Single Droplet Heat Transfer through Shallow Liquid Pools

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Abstract

Many studies exist examining the underlying physics behind single droplet impact splashing and cooling. However, despite its practical importance, little information exists concerning the influence of liquid surface films on resultant heat transfer. In this study, water droplet impact behavior into quiescent liquid pools was visualized using a high-speed video camera set at 3000 fps. The impacting droplets were dyed in order to promote contrast and visualization. Pool depths ranging from 0 to twice the droplet diameter were used in order to assess its influence on impact dynamics. Additionally, heat transfer was measured from an epoxy block substrate. The epoxy block surface was heated to 42˚C to induce heat transfer with the impinging droplet which was kept at room temperature. Transient surface temperature history was recorded with a flat, fast-response thermocouple embedded at the substrate surface. Heat flux and overall heat extraction was subsequently calculated using Duhamel's Theorem. Droplet diameter and velocity were varied from 2.5-3.7 mm and 0.5-2 m/s, respectively.

It was found that with dry surfaces, heat transfer was highest and could be divided into a convective phase in which the droplet is initially impacting and spreading, and a conductive phase where the droplet becomes relatively stagnant while still cooling the surface. Since the impacting droplets must penetrate through the liquid pools to reach the substrate, heat transfer was significantly reduced for cases with pools. However, some unusual convective phenomena were observed for cases in which the pool depth was comparable to the droplet diameter. Cooling could be slightly enhanced through convective eddy formation which is inhibited in thin pools. Also, deeper pools allowed for separate, isolated cooling periods in which the impacting droplet contacted the substrate surface multiple times through oscillation of the pools surface. The results provide insight into the processes occurring during spray cooling.

Introduction

Liquid cryogen fuels such as LO2, LH2, and LNG may be released, purposefully or accidentally, from highly pressurized containers, inducing sudden flash evaporation and subsequent impact of liquid droplets onto solid surfaces. These droplets often deposit onto solid surfaces, resulting in droplet spreading, splashing and heat transfer. In this scenario and in most other spray cooling applications, a resident liquid pool or film forms on the substrate surface and significantly affects the dispersion and heat transfer phenomena. It is the purpose of this study to measure and provide some insight into the surface temperature variations that result beneath a liquid pool after the impact and splashing of droplets at different temperatures. The overall objective is to shed some light on the heat transfer mechanisms that dominate during these events. Existing fundamental studies of single droplet impacts have revealed much of the underlying physics behind splashing and cooling [1-4]. Additionally, studies have also examined the influence of shallow liquid pools on splashing behavior [5-7]. However, little information exists concerning the influence of liquid pools on heat transfer phenomena. This is a problem of great practical importance because in many spray cooling applications, a resident liquid layer will form on the target substrate, greatly affecting heat transfer.

This study examines the hydrodynamic phenomena of single droplets impacting into thin liquid pools and effects on resultant heat transfer from a heated substrate. In order to simplify the problem, temperatures are kept below boiling so phase change and latent heat transfer do not take place.

Materials and Methods

A pneumatic micro-liter valve (Model 740V-SS, EFD Inc., East Providence, RI, USA) with stainless steel tips of various outer diameters was used to generate droplets of 2.5-3.7 mm diameter. The distance from the nozzle tip to the impact surface was varied from 0.013 to 0.816 m to produce impact velocities from 0.5 to 4 m/s. Water at room temperature was the fluid of choice.

For the hydrodynamic study, liquid pools were created using a custom-made glass reservoir of 25.5 x 25.5 x 11.5 mm dimensions. The impacting droplets were dyed with Brilliant Blue R (Sigma-Aldrich, St. Louis, MO) in order to promote contrast and imaging was performed horizontally through the reservoir walls with a high-speed camera (Photron Fastcam, Photron USA, San Diego, CA) set at 3000 fps and 128 x 120 pixel resolution. In order to reduce the degree of meniscus formation at the reservoir walls, they were coated with a silicone spray lubricant. Pool depths used ranged from 0 to twice the droplet diameter.

