainey et al., 2003; You et al., 2005;
Puterbaugh et al., 2007; Yerkes et al., 2006; Pautsch and Shedd, 2005; Kim, 2006; Silk et al., 2007). A Spraying
Systems full cone 1/8G-1 brass nozzle was used to produce a spray with an average diameter of 48 \( \mu \)m and velocity
of 12 m/s (Yerkes et al., 2006). The heater surface is a 1.46 cm\(^2\) Thick-Film Resistor (TFR) capable of reaching 120
W/cm\(^2\) with the current DC power supply.

Contact charging is used to electrically charge the droplets by connecting the spray nozzle directly to a Glassman
model EL30R1.5 reversible polarity high voltage power supply capable of reaching 30 kV set to negative polarity;
this setup created two separate phenomena. First, the electrode charged the spray droplets with a negative charge as
they were ejected from the spray nozzle. Secondly, an electric field was created between the negatively charged
electrode and the grounded heater surface. The combination of these two reactions creates an EHD body force on
the droplet in the direction of the heater surface. Changing the polarity of the high voltage power supply will
reverse the charge seen by each droplet. However, the electric field present will also change direction, so the end
result does not affect the magnitude or direction of the body force seen by the spray droplets; see Figure 2.

![Diagram](image)

**FIGURE 2.** Experiment Diagrams, (a) Electrode Design, (b) Electric Field Direction.

Imagery has been obtained using a Vision Research Phantom v4.2 digital high speed video camera, capable of
framing rates of 2200 fps at a resolution of 512x512 pixels and up to 97,000 fps at a resolution of 32x32 pixels. All
of the images in this paper have been taken below 10,000 fps. A Nikon macro lens was used to frame the nozzle and
pedestal resulting in full resolution images. For some of the visualization studies the high speed camera was mounted above the spray chamber and positioned to view as much of the heater surface as possible (Figure 3). Other studies were more focused on the spray behavior and so the high speed camera was positioned level with the spray (Figure 4). To slow the motion of the spray droplets better illumination was required using a combination of lighting techniques. To accomplish this, a laser light sheet was generated using a series of optical lenses and a 2 W Argon ion laser and was combined with high power work lights to produce highly illuminated images.

RESULTS AND DISCUSSION

For the present experiment, the flow rate was varied from 2 GPH to 6 GPH, the heater power ranged from 0 W to 80 W, and electrode voltages ranged from 0 kV to 30 kV. Figure 3 shows single sample images from video clips taken at each heater power level at each respective flow rate without the presence of an electric field. Examining the three images in row 1 with no heat, for the increasing flow rates it is possible to see that an increase in spray density and velocity occurs; however, the appearance of the liquid film on the heater surface remains similar for each flow rate. However, looking at the images as the power level increases for a constant flow rate (vertical columns in Figure 3) it is possible to see that the spray behavior remains similar but the events occurring on the heater surface change quite drastically.

Comparing the images of Figure 3 for 2 GPH (2.1x10^-6 m^3/s) with no heat and 20 W it is possible to see the beginning of the formation of bubbles on the heater surface. At 20 W the surface temperature is very near the saturation temperature. Increasing the heater power level to 40 W the saturation temperature is exceeded and boiling occurs. Increasing the heater power to 60 W it is clear that the amount of vapor bubbles in the liquid film on the heater surface has increased dramatically from the initial no heat case. Similar observations can be made for both the 4 GPH (4.2x10^-6 m^3/s) and 6 GPH (6.3x10^-6 m^3/s) images; see Figure 3.

The voltage applied to the nozzle electrode charges the spray droplets, as can be seen more clearly in Figure 4 below, at a spray flow rate of 3 GPH (3.16x10^-6 m^3/s). As the electrode voltage level is increased from 0 kV to 30 kV the behavior of the spray droplets changes significantly. Little change is seen between 0 kV and 7.5 kV with the largest difference being the formation of large liquid droplets on the bottom of the spray nozzle. However, between 10 kV and 12.5 kV the appearance of the spray cone changes noticeably, with the onset of the generation of finer droplets. The calculated Rayleigh limit for 48 μm droplets will occur at 15 kV. From the image analysis it can be determined that the droplets begin to be electrostatically atomized approximately between 10 kV and 12.5 kV; this is in good agreement with previous research (Shrimpton, 2005). As the voltage level is increased beyond 12.5 kV the magnitude of the change in droplet behavior increases, forming a finer mist between the nozzle and heater surface. Visualization is partially obscured beyond charging voltages of 15 kV, due to the increased droplet charge and increased Coulomb force leading to the collection of a liquid film and droplets on the viewport.

