Single Droplet and Droplet Train Impingement Pool Cooling

Ajawara, C., Banks, D., Cervantes, A., and Aguilar, G.
Department of Mechanical Engineering
University of California, Riverside
Riverside, CA 92521 USA

Abstract

The cooling behavior of an impacting single droplet and train of droplets on a heated substrate (T = 60°C) for various pool conditions is explored. The effects of several variables such as impact velocity (1-4 m/s), droplet diameter (4.8 mm), pool depth (0-34 mm), and impact frequency (0.5-32 Hz) on the cooling dynamics are explored. A fast response RTD embedded at the surface of the substrate allows for temperature measurement below the droplet impact. A high-speed video camera recorded the dynamics of cavity formation and collapse upon impact with the pool surface. Droplet diameter and impact velocity were also measured using the high-speed video. The instantaneous heat flux and net heat extraction at the surface were obtained using a finite-time step integration of Duhamel’s theorem.

Heat transfer appears to be maximized within an intermediate region of impact Weber number for the single droplet impacts. At this intermediate Weber number range, the impact crater almost reached the pool bottom, suggesting that cold droplet fluid made contact with the substrate, maximizing the cooling effect. Outside this intermediate region of Weber number, the heat flux appears decrease. At the higher Weber number range, cold droplet fluid is pushed away from the measurement point once the cavity reaches the substrate. Below the optimal range of Weber number, the droplet does not enter the crater formed by the previous droplet, preventing it from reaching the substrate. For a train of droplets, there seems to be several regions where the heat flux is further reduced due to collision of droplet with emerging jet.

Corresponding author: gaguilar@engr.ucr.edu
Introduction

Among the most powerful heat transfer techniques is that of an atomized liquid spray. The combination of driven convection, phase change, and built-in vapor dispersion makes spray cooling extraordinarily capable of high heat fluxes, and the small liquid volumes involved lead to small spills and minimal supporting hardware. Sprays have great potential to improve thermal management in applications such as electronics, dermatology, and high-energy lasers, among many others. Making use of the fullest capability of spray cooling requires insight and control over complex fluid dynamics, a challenge which is driving research around the world. Mudawar described sprays as having the potential for ultra-high heat fluxes demanded by modern applications, with the potential for upwards of 100 W/cm² [1]. In that paper, sprays are demonstrated as exceeding the optimum heat flux of submersion boiling, while providing a more consistent heat flux over a wider area than jet impingement cooling. Kim reinforces the idea that spray cooling is a potential successor to current air-cooling and submersion-cooling of electronics in his review, reporting heat fluxes marginally larger than Mudawar's earlier findings [2].

The starting point for spray dynamics studies has been the behavior of a single droplet impacting a surface. Many studies have been performed in this line, starting from Worthington in 1876 with dust-splat shape studies and continued through the present. Yarin provides an extensive review of droplet impact studies in [3]. The findings of Vu, et al., who explored single droplet cooling in shallow heated pools and reported secondary cooling effects, delayed slightly after impact of the droplet into the pool, due to droplet fluid deposition [4].

The behavior of a single droplet impacting any of a wide range of surfaces, under varying conditions (atmospheric, kinetic, etc.), has been very well explored. Recent study by Trujillo, et al simulated cooling behavior of impinging droplet trains and free surface jets over heated and pre-wetted surface [5]. Connecting a single droplet impact behavior to the cumulative dynamics of a spray, consisting of many thousands or millions of droplets, is the focus of this study. By examining the droplet impact fluid and thermal dynamics in the context of trains of droplets over a range of impact frequencies, the goal of this study is to establish a framework for measuring and comparing the cooling effectiveness of these trains. This framework is needed because of the wide range of conditions that can occur over even a single spray duration- the droplet frequency can change as the spray develops, the film thickness on the surface can build up, or droplet size distribution can change, to name a few possible factors.

Existing studies on droplet trains describe a quasi-steady cavity within a pool that develops- the walls of the cavity are nearly quiescent as incoming droplets prevent the collapse of the cavity [6]. The cited study used high frequency trains (1-10 kHz) of micron scale droplets and found that the steady condition was achieved in the order of milliseconds after the first droplet impact, and after order O(10) droplets had struck, accompanied by heat fluxes ranging from 5 to 35 W/cm², increasing with droplet frequency [6]. This study builds upon Trujillo, et al.’s work, extending to larger (O(1) mm diameter) droplets and lower (0.5-30 Hz) frequencies. The intent is to provide detailed insight into the interactions between successive droplets that lead to the heat transfer that has been measured.