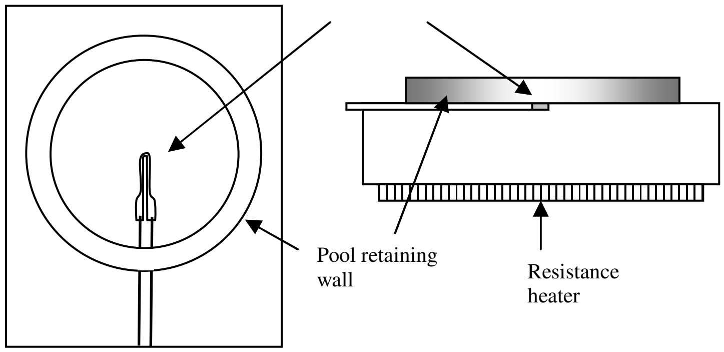

Figure 1: Thermal sensor with pool retaining wall.

Droplet impact heat transfer was measured using a sensor (Figure 1) consisting of an epoxy block substrate of 6 mm depth with an embedded fast-response flat thermocouple at the top surface (CO2-K, Omega Engineering, Stamford, CT). Liquid pools on the top of the sensor were produced with the aid of a cylindrical retaining wall of 0.03 m diameter. The sensor was heated from the bottom with an electric pad heater to produce a steady top surface temperature of ~43 ˚C or 20 ˚C above the impacting droplet temperature in order to create a thermal gradient. The water used to produce the pools was also preheated to 43 ˚C prior to deposition on the sensor surface.

The thermal sensor measures the transient surface temperature changes due to the impacting droplet. Heat flux and overall heat extraction was also computed from this data using Duhamel's Theorem [8]. Duhamel's theorem is based on the principle of superposition and states that the substrate thermal response at *t* equals the total sum of what the substrate experienced in small steps prior to *t*. For constant thermal properties, the temperature form of Duhamel's theorem is

$$\theta(z,t) = \theta_o + \int_{t_o}^{t} u(z,t-\tau)\frac{dT}{dz}\,\mathrm{dz}, \tag{1}$$

where θ is the substrate temperature, θ_o is the uniform initial temperature, u is the temperature response function of the substrate (initially at zero temperature) to a unit step in surface temperature, z is the coordinate perpendicular to the surface, $t-\tau$ is the time that has elapsed since the step at τ, and T is the surface temperature (Carslaw and Jaeger 1959, Meyers 1971). Using equation (1), Fourier's law, for a continuous surface temperature in time, can be written as

$$q(t) = -k\frac{\partial\theta}{\partial z}\bigg|_{z=0} = -k\int_{t_o}^{t}\frac{\partial u(z,t-\tau)}{\partial z}\bigg|_{z=0}\frac{dT}{dz}dz, \tag{2}$$

where partial derivatives are evaluated at the surface. The unit step function for a semi-infinite planar solid is

$$u(z,t) = 1 - \mathrm{erf}\left(\frac{z}{2\sqrt{\propto t}}\right), \tag{3}$$

Substituting equation (3) into (2), the surface heat flux, $q(t)$, can be written as

$$q(t) = \sqrt{\frac{k\rho c}{\pi}}\int_{t_o}^{t}\frac{1}{\sqrt{t-\tau}}\frac{dT}{dz}dz, \tag{4}$$

Assuming that the surface temperature is measured at discrete times t_i and that the surface temperature varies linearly in time between successive times, equation (6) can be integrated analytically to obtain

$$\hat{q}_I = 2\sqrt{\frac{k\rho c}{\pi}}\sum_{i=1}^{I}\left(\frac{T_i - T_{i-1}}{t_i - t_{i-1}}\right)\left(\sqrt{t_I - t_{i-1}} - \sqrt{t_I - t_i}\right), \quad (5)$$

where $q\hat{}$ is the approximate surface heat flux for a semi-infinite planar body. A more detailed discussion about this approximation can be found in [8]. For simplicity, $q\hat{}$ is written as q in the following sections.

