BRIEF COMMUNICATIONS

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The influence of liquid pool temperature on the critical impact Weber number for splashing

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An experimental study is presented to determine the influence of liquid pool temperature on splashing behavior. Water droplets with initial diameter of 3.1 mm $\pm$0.1 mm impacted a water pool 40 mm in depth. The impaction process was recorded using a high-speed digital camera at 1000 frames/s. The impinging droplet was fixed at room temperature and the liquid surface was heated using a hotplate. To determine the critical Weber number for splashing, the impact velocity was varied. The critical impact Weber number for splashing was found to be dependent on liquid pool temperature, decreasing with an increase in liquid temperature. [DOI: 10.1063/1.1526696]

Liquid droplet interaction with a surface has been studied for more than 100 years.[1,2] Practical applications of a droplet colliding with a surface include spray cooling of turbine blades, electronic devices, and internal combustion engines. An important distinction made for liquid droplet/surface interaction is the type of impacted surface. The target surface can be either a solid or a liquid surface. Depending upon the type of surface, the collision dynamics of the impinging droplet can be vastly different.[3]

For deep pools, the impact of a liquid droplet with a liquid surface can result in droplet floating, bouncing, coalescing, and splashing on the liquid surface. Rodriguez and Mesler[4] delineated the processes of coalescence and splashing for water droplets impacting upon a water pool. Impacts that resulted in the formation of jets were termed splashes and drops causing formation of vortex rings were defined as coalescing drops.[4] They generated a regime map dependent on the Froude number, $\mathrm{Fr}=V/(g/D)^{1/2}$, and Reynolds number, $\mathrm{Re}=DV\rho/\mu$, where g is the gravitational acceleration, V is the droplet impact velocity, D is the droplet diameter, ρ is liquid density, and μ the liquid viscosity. For a Reynolds number larger than 3000 and for a Froude number between 6 and 18, impact of a water droplet with a water pool will result in a splash.

Hsaio *et al.*[5] postulated that a critical We number may exist that separates vortex formation from splashing. In their experiments, the impact We number was defined as the ratio of the surface energy time scale to the convective time scale, $\mathrm{We}=V(\rho D/\sigma)^{1/2}$. Data obtained from their experiments were plotted in conjunction with data from the experiments of Chapman and Critchlow,[6] Rodriguez and Mesler,[4] and Thompson and Newell.[7] To test their hypothesis, experiments were performed with mercury droplets impacting upon a mercury pool. It was reported that when plotting the We number as a function of Fr number, a critical We number ≈ 8 was observed to delineate vortex formation from splashing. The critical We number was observed to be independent of Fr number.

Rein[8] extended the work of Rodriguez and Mesler[4] by investigating the transition regime for coalescing and splashing water droplets on a deep water pool. The impact We number was found to be the main parameter influencing the transition from coalescing to splashing. The Fr number was found to influence transition, but to a lesser degree than the We number. He observed that below a critical We number, coalescence of the impinging droplet resulted. As the We number was increased, a jet was observed to rise above the free surface.

To the authors' knowledge, no investigation has considered the influence of liquid pool temperature on splashing behavior. All previous work is predicted upon water droplets impacting upon a liquid pool at room temperature. The motivation for the present study was to examine droplet impingement on a heated liquid pool. Heating the liquid pool was imperative since the goal of the authors is to study droplet dynamics with a burning liquid surface from a fire suppression perspective. Under these conditions, the liquid pool temperature at the surface is near the boiling point of the

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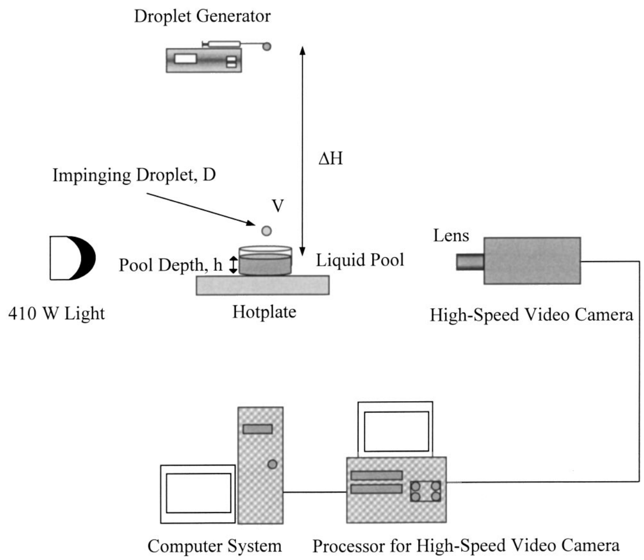