Fathi, et al, in their study of droplet trains for additive manufacturing, reports that literature regarding droplet trains impacting moving surfaces is scarce [7]. That study looks at droplets of O(100) microns impacting with kHz frequencies; the test fluid is a non-Newtonian shear-thinning but highly viscous resin droplets. The primary focus is on the fluid dynamics, specifically the interactions between successive droplets as they move with the surface [7].

A recent study by Fujimoto, et al, examined the interaction between two droplets impacting coaxially upon a heated solid surface [8]. The 0.5-0.6 mm diameter water droplets were spaced to impact at a with a separation of O(1) ms. The spreading of liquid across the otherwise dry surface was characterized over a range of substrate superheats (170 < T_s < 500 °C). High within that range, the droplets experienced instantaneous boiling and disintegrated. The heat transfer at impact was not measured, however. The thermal and hydraulic mechanisms produced by droplet trains have been studied by Soriano, et al [9].

To adequately characterize and discuss the heat transfer of a given droplet train, a comprehensive, precise experimental system is being developed. A variable frequency droplet generator produces trains of millimeter-scale that impact a heated substrate. High speed video records the impact, to gain insight into the instantaneous fluid dynamics. A fast response temperature sensor embedded into the substrate provides point measurement of temperatures. The temperature record and the video are synchronized such that observed fluid and cavity dynamics can be related to small time periods within the temperature record.

The focus of this study is to develop droplet train studies towards predictors of spray dynamics. We will be examining primarily the initial impingement dynamics of a train impacting both a dry solid surface and a liquid pool. An overview of the initial cavity growth and collapse from a single droplet impact are included. The impacts of droplet trains over a range of frequencies are observed as they initiate and develop.
towards the quasi-steady-state conditions observed by Trujillo, et al [6]. This quasi-steady state occurs when the droplet frequency is high enough that each successive droplet impacts within the cavity of the previous. The walls of the cavity are thus pushed outward radially before cavity collapse can occur, leading to a cavity diameter that fluctuates around a constant mean [6].

**Experimental Setup**

Figure 1 shows the droplet production and measurement setup. Droplets and droplet trains are produced using a microliter valve (EFI 740V). The valve is opened by a pneumatic controller (EFI Valvemate 7000) triggered by a programmable microcontroller (Arduino Uno R3). The microcontroller can produce voltage pulses with a time resolution on the order of microseconds at set frequencies, and those pulses trigger the valve to open for a prescribed time. The valve is fed from a pressurized liquid reservoir. When actuated, the valve releases pressurized liquid through a steel needle (outer diameter 3.15 mm, inner diameter 2.50 mm, length 110 mm) and a droplet forms at the tip of that needle. After a set time, the valve closes and liquid ceases passing through the needle. When the droplet is large enough, gravity overcomes the surface tension holding the droplet to the needle and the droplet falls. For the described needle, the droplet diameter when separation occurs is typically 4.6 mm. The duration of the valve's opening is calibrated such that one cycle of the valve results in the production of one droplet. Thus, the valve’s cycling frequency, regulated by the microcontroller, corresponds to the droplet production frequency. The setup is capable of producing droplet trains with frequencies of up to approximately 50 Hz; any faster and the droplets become irregularly sized.

Deionized water is used as the fluid for both the droplet and the pool (study-relevant properties listed in Table 1. Droplets fall under gravity acceleration from the needle when they reach a diameter of 4.6±0.1 mm, and the impact velocity varies from 1 to 4 m/s. This results in an impact Weber number range of $42 < We < 1064$ and an impact Reynolds number range of $4314 < Re < 21573$, based on the properties in Table 1. For a train of droplets, the Strouhal number range of $0.00115 < St < 0.0736$ is observed. If $U$ is the velocity, $d$ the diameter, and $\rho$, $\nu$, $f$, and $\sigma$ are the density, kinematic viscosity, frequency, and surface tension, respectively, then the Weber, Reynolds, and Strouhal numbers can be defined by Equations (1), (2), and (3).