Results and Discussion

Figures 2-4 show the results of the droplet impact imaging. For 3.7 mm droplets impacting at 0.5 m/s (Figure 2), the case for the dry surface (2a) reveals a non-splashing regime in which the droplet spreads and oscillates for some time. With the addition of the shallow (2b) and deeper pools (2c) the droplet must overcome the surface tension of the pool surface to penetrate the pool and reach the bottom surface. A crater forms at the surface which permits only a portion of the droplet to penetrate while the remaining droplet remains at the surface. Because of the low momentum of the impacting droplet, crater depth remains shallow and there is little oscillation of the pool surface. Noticeable eddy formation and convective effects are present in the deeper pool (2c), however, that are absent from the shallow pool (2b).

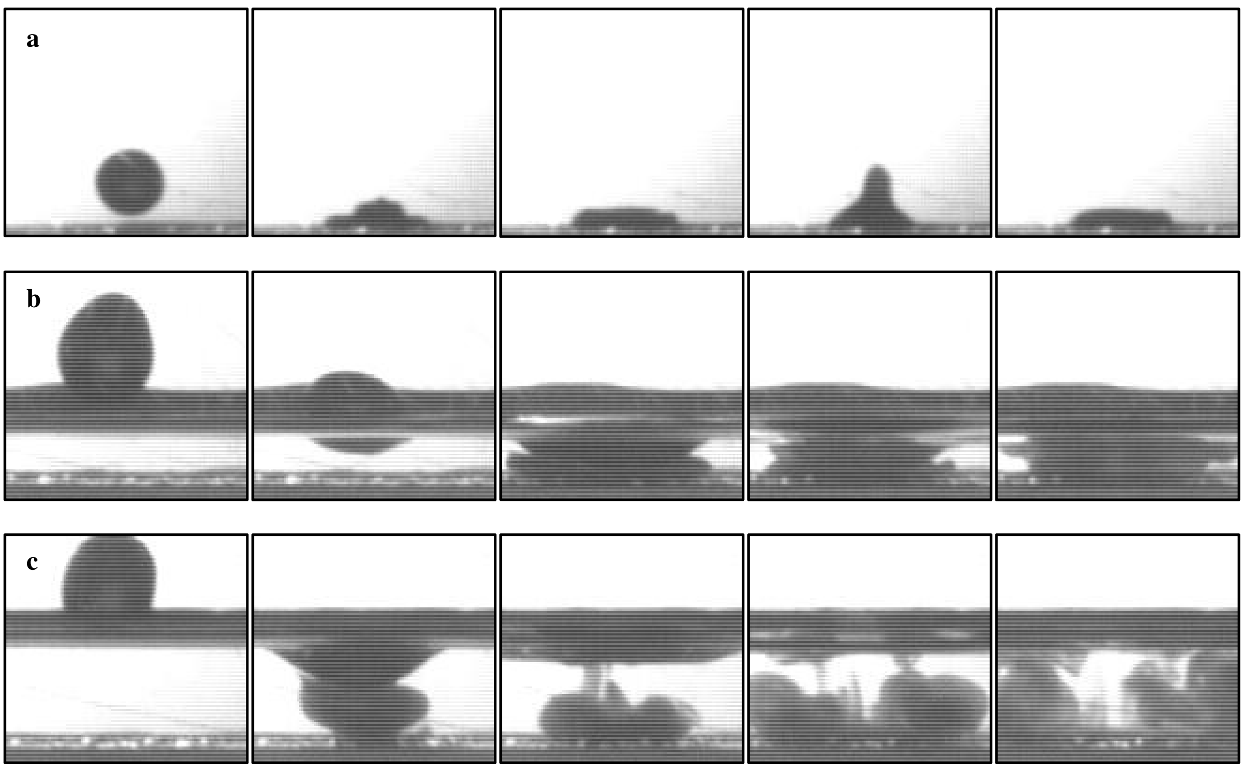

Figure 2: Video of a 3.7 mm diameter, 0.5 m/s droplet impacting into a **a)** dry surface, **b)** 1.85 mm depth, **c)** 3.7 mm depth.

As the droplet velocity is increased to 2 m/s (Figure 3), the dry surface (3a) reveals that the droplet has reached a splashing regime in which significant splashing and spreading occurs. Corona formation and craters which penetrate to the bottom surface are evident with both the shallow (3b) and deeper pools (3c). Again, some convective effects are evident with the deeper pool but absent in the shallow pool. Rebounding of the pool surface seems to pull some of the liquid back up.

