

On the collision dynamics of a water droplet containing an additive on a heated solid surface

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An experimental study is presented for water-droplet impingement containing an additive upon a heated stainless-steel surface. A solution of 30% (mass fraction) sodium acetate trihydrate, $CH_3COONa3H_2O$, was used for the experiments. The impaction process was recorded using a high-speed digital camera at 1000 frames per second. The initial droplet diameter was fixed at 2.7 ± 0.1 mm and all experiments were performed in atmospheric air. Three different impact Weber numbers were considered, namely 15, 80 and 181. The droplet-evaporation lifetime was measured as a function of temperature for 30% (mass fraction) sodium acetate trihydrate. Collision dynamics were investigated for each impact Weber number, with the temperature of the stainless-steel surface varied from film evaporation to film boiling. The temporal variation of the liquid-film diameter was measured as a function of temperature for each impact Weber number. Experiments were also performed using water for direct comparison of the collision dynamics with the additive-containing droplets. The collision dynamics were observed to be different for water droplets containing an additive at low impact Weber number, but became increasingly similar as the impact Weber number was increased.

Keywords: droplet; impact; heated surface

1. Introduction

Due to the ban on Halon 1301 under the Montréal Protocol, new liquid fire suppressants have been proposed as possible alternatives to Halon 1301 in certain fires (King *et al.* 1997). Typically, these new liquid fire suppressants are delivered to the fires in the form of droplets. Downie *et al.* (1995) have reported that, in the case of water-mist fire-suppression systems, a large fraction of the water droplets does not penetrate the fire, since the droplet momentum is so small that the droplets can be directed away from the rising fire plume. King *et al.* (1997) suggest that these deflected droplets impinge upon heated surfaces near the fire and ultimately evaporate. These droplets can still act to suppress the fire, since evaporating droplets provide surface cooling of nearby heated surfaces and the vapour from these evaporating droplets may ultimately be entrained into the fire, leading to extinguishment. Therefore, understanding droplet impingement upon heated surfaces can have implications upon fire suppression.

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Under practical conditions, the dispersion of the liquid agent results in the generation of numerous droplets that can be difficult to study systematically. Therefore, a simpler approach can be adopted to understand the influence of droplet impingement on a heated surface. One such approach is the study of single-droplet impingement upon heated surfaces.

Liquid droplet interactions with a surface have been studied for more than 100 years (Reynolds 1875, 1881). The characteristics of the droplet–surface interactions depend on the properties of the droplet, the impacted surface, impact velocity, geometry and the medium (liquid, gas, dispersion) through which the droplet traverses prior to impact (Rein 1993). Despite many investigations (Engel 1955; Wachters & Westerling 1966; Bowden & Field 1964; Lesser 1981; Al-Durrah & Bradford 1982; Avedisian & Koplik 1987; Chandra & Avedisian 1991, 1992; Ko & Chung 1996; Bola & Chandra 1999; Aziz & Chandra 2000; Kang & Lee 2000; Manzello & Yang 2002), the complicated fluid-mechanical processes associated with liquid-droplet–surface interaction are not yet well understood.

The impact of a liquid droplet with a solid surface can result in droplet spread, splash or rebound (Rein 1993). Whether a droplet will spread, splash or rebound is dependent upon the impact energy, surface temperature and surface roughness (Bernardin *et al.* 1997*a*; Chandra & Avedisian 1991; Wachters & Westerling 1966). The parameter used to quantify the impact energy is the droplet Weber number (Rein 1993). The Weber number is defined **as** We = $\rho V^2 D / \sigma$, where *p* is the liquid density, *V* is the impact velocity of the droplet, *D* is the initial droplet diameter and σ is the liquid surface tension.

The heating of the solid surface can influence the droplet-collision process as well (Chandra & Avedisian 1991). Understanding the influence of surface temperature on droplet-collision dynamics for a particular fluid requires the mapping of various boiling regimes. The droplet-evaporation lifetime as a function of surface temperature can be used to delineate different heat-transfer regimes, thus providing a mechanism to better understand the influence of surface temperature on droplet-collision dynamics (Tamura & Tanasawa 1959). For a droplet gently deposited on a surface, the total droplet-evaporation lifetime will decrease with increasing surface temperature until a minimum evaporation time is obtained. The minimum evaporation time marks the departure from nucleate boiling. After the minimum evaporation time is reached, the total evaporation lifetime of the droplet will begin to rise with surface temperature. The Leidenfrost temperature occurs where the total evaporation lifetime of the droplet reaches a local maximum. For temperatures greater than the Leidenfrost temperature (film boiling), the droplet-evaporation lifetime will monotonically decrease with further increases in surface temperature.