$$We = \frac{\rho U^2 d}{\sigma}$$  \hspace{1cm} (1)

$$Re = \frac{U d}{\nu}$$  \hspace{1cm} (2)

$$St = \frac{f d}{U}$$  \hspace{1cm} (3)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$998 \text{ kg/m}^3$</td>
</tr>
<tr>
<td>Kinematic Viscosity</td>
<td>$8.9 \times 10^{-7} \text{ m}^2/\text{s}$</td>
</tr>
<tr>
<td>Surface Tension</td>
<td>$0.072 \text{ N/m}$</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>$0.5985 \text{ W/m·°C}$</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>$4184 \text{ J/kg·°C}$</td>
</tr>
</tbody>
</table>

**Table 1.** Properties of deionized water.

The impact substrate consists of an aluminum plate, heated by resistance heaters from within. The heaters are regulated by a temperature controller (Omega CSC32) which receives feedback from a thermocouple placed within the pool away from the impact location. A channel in the face of the aluminum has been filled with cast epoxy resin to hold a fast-response resistance temperature detector (RTD) at the level of the substrate surface. Glass walls surround the plate, retaining a pool of liquid on the aluminum substrate while allowing video recording of the plane of impact. The glass walls are 50 mm tall and have an inner diameter of 127 mm. The impact is centered within the pool, so the wall effects can be reasonably neglected. For this study, the focus is on the heat transfer induced at the substrate, so the focus is on shallow pools, with depth ranging from dry surface to 15 mm (approximately 3 times the droplet diameter). Deeper pools appear to prevent interaction between the droplet and the substrate, minimizing the heat transfer.

**Fluid and Thermal Behavior Measurement**

A two-pronged approach is used to measure the dynamics of the droplet impacts. A high speed video camera (Phantom v7.1, Vision Research) is used to record the droplet in freefall and the impact cavity from

![Figure 1. Experimental Setup.](image-url)
the side- within the plane of the substrate. The camera records at 1000 frames per second at a resolution of 800 x 600 pixels. The exposure time per frame is 40 microseconds. Distance and velocity measurements are taken using the Phantom Camera Control software. Calibration is obtained from video using still frames of objects of known dimensions; from these frames the length corresponding to one pixel on video can be calculated. Measuring the distance a droplet moves between successive frames of video at a known interval between those frames gives the velocity the droplet is moving during that time. The camera is positioned at a height such that the cavity below the surface of the pool is visible as well. Calibration lengths are taken both above and below the surface of the pool to account for refraction. One pixel above the surface of the pool corresponds to 0.030 mm, and below the surface to 0.028 mm.

To provide repeatability, each droplet was assessed before impact. The impact velocity was measured and required to be ±0.05 m/s of the nominal velocity. The droplet diameter was measured both horizontally and vertically in the video plane, and both axes were required to be within ±0.05 mm of each other and of the nominal diameter for the particular needle used. This ensures comparisons between droplets are not subject to variation due to the pre-impact conditions. Further, the shape of the droplet at impact has been observed to greatly influence subsequent cavity, splashing, and vorticity dynamics [10]. Ensuring the droplet is spherical at impact will alleviate these geometry effects.

The second experiment prong is a fast-response RTD cast in the epoxy upon the substrate (Minco S10044PD12). It is advertised with a response time constant of approximately 3 milliseconds, and it is exposed but flush with the substrate. The droplet impacts are centered upon the RTD. The RTD is sampled at 1000 Hz and the data is digitally smoothed using a moving average filter. The RTD provides detailed and fast-response insight into the heat transfer at the point of impact.

**Thermal Analysis**

The RTD provides a record of the temperature at the substrate. From this, the heat flux is calculated using a numerical integration of Duhamel’s theorem. Duhamel’s theorem is a method of solving the heat equation for time-fluctuating boundary conditions, enabling the heat flux through a surface to be solved based on a measurement of temperature history [11]. Duhamel’s theorem in temperature form, assuming constant thermal properties, is given by Equation (4).

\[
T(z, t) = T_0 + \int_{t_0}^{t} S(z, t - \tau) \frac{dT}{dz} dz
\]

Modeling the substrate as a solid, semi-infinite plane, \( S \) takes the form of Equation (5).

\[
S(z, t) = 1 - \text{erf} \left( \frac{z}{2\sqrt{kt\rho c}} \right)
\]

With that response function, and using Fourier's Conduction Law (\[ q'' = -k \frac{dT}{dz} \]), Equation (4) can be integrated and solved for the heat flux.

\[
q'' = 2 \sqrt{\frac{kpc}{\pi}} \sum_{i=1}^{l} \frac{t_i - t_{i-1}}{t_{i-1} - t_{i-1}} \left( \sqrt{t_i - t_{i-1}} - \sqrt{t_{i-1} - t_{i}} \right)
\]

Where \( T \) is the temperature at each time step, \( t \) the time, \( k, \rho, c \), the thermal conductivity, density, and specific heat of the substrate containing the sensor, respectively, and \( q'' \) is the heat flux per unit area. The overall heat extraction, \( q \), is calculated by taking the sum of each instantaneous heat flux multiplied by the time step.