Figure 4 shows the case for 2.5 mm diameter droplet impacting at 4 m/s. These conditions are again in the splashing regime as shown by the dry surface case (4a). Corona and deep crater formation are evident, but it appears that less of the droplet volume actually reaches the bottom surface. Also, some of the droplet rebounds upward and

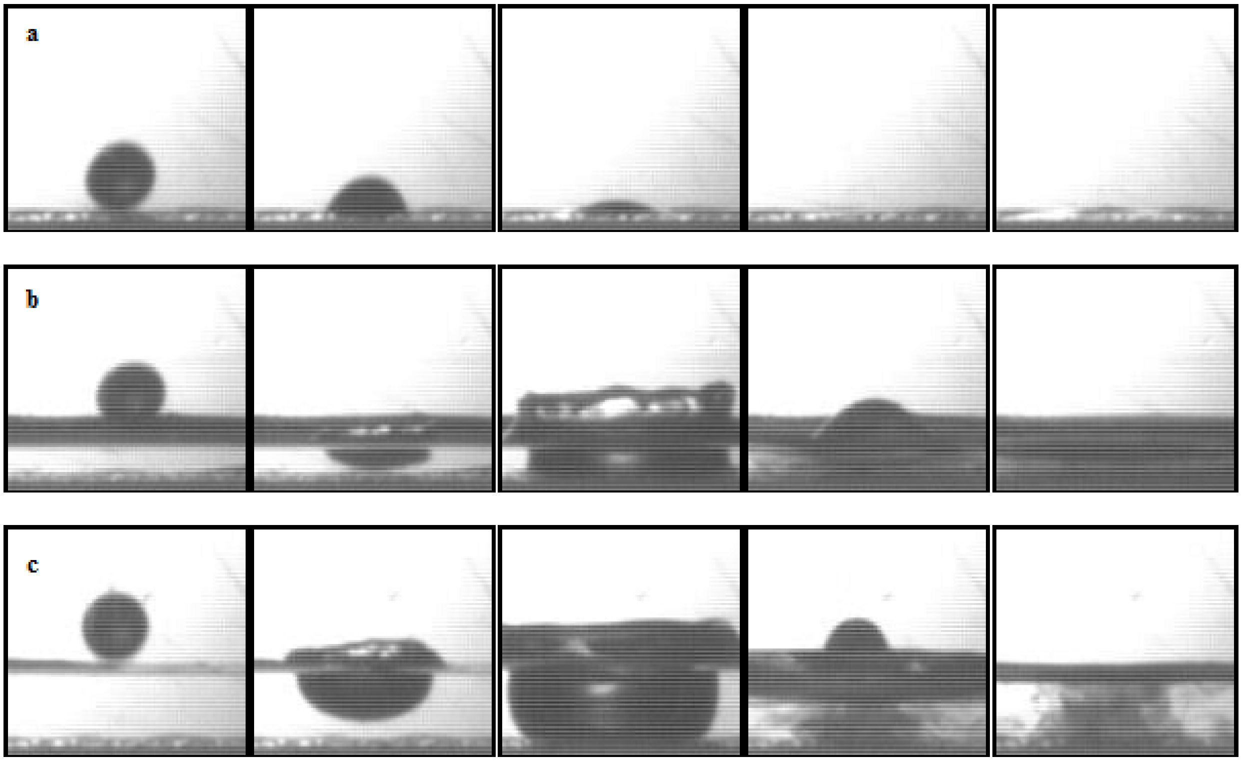

Figure 3: Video of a 3.7 mm diameter, 2 m/s droplet impacting into a **a)** dry surface, **b)** 1.85 mm depth, **c)** 3.7 mm depth.