Examining the video, time scales can be calculated for different spray behaviors. Kuhlman et al. (2007) have used the spray Sauter mean diameter and velocity data from Yerkes et al. 2006, and found that at a heater power of 100 W and a spray flow rate of 10 GPH (10.5x10^-6 m^3/s) the time scales for heating and boiling of the thin films formed in droplet impact craters are longer than the average time until another droplet impact into the existing droplet impact crater. Original time scale estimates are reproduced in Table 2(a), for FC-72 as the working fluid and with a flow rate of 10 GPH, assuming an average droplet diameter of 48 μm and a liquid film thickness of 150 μm (Kuhlman et al., 2007). For the significantly larger spray features seen in the current spray visualizations (Figure 1 and Figure 4), the length and time scales will differ; Table 2(b) shows time scale analysis for HFE-7000, with a 10 GPH flow rate and assuming a droplet diameter of 150 μm and a film thickness of 300 μm, as estimated from still images from the present high speed video. Comparing the values obtained for each analysis shows that the smallest value is the time between impacts in a crater for both calculations. This indicates that this time scale dictates the amount of time available for heat transfer to take place. However, further preliminary analysis of the present video indicates that the actual time scale between impacts of the largest spray features onto the same area of the heater (largest droplets, or filaments of sheets) is on the order of 0.5 ms to 2 ms. This observed time scale is on the same order as the time required to heat and vaporize the observed 150 mm diameter large droplets assuming no splashing (Table 2). Significant droplet splashing is observed, consistent with the splashing criteria of Cossali et al. (1997). The observation that the time between large droplet impacts is on the order of the calculated time to heat and
vaporize these drops is consistent with the observation of the onset of CHF at heater powers on the order of 80–100 W, for the current apparatus.

<table>
<thead>
<tr>
<th></th>
<th>2 GPH</th>
<th>4 GPH</th>
<th>6 GPH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No Heat</strong></td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td><strong>20 Watts</strong></td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td><strong>40 Watts</strong></td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td><strong>60 Watts</strong></td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td><strong>80 Watts</strong></td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

*FIGURE 3. High Speed Image Comparison at 0 kV, 4500 fps, 200 μs Exposure; Comparing Flow Rate and Heater Power.*
FIGURE 4. High Speed Image Comparison at 3 GPH, 4100 fps, 100 μs Exposure with Electrode Voltage Varied from 0 kV to 30 kV.
TABLE 2. Time Scale Analysis Comparing a.) FC-72 Spray Behavior with b.) HFE-7000 Spray Behavior.

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>a (Time)</th>
<th>b (Time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Between Droplet Impacts</td>
<td>610 μs</td>
<td>1.93 ms</td>
</tr>
<tr>
<td>Time Between Impacts in a Crater</td>
<td>21.5 μs</td>
<td>67.5 μs</td>
</tr>
<tr>
<td>Time of Droplet Impact</td>
<td>4.0 μs</td>
<td>12.5 μs</td>
</tr>
<tr>
<td>Time of Gravity Wave to Fill in Crater</td>
<td>3.93 ms</td>
<td>6.85 ms</td>
</tr>
<tr>
<td>Time of Surface Tension Wave to Fill in Crater</td>
<td>717 μs</td>
<td>2.4 ms</td>
</tr>
<tr>
<td>Time to Cause Droplet to Vaporize</td>
<td>224 μs</td>
<td>960 μs</td>
</tr>
<tr>
<td>Time to Heat Droplet 30 Degrees and Vaporize</td>
<td>312 μs</td>
<td>1.24 ms</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Contact charging significantly changes the behavior of droplets in the spray cone. As the electrode voltage levels are increased the number of droplets in the spray cone also increases, while the size of the droplets decreases due to electrostatic atomization. From calculations the theoretical Rayleigh limit for the average 48 μm droplet should be reached at an electrode voltage level of 15 kV. In accordance with previous research the electrode voltage that causes a significant change in droplet size and number is 12.5 kV, which matches the estimated onset of 70–80 % of the calculated value. In conclusion EHD shows promise in altering the spray behavior, ultimately resulting in the possibility of future enhancements of spray cooling heat transfer values. Time scale analysis based on the average droplet diameter indicates that the time between droplet impacts is of the shortest time scale and thus will limit the amount of heat transfer that may take place during spray cooling. However, the observed time scale between large droplet impacts onto the same heater location is on the same order as the time to heat and vaporize the drop. This indicates a new mechanism for the onset of CHF; localized dryout of the original large droplet impact craters.

NOMENCLATURE

EHD = Electro-hydro-dynamics
fps = Frames per second
E = Electric potential gradient (N/C)
\( \varepsilon_0 \) = Permittivity of air (C²/N-m²)
\( \varepsilon \) = Relative dielectric permittivity
\( F_e \) = Force on droplet (N)
\( \rho \) = Density (kg/m³)
\( \rho_e \) = Free electric charge density (C/m³)
\( q_{ray} \) = Rayleigh limit charge (C)
\( r_d \) = Radius of droplet (m)
\( \sigma \) = Surface tension (N/m)
\( T \) = Droplet Temperature (°C)

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REFERENCES