FIG. 1. Schematic of experimental setup.

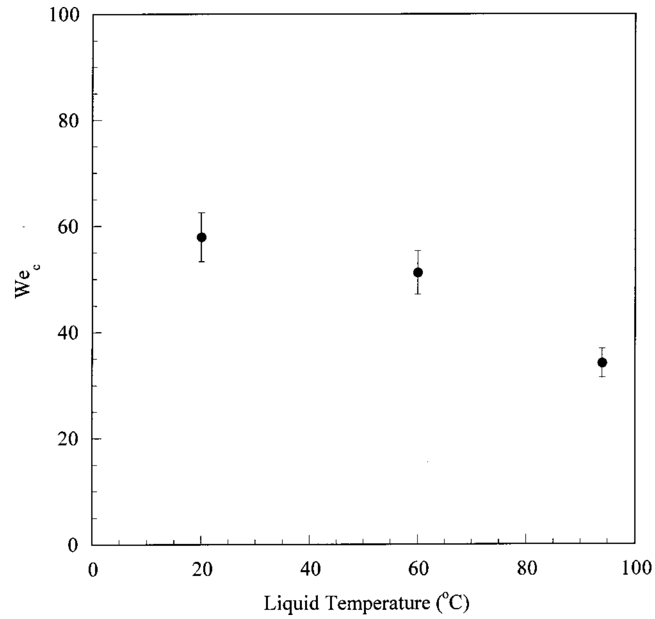

FIG. 2. Critical impact We number for splashing as a function of surface temperature.

fluid. Such high temperatures may result in differences in the critical impact We number for splashing.

Figure 1 is a schematic of the experimental setup. The water droplets were generated using a syringe pump which was programmed to dispense the liquid at a rate of 0.001 ml/s. The droplet was formed at the tip of the needle and detached off the syringe under its own weight. To vary the droplet impact velocity, the height of the syringe pump above the liquid pool was varied (see Fig. 1). The container used to hold the liquid pool was a glass cylinder, 125 mm in diameter. Since the droplet size for all experiments was fixed at 3.1 mm $\pm$0.1 mm (mean$\pm$standard deviation), the diameter of the pool was 40 times larger than the initial droplet size, thus wall effects are not deemed important in the present study. In addition, the depth of the liquid pool was fixed at 40 mm. Such a depth was required to ensure the pool was deep (i.e., no influence of depth on collision dynamics).

A detailed discussion about the imaging system used for droplet impingement can be found in Manzello and Yang.[9] Distilled water was used to fill the syringe fitted in the syringe pump for droplet generation and to fill the liquid pool. To heat the liquid, a commercial hotplate was used. The hotplate was switched on and the temperature was monitored inside the liquid pool at various locations using a fast response thermocouple. It was observed that the temperature varied by at most 2 °C$\pm$1 °C from the bottom to the top of the liquid pool. This resulted in a temperature gradient within the liquid pool of 0.05 °C/mm.