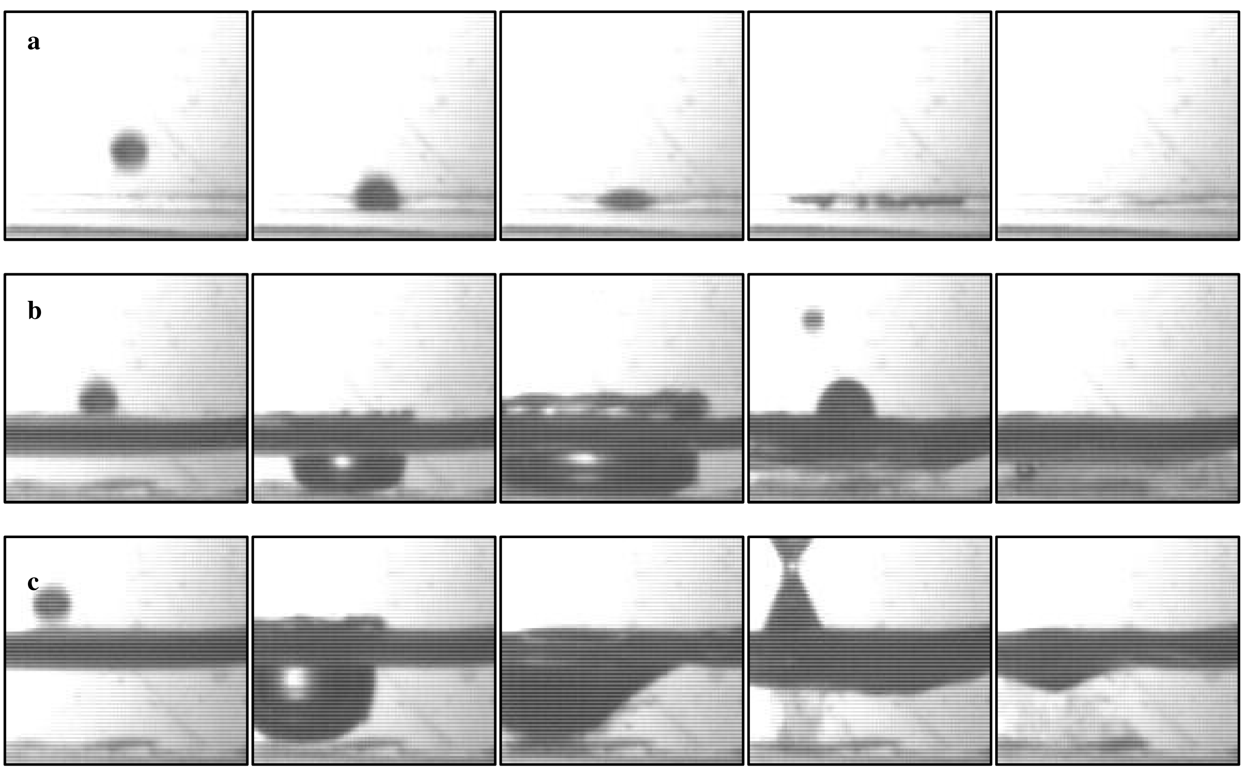

Figure 4: Video of a 2.5 mm diameter, 4 m/s droplet impacting into a **a)** dry surface, **b)** 1.25 mm depth, **c)** 2.5 mm depth.