While a variety of fluids has been considered for droplet impact on heated surfaces (i.e. various hydrocarbons, emulsified hydrocarbons, surfactants), experimental investigations that have employed water as the fluid are reviewed here, since waterbased studies are most relevant to fire-suppression applications.

Engel (1955) considered collision of water droplets on a glass surface maintained at 20 °C. Water droplets were allowed to fall a distance of up to $\boldsymbol{6}$ m. A schlieren photography system and a high-speed camera were used to image the collision dynamics. In addition, a chemical tracing method was used to 'trace' the radial flow of the water droplet after collision with the glass surface. In this method, a crystal of sodium dichromate was injected into the bottom of the droplet prior to impact.

The droplet impacted on a glass surface lined with filter paper wetted with acetified starch and potassium iodide. The influence of surface roughness on droplet collision was investigated by using a variety of surfaces, namely, rubber, iron and fine sand. An equation was developed that determined the liquid-film radius from the time 'after the head of the drop vanished' until the time of maximum liquid-film radius.

Wachters & Westerling (1966) investigated water-droplet impact on a heated surface. In these experiments, the water droplet sizes were fixed at *ca.* 2 mm and a polished gold surface maintained at 400 °C was used. Three distinct regions were identified, each a function of the impact Weber number. For an impact Weber number greater than 80, the droplet was observed to form a thin, spreading liquid film upon impact. This film ultimately disintegrated into many tiny droplets. With an impact Weber number between 30 and 80, the droplet was never observed to disintegrate upon impact. Rather, the droplet disintegrated after it was observed to rise above the surface. When the impact Weber number was reduced to below 30, the droplet impacted on the surface and subsequently lifted *aff* the surface after impact without break-up.

Gottfried et *al.* (1966) deposited water droplets of 1.5-2.0mm in diameter on a heated surface. The Leidenfrost temperature for water was found to be dependent on the type of impacted surface and varied from 150 to 210 "C above saturation. The Leidenfrost point for water was observed to be independent of droplet size. Xiong & Yuen (1991) extended the work of Gottfried et *al.* (1966) to incorporate impact of droplets with very small initial diameter (down to 0.068 mm) on a heated surface. The Leidenfrost temperature was found to be essentially independent of droplet size for water and varied from 180 to 210 "C above saturation. It must be mentioned that both Gottfried et *al.* (1966) and Xiong & Yuen (1991) considered a plethora of hydrocarbons in addition to water impact.

Makino & Michiyoshi (1984) performed a water-droplet-impact study using four different impact surfaces, namely, copper, brass, carbon steel and stainless steel. The initial diameter was varied from 2.54 to 4.50 mm and the surface temperature was varied from 80 to 450 "C. For all experiments, the impact velocity was low, since the authors state the droplet was deposited 'softly' on the surface. The contact period, defined as the time the droplet was in contact with the surface, was measured using three methods. The first method made use of a nickel-wire probe inside the syringe used for droplet deployment. This probe was fixed at a distance of 0.1 mm above the surface. When a droplet touched the tip of the probe and the surface, a circuit was closed and the change in the voltage was measured. The duration of the voltage change was defined as the contact period. The second method used was to measure the contact period directly from visible inspection of the high-speed-film footage. Finally, the third method monitored the surface temperature during droplet impact, using a thermocouple embedded within the surface. Data collected using these three methods were plotted and a correlation for the contact period was obtained for all surfaces. Additional correlations were obtained for the waiting period and change in the base radius of the droplet. The waiting period was defined as the time before boiling occurred.