Several experiments were performed at each droplet impact velocity. The collision dynamics were repeatable for each case. Since each experiment displayed the same qualitative trends, results of three consecutive experiments were used for data analysis. Figure 2 displays the critical impact We number for splashing as a function of liquid surface temperature. The impact We number in this study was defined as $\mathrm{We}=\rho V^2 D/\sigma$, where σ is the droplet liquid surface tension. The surface tension and density used in forming the We number in this study were based on properties of the impacting droplet. The droplet properties were taken at 20 °C. If the surface tension of the hot pool liquid were used, the critical We number for splashing would increase and the dependence of the critical We number on temperature would be reduced. The error bars in Fig. 2 represent a combined relative standard uncertainty in determining the critical We number of 8%. Splashing was defined as the appearance of a jet rising from the liquid free surface. The critical impact We number for splashing did not decrease significantly as the pool temperature was raised to 60 °C. The most dramatic reduction occurred at 94 °C. At 20 °C, the critical We number for splashing was 57. This corresponded to a Fr number of 44. These values compared favorably to the critical We number ($\approx$60) for splashing obtained in the literature for impact at 20 °C.[8]

In an attempt to understand the mechanism for the difference in the critical We number for splashing with increasing temperature, it is imperative to consider the physics of splashing. It is known that, for splashing, as the droplet impacts the liquid surface, a crater is formed. The crater ultimately reaches a maximum depth and fluid begins to flow radially inward to fill the crater. As fluid begins to flow into the crater, the bottom-most point of the crater remains fixed.[8] After this, a column of liquid begins to rise up from the bottom of the cavity. A jet is formed at the bottom of the crater and propelled toward the free surface as the bottom of the crater rises.

It was speculated that differences in crater dynamics may be responsible for the difference in the critical We number for splashing. To test this hypothesis, experiments were performed at fixed impact energy (fixed We number) while the temperature of the pool was varied. The impact We number considered was within the splashing regime for all liquid pool temperatures. Under these conditions, the maximum depth of the crater was measured as a function of temperature and is shown in Fig. 3. At each temperature, the mean maximum crater depth is displayed with the error bars rep-

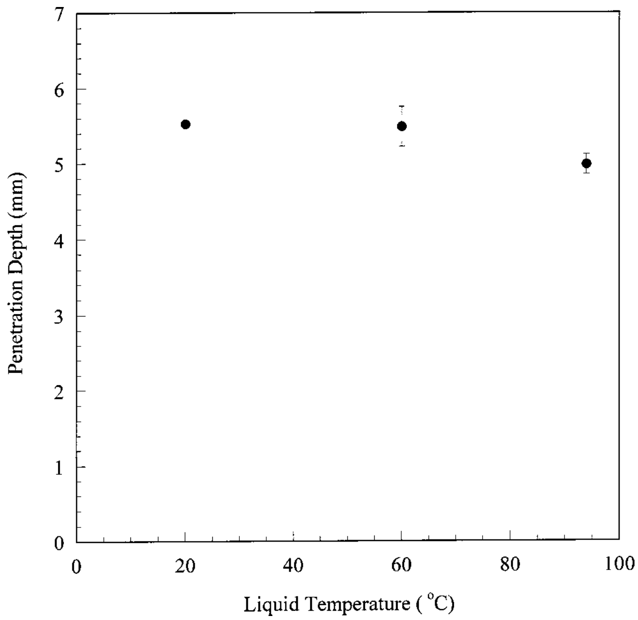

FIG. 3. Maximum penetration depth as a function of temperature.

resenting the standard deviation. For fixed impact energy, the maximum crater depth did not decrease significantly as the liquid pool temperature was increased to 60 °C. The most significant decrease occurred at the highest temperature considered, 94 °C. It is interesting to note that the greatest variance in critical impact We number for splashing occurred at 94 °C as well.

Differences in the penetration depth are believed to be due to convective flow within the liquid pool at high temperature. It is known that when heating a pool of liquid from the bottom, a convective flow is present.[10,11] Rayleigh[12] considered the case where both the top and bottom surfaces were isothermal and free. Based on the analysis, he concluded that a viscous fluid may be stable up to a certain point. The region of stable and unstable fluid was delineated by the nondimensional Rayleigh number:

$$\mathrm{Ra}_h = \frac{g\beta h^3 \Delta T}{\nu\alpha}, \tag{1}$$

where β is the volume expansion coefficient at constant pressure, h the depth of the pool, ΔT the temperature difference between the bottom and top surface, ν the liquid kinematic viscosity, and α the liquid thermal diffusivity. The critical Rayleigh number for the inception of convection in a pool of infinite horizontal expanse with a free surface is 1100.[13] Calculations have been made for a pool of finite horizontal dimension but the difference in critical Rayleigh number is not substantial based on the geometry employed in the present experiments.[13]