This solution assumes a finite time step. Vu, et al, used this method to compute the heat fluxes of single droplets impinging upon shallow heated pool [4]. Equation (6) is used to estimate the heat flux from the temperature history recorded by the embedded RTD.

**Results and Discussion**

**Single Droplet Cavity Dynamics**

The first experiment is an investigation of cavity-substrate interaction for a single droplet impinging upon a shallow pool. The depth and duration of the cavity is recorded on high speed video, and the temperature history is recorded by the RTD. Figure 2 depicts the cavity depth over time for a droplet impinging upon a 5 (Fig. 2a), 9 (Fig. 2b), and 15 (Fig. 2c) mm pool at 2 m/s. This corresponds to \( \text{We} = 270 \). The measurements are of the depth of the cavity vertically below the point of impact of the center of the droplet. Figure 3 shows still frames from the video recording of these droplet impacts.

In Figure 2, there appear to be three qualitative regimes of droplet-substrate interaction based on the cavity’s behavior. First, the deep-pool regime is observed through the cavity behavior of the 15 mm deep pool impact (Fig. 2c). The cavity does not approach the bottom of the pool- it only penetrates approximately halfway through. The cavity follows a smooth curve except for a small jump during collapse. This jump, also observed in the 9 mm pool (Fig. 2b), corresponds to a brief instant when the bottom of the cavity narrows radially and vertical collapse is delayed momentarily, a process observed and discussed by Rein [10]. He describes this radial collapse as occurring in the absence of a vortex ring that forms at lower impact.
Weber numbers. When it occurs, the vortex redirects flow upward; without the vortex ring the radial collapse becomes more dominant.

In contrast, the 5 mm pool (Fig. 2a) reveals a thin-film regime, where the cavity almost immediately reaches the bottom of the pool. This thin-film regime necessitates that the momentum of the droplet impact be directed radially from the point of impact, leading to an extended period of time when the substrate below the pool is exposed. The quasi-steady cavity condition observed by Trujillo, et al occurs in this regime, as the radial redirection of droplet momentum is what maintains the position of the cavity walls [6].

The intermediate pool depth 9 mm, Fig. 2b) results in a cavity that qualitatively does not appear to be in the thin-film regime- the cavity does not reach the substrate; however, it shows slightly different behavior than the deep pool regime. The smooth curve observed for the deeper pool cavity is replaced with a series of small jumps around the maximum depth, punctuated by a sharp transition to collapse. If the deep pool regime is specified by a lack of droplet-substrate interaction, then this case appears to have some substrate interaction, potentially through viscous effects within the thin layer of fluid that remains between the cavity and the substrate. Figure 3b shows the cavity at this instant, with 2a and 3c representing the same condition—maximum cavity depth— for the thin film and deep pool conditions, respectively.

In the context of trains of droplets, the interaction between one droplet impact and the next depends on the condition of the cavity and pool at the time of the subsequent impact. It is important to note the duration of the cavity for each of these impacts. The thin-film cavity appears to last the longest, collapsing approximately 45 ms after impact. A droplet train
exceeding 23 Hz and producing cavities of that duration would lead to successive impacts before the cavity has collapsed. The intermediate and deep-pool cavities collapse more quickly, at approximately 30-35 ms after impact. This duration would require a higher frequency, < 30 Hz, for incoming droplets to impinge upon open cavities. The longer duration in the thin-film regime is likely due to the radial forcing of the droplet momentum, driving the cavity to a larger diameter than the other regimes.

Figure 4. Temperature measurements for We = 270 droplet impacts onto pools of 5, 9, 5 mm depth. The droplet fluid is at 22°C and the pool is heated from below to 60°C.