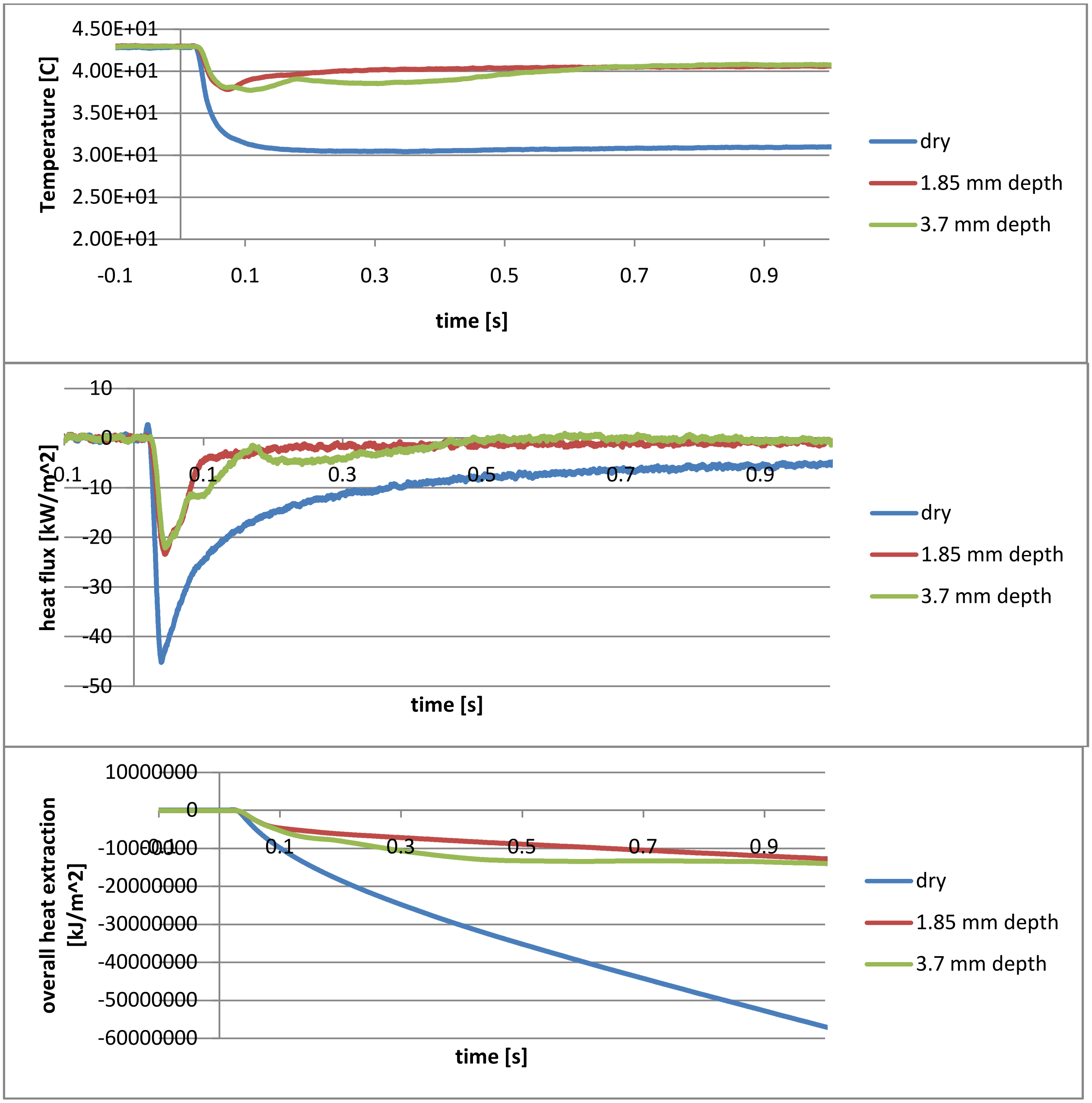

Figure 5: Heat transfer measurements using a 3.7 mm droplet at 2 m/s. Initial pool and substrate surface temperatures were 43 ˚C.

detaches from the pool surface. The secondary impact of the satellite droplet, however, does not overcome the pool surface tension.

Figure 5 shows the results of the heat transfer measurements. It is clear that the dry surface exhibits superior heat transfer. A period of rapid temperature decrease is observable where the initial temperature gradient and convective effects of the impacting and deforming droplet are high. This is followed by a pseudo-steady region in which the surface remains at the droplet temperature and conductive heat transfer is likely dominant. With the introduction of the pools, temperature decrease, heat flux, and overall heat extraction are all reduced significantly. However, it is interesting to note that for the case of the pools depth equivalent to the droplet diameter, maximum heat flux remains nearly identical to the shallow pool and overall heat extraction is actually higher. This may be attributable to the convective effects previously observed that were not evident in the shallow pool. The authors hypothesize that eddy formation does not occur in the shallow pool because the upper boundary of the pool prevents circulation of the liquid. The influence of pool depth, therefore, is a balance between reduction in droplet penetration and enhancement of convective effects.

Conclusions

Thermo-fluid phenomena of single droplets impacting into heated shallow pools, with depths on the order of the droplet diameter were studied for which little to no information exists. It was found that only a fraction of the droplet penetrations an remains within the liquid pool following crater formation. The remaining liquid appears to stay at the pools surface. Convective effects were observable in the deeper pools that enhanced heat transfer from the bottom surface. The study may lead to adjustments in droplet characteristics, impact timing and spacing to improve heat transfer in cooling applications.

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