Inada & Yang (1993) delineated the mechanics of a phenomenon termed 'miniaturization' of water droplets on a heated surface. Miniaturization was defined as the expulsion of minute droplets from the surface of the droplet after deposition on the heated surface. Water droplets were allowed to impact on a heated platinum

surface and measurements of the frequency and amplitude of elastic-longitudinal waves produced from boiling were monitored. Measurements of the acoustic pressure of the boiling droplets were also made, using a microphone. Surface temperatures within the transition-boiling regime resulted in maximum magnitude and frequency of elastic-longitudinal waves and largest acoustic pressure. Inada & Yang (1993) reported that miniaturization was strongest within the transition-boiling regime but 'miniaturization' was also observed slightly below the transition-boiling regime.

Bernardin *et al.* (1997*a*) performed a comprehensive study of water-droplet impingement on a heated aluminium surface. The impinging droplet diameter was fixed at 3.0 mm and the impact velocity was subsequently varied from 0.70 to 2.34 m s⁻¹. This resulted in impact Weber numbers of 20–220. The temperature of the heated surface was also varied from 100 to 280 "C. The impact dynamics were imaged using high-speed photography at 1000 frames per second in conjunction with single-flash photography. Regime maps were generated as a function of temperature for the impact Weber numbers considered. It was observed that the impact Weber number greatly influenced the spreading characteristics and the stability of the droplet upon impact. The liquid-film radius was also measured as a function of temperature and impact velocity and compared with water-droplet impingement correlations in the literature. These correlations provided poor agreement with the measured liquid-film radius. In a subsequent publication, Bernardin *et al.* (1997*b*) considered the influence of surface roughness on water-droplet impact.

Based upon a review of the literature, significant work has been performed for water-droplet impingement on heated surfaces. A dilemma exists for water-droplet studies when viewed from a fire-suppression perspective. Water has a freezing point of 0° C. In many practical fire-suppression systems, the fire suppressant must be stored at temperatures below 0 "C. Such low temperatures may result in the liquid fire suppressant freezing. To prevent water from freezing, additives must be used to lower its freezing point. It has been demonstrated that some salt-containing additives not only reduce the freezing point of water but can also be more effective in suppressing fires than pure water droplets (Finnerty *et al.* 1996). In light of this information, however, few studies have addressed the impingement of water droplets containing additives relevant to fire suppression on heated surfaces.

King *et al.* (1997) studied droplet evaporation on a heated surface using solutions of water-potassium acetate and watersodium iodide. The impact Weber number was fixed at 80 and the surface temperature of the stainless-steel surface was varied from 20 "C *to* a maximum of 100° C, since droplet evaporation was the focus of this study. It was reported that the evaporation rate decreased significantly with increasing salt concentration.

In recent work, Cui *et al.* (2001) considered the impact of droplets containing solutions of 1% (mass fraction) water–sodium carbonate and 1% (mass fraction) water–sodium bicarbonate. The impact Weber number was not specified by the authors, but it was stated that the droplets were allowed to fall a distance of 50 mm. The authors reported that the addition of 1% sodium carbonate and 1% sodium bicarbonate did not alter the surface tension compared with that of pure water. Based on this information, the impact Weber number was estimated to be *ca.* 30. Although the impact velocity was fixed, the surface temperature was varied from 100 to 300 °C. It was reported that, for surface temperatures below the onset of nucleate boiling, addition of sodium carbonate and sodium bicarbonate decreased the evaporation rate com-



Figure 1. Schematic of experimental set-up.

pared with pure water droplets. This finding was in qualitative agreement with the work of King *et al.* (1997). Within the nucleate-boiling regime, droplets containing sodium carbonate and sodium bicarbonate increased the droplet-evaporation rate. Such differences in the evaporation behaviour due to the presence of dissolved salts in water suggest that extrapolating available data for water-droplet impact studies on heated surfaces to those containing additives is not justified.

In this paper, an experimental study of droplet–surface interaction was performed using droplets containing 30% (mass fraction) sodium acetate trihydrate and a heated stainless-steel surface. Sodium acetate trihydrate was selected as the additive in this study, as it has the characteristic properties of salts reported as effective fire suppressants (Finnerty *et al.* 1996). A concentration of 30% sodium acetate trihydrate was selected, since it fell within the range of salt concentrations used by Finnerty *et al.* (1996). The droplet-evaporation lifetime was obtained as a function of surface temperature to delineate various heat-transfer regimes. The collision dynamics were examined within the nucleate-boiling, transition-boiling and film-boiling regimes. In addition, three different droplet impact Weber numbers were considered in conjunction with the variation in surface temperature to map out the collision dynamics. Finally, distilled water droplets were used for direct comparison with those containing additives.