Figure 4 is the temperature history from each of the droplet-pool impacts depicted in Figures 2 and 3. The first observation is that the idea of the deep pool regime occurring when the droplet has no interaction with the substrate clearly did not occur for these cases. All three droplets show a clear temperature effect- a drop in temperature occurs, suggesting that at least some cool droplet fluid penetrates the pool and reaches the substrate. This means the droplet fluid distribution differs significantly from the cavity shape and position. The significance of this is that, for some impact and pool conditions, the droplet fluid may be deposited near the substrate as the cavity collapses, for example, leading to an extended cooling period.

<table>
<thead>
<tr>
<th>Pool Depth (mm)</th>
<th>Heat Flux (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-13.2</td>
</tr>
<tr>
<td>9</td>
<td>-14.2</td>
</tr>
<tr>
<td>15</td>
<td>-2.99</td>
</tr>
</tbody>
</table>

Table 2. Peak heat fluxes for droplet impacts (We = 270) into pools of 5mm, 9mm, and 15 mm depth.

In Figure 4, the intermediate pool shows a larger temperature drop than the other two cases. This suggests that the droplet fluid has the most contact with the substrate at the sensor location. The implication is that the sensor location is subjected to a higher heat flux for that case than the others. It is obvious from video why the thin-film regime experiences this- the droplet liquid is forced radially by the pool substrate, exposing the substrate to air and a drastically weaker convective process. The deep pool, also, has an intuitive reason for lesser cooling effects. While some of the droplet fluid does reach the substrate, the deeper pool does prevent more of the cool fluid from penetrating.

The observation of enhanced cooling for certain pool depths was noted by Vu, et al [4]. The effect was at that time attributed to a secondary convective phase, due to eddies at the substrate observed using dyed droplet fluid. These eddies are evidence of droplet fluid deposition at the substrate, as the droplet fluid is left behind and subsequently circulated as the cavity recedes. More detail about these vortices is widely available in literature; for now we posit that they are complementary evidence of the findings of cool fluid deposition near the pool substrate. Droplet-film impact vortices are well explored, starting from Thomson and Newell in 1885 [12] and continuing through the present. Rein, among others, attributes the penetration of these vortices, composed primarily of droplet fluid, to the droplet's shape at impact- a prolate (along impact axis) drop produces a more powerful and penetrating vortex than an oblate one [10]. Watanabe, et al, discussed these vortices that form around the cavity extensively from the results of their numerical models [13].

An optimal heat transfer regime for a single droplet impact and further potential for enhanced droplet trains. If the droplet's impact conditions are such that significant and extended deposition occurs, the cooling effect ought to be larger than cases where the droplet rebounds or otherwise moves away from the substrate.

For reference, a droplet impact onto a heated ($T_{sub} = 68 °C$) dry surface at the same velocity (2 m/s, We = 270) was measured to compare the cooling effects with the impacts onto liquid pools. Figure 5 shows the temperature history for the dry surface impact. The temperature drops by 36°C, a significantly larger decrease than any of the pool impact cases and the peak heat flux is 50.6 W/m². The temperature gradually rises but it is not a fast increase as can be seen with the pool. In Figure 6 the droplet is seen impacting the dry substrate, coalescing, and then coming to a rest.
Minimal to no cooling effect is observed with 34 mm pool depth. In Figure 7 the cavity can be seen forming but quickly collapses without even reaching the middle of the pool. The temperature drop at this depth is less than 0.5 °C which is less than the 15 mm deep pool caused the cooling effect to be considered negligible.

To explore and better define the cavity regimes, droplet impacts into a single pool (9 mm depth) and with varying velocities, of 1, 2, and 4 m/s (We = 70, 270, 1064). Figure 8 shows the cavity depth those three cases.

Figure 8a reveals the deep pool regime dramatically, giving a drastically different cavity depth record than previously observed. The cavity is short-lived and does not approach the substrate. Figure 8b shows the cavity almost reaching the surface giving an opening for the droplet to fall through and touch the substrate. Figure 8c reveals a cavity that reaches the substrate and rests before collapsing.

Figure 9 gives the temperature history recorded for the droplets of different velocities into an intermediate pool depth of 9 mm. The most effective cooling is seen at 4 m/s where the droplet velocity is high enough that it pushes through the pool allowing for the droplet to reach the substrate for better cooling.
Figure 9. Temperature histories for droplet impacting at 1, 2, and 4 m/s, corresponding to Weber numbers of 70, 270, and 1064.