The Rayleigh number was calculated for the present experiments. At higher temperatures, the critical Rayleigh number was exceeded, suggesting convective motion was present. In order to visualize convective motion within the pool, aluminum powder was added. The addition of aluminum powder is a standard method for convection visualization.[13] From these experiments, convection is indeed occurring within the liquid at 94 °C. It is speculated that the difference in the penetration depth, and consequently the critical We number for splashing with temperature, may be related to internal motion in the fluid due to convection. With convection present, a greater degree of mixing is occurring within the heated liquid pool compared to a liquid pool at room temperature. Enhanced mixing dissipates more of the impact energy contained in the droplet that is ultimately used to form the crater. This may be the reason for the reduction in penetration depth with temperature.

Engel[14] derived an expression for the work required to lift the liquid crater up to the liquid free surface. She found that the work required scaled as the depth of the crater to the fourth power:

$$W = \pi g \rho \int_0^R (R^2 - r^2) r \; dr = \frac{\pi g \rho R^4}{4}, \tag{2}$$

where R is the maximum crater depth, and r is radial position. In the analysis, the crater was assumed to be hemispherical, as evidenced by integration over a hemisphere.[14] A conjecture for the difference in splashing behavior may be related to differences in the maximum crater depth as the temperature is increased (see Fig. 3). The impact of the droplet into the pool results in a depression of the pool liquid, namely the energy of the impinging droplet is used in order to form a crater. The total impact energy can be written as

$$E_{\mathrm{total}} = E_{\mathrm{crater}} + E_{\mathrm{dissipated}}, \tag{3}$$

where E_{total} represents the total initial impact energy, E_{crater} is the energy used in forming the crater, and $E_{\mathrm{dissipated}}$ is the energy dissipated during impact. With the total energy fixed, at higher temperature, more of the initial impact energy is dissipated, resulting in less available energy for crater formation, reducing the penetration depth (Fig. 3). With a reduction in the penetration depth of the crater, the work required to raise the crater to the free surface is less since it scales as the penetration depth to the fourth power.[14] This suggests that, for fixed impact energy, less work is needed to raise the crater to the free surface and have splashing at high liquid pool temperatures. Consequently, this may be the reason for the reduction in the critical impact We number, for splashing as the liquid pool temperature is increased.

The purpose of these experiments was to determine the critical impact We number for splashing. While the degree of convection in a liquid pool heated from below is a combination of buoyancy drive convection and surface tension drive convection,[15] it is assumed that most of the convection present in these experiments is buoyancy drive.[16] Methods that can be used to reduce buoyancy drive convection are to reduce the depth of the liquid pool, or reduce the temperature difference across the pool. To determine the critical impact We number for splashing, the liquid pool depth must be sufficiently deep in order to circumvent the influence of the pool depth on collision dynamics. It is known that for shallow pools, the crater interacts with the bottom of the container, greatly complicating the dynamics.[9,17,18] Since the pool must be deep, this leaves reducing the temperature difference across the pool to reduce the Rayleigh number. Reduction of temperature difference across a deep liquid pool is difficult.

In pool fires, the liquid pool is heated from above in the form of radiative feedback from the flame. In this work, heating the liquid from above was not selected due to the severe difficulty in doing so. Additionally, one might think that if the pool was heated from above, convection can be mitigated. While buoyancy induced convection is mitigated, Block[19] observed that if the pool is cooled from below, analogous to heating from above, cells are observed due to surface tension driven convection. Thus, convection within the pool is expected to occur in pool fires even though the presence of flame heats the pool from above. Therefore, attempting to mitigate convection was difficult and to be representative of an actual pool fire, convection mitigation is, in fact, unrealistic.

The present results suggest that, for droplets impacting on a burning pool fire, splashing may occur at lower impact We number than droplets impacting a pool at room temperature. This, in turn may influence the dynamics of the fire.

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