**Droplet Train Heat Transfer**

Droplet trains consisting of 5 droplets were used to explore the thermal effects of trains with varying frequencies. The trains impacted on a 9 mm pool. The trains had constant velocity of 2 m/s. This places the initial impact in the optimal single-droplet cooling regime observed previously. The pool conditions for subsequent droplets are altered by the prior impact. The frequencies used were 0.5, 8, 10, 28, and 32 Hz. Figure 10 shows still frames of successive droplet impacts for each frequency, to explore how exactly the pool conditions are altered for each impact. Figure 11 shows the temperature history for each train.

At 0.5 Hz, successive droplet impacts were nearly isolated from each other— the cavity of one droplet had collapsed and the pool was settling by the time the next droplet arrived (Figure 11a). Consequently, each successive droplet gives a similar temperature drop, with a sharp initial decrease and smooth minimum. However, the temperature continues to decrease with each successive droplet, giving a cumulative cooling effect (Figure 11a).

At 8 Hz, the droplets started to show overlap in their impacts. The successive droplets fall into the small cavity created by the previous droplet’s jet rebound which allows for better cooling.

At 10 Hz, the jet from the cavity collapse intercepts the next oncoming droplet causing a delay in cooling which reduces the overall cooling effect.

At 28 Hz, the cavity dynamics of successive droplets begin to overlap. The pool has not yet become quiescent from one droplet by the time the next has arrived.

At 32 Hz, each successive droplet impinged within the cavity of the previous, developing towards the quasi-steady cavity condition [6].

Figure 10. Still frames of successive droplets impacting on 9 mm pool at 2 m/s (We = 270).

For the frequencies studied, the most effective cooling in terms of heat flux occurs as the frequency increases. The cooling period of each droplet at higher frequency overlaps with the next, leading to a cumulative high heat flux. However, at the lowest frequency (0.5 Hz), the overall temperature decrease after 5 droplets is largest. Each droplet strikes after the previous has reached minimum temperature, so the heat flux is divided into discrete peaks. The temperature has yet to recover to the pool’s initial condition, however, so the successive droplets lower the temperature further. At higher frequencies, the overlap in cooling between successive droplets prevents this.
Figure 11. Temperature history of droplet trains impacting a heated pool at varying frequencies.

Conclusions
While the presence of a liquid pool at the point of droplet impact reduces heat transfer over a dry surface impact, pool-impact phenomena can be used to optimize heat transfer. Both very deep pools and thin films on a substrate decrease the cooling effect of a single liquid droplet. In an intermediate condition between those, droplet liquid is deposited at the substrate after the cavity collapse, leading to a prolonged and magnified cooling effect when compared to the deeper and shallower pools.

Droplet trains appear to produce higher heat fluxes as the frequency increases, over the range of frequency examined. Lower frequency leads to larger temperature decrease, but the magnitude of the peak heat flux is reduced. The larger temperature drop occurs due to each droplet cooling the substrate for a discrete duration, allowing the temperature to ‘bottom-out’ for that droplet by the time the successive one arrives. At higher frequencies, the temperature does not have a chance to bottom-out in the same fashion before the next droplet arrives and displaces the previous droplet, leading to overlapping cooling periods.
Future Work

Development of a sensor using multiple fast-response RTDs is underway. The RTDs will be arranged radially around the point of impact. This, combined with existing and improved HS video recording, will allow further exploration of the droplet deposition near the substrate-if the droplet fluid deposits away from the impact site, for example, the results from this study would not reflect the cooling of the surrounding area of the substrate. Variations in heat flux radially surrounding the impact point will also be measured.

Expanding the range of train frequencies, using multiple axis trains (i.e., offset radially from the first droplet's impact point), and varying the droplet size is another step to build from this study. Existing studies on droplet trains have typically used much smaller (often micron-scale) droplets at much higher frequencies (O(kHz)) [6]; the gap between this study and those conditions is worth closing. Using multiple nozzles to generate droplets and changing the droplet generator to achieve more droplets with each run will allow for the connection between individual droplets and sprays.

Changing the surface conditions of the substrate will be explored. Hydrophobic and hydrophilic conditions will be studied through the nano/micro-patterning of the surfaces. The hydrophobicity condition can be used in applications where corrosion is not desired.

Acknowledgements

The authors would like to thank Molly Daniels, Hamza Surti, and Jonathan Campo for laboratory assistance, Anthony Fong for his machining assistance, Jie Liu for discussions and support, and the UCR Graduate Division for student support.

References