2. Experimental description

Figure 1 is a schematic of the experimental set-up. Both the 30% sodium acetate trihydrate and water droplets were generated using a syringe pump programmed to dispense the liquid at a rate of 0.001 ml s^{-1} . The droplet was formed at the tip

of the needle and detached from the syringe under its own weight. To measure the droplet-evaporation lifetime, droplets were gently placed on a rectangular stainless-steel surface (SS 304), 3 cm wide, 5 cm long and 0.5 cm thick. The stainless-steel surface was polished based upon the recommendations of previous work (Chandra & Avedisian 1991). Sandpaper (600 grit) was first used to polish the surface, with subsequent application of metal polish to create a mirror finish. Surface heating was accomplished using a copper block with two miniature cartridge heaters embedded within it. The surface temperature was measured using a thermocouple embedded within the stainless-steel surface. It must be noted that all temperatures reported in this study correspond to those in the solid. The surface temperature was controlled to within ± 1 "C using a temperature controller. A charge-coupled-device camera (with a framing rate of 30 frames per second) was used to measure the droplet-evaporation time.

Droplet-impingement dynamics were imaged using a Kodak[†] EktaPro 1000 HRC Digital High Speed Camera at 1000 frames per second, with the shutter speed set to 50 μ s. The camera was fitted with a Nikon 60 mm micro-lens to obtain the required spatial resolution to capture droplet impingement. The camera was aligned at an angle $\theta = 33$ " with respect to the horizontal. The light source used for back-lighting was found to be the most important parameter that influenced the image quality of the collision dynamics. If the back-light was too dim, the collision dynamics were barely visible. A very bright back-light resulted in the converse problem: image saturation. A singular 410 W light source (see figure 1) proved to be the best. A ground-glass diffuser was placed in front of the light source to provide more uniform illumination of the stainless-steel surface.

The impact velocity was measured by tracking the location of the droplet centroid 2 ms prior to impact using image-processing software. The initial droplet diameter was determined 2 ms prior to impact. The image-processing software was used to threshold the droplet from the background and the diameter of the droplet was measured in both the horizontal and vertical directions. The difference between the diameter measurements in the vertical and horizontal directions was at most 0.3 mm. The droplet diameter was defined as the average of the two measurements. The computer system was used to store the digital images for subsequent analysis (see figure 1).

Chandra & Avedisian (1991) have used single-shot photography to provide highly temporally resolved pictures of droplet-collision dynamics. In single-shot flash photography, droplet-collision dynamics are constructed from an ensemble of photographs of individual droplets impacting on the surface at different times. In many subsequent publications, the technique was honed to capture droplet impingement, from molten metals to surfactant-laden droplets (Qiao & Chandra 1997; Aziz & Chandra 2000). Their justification for using the single-shot method was predicated on the poor quality of images obtained from high-speed cameras in the past. Using the current set-up, we are able to capture droplet impingement clearly using a digital high-speed camera. An advantage of the high-speed technique is that the same droplet is followed during the impingement process. The temporal resolution of the high-speed photographs, however, is limited to 1ms, the framing rate of the camera.

[†] Certain commercial equipment is identified in this paper in order to accurately describe the experimental procedure. This in no way implies recommendation by NIST.



Figure 2. Measured evaporation lifetime for 30% sodium acetate trihydrate and water as a function of surface temperature.

3. Results and discussion

(a) Droplet evaporation

Figure 2 displays the evaporation lifetime as a function of surface temperature for a **30%** sodium acetate trihydrate droplet with an initial diameter of 2.7 ± 0.1 mm. The evaporation lifetime as a function of surface temperature was obtained by placing the droplet gently on the surface. The droplet-evaporation lifetime was recorded in 10 "C intervals with a reduced interval of 5 °C near the minimum evaporation time and the Leidenfrost point. At each temperature, three sequential experiments were performed and the evaporation time at each temperature represents the average of the three runs, with the error bars representing the standard deviation of the measurements (mean plus or minus standard deviation).

The parameters influencing the uncertainty in determining the temperature for the departure from nucleate boiling and the Leidenfrost point were the dropletevaporation time, measured temperature of the surface and the temperature interval at which the evaporation time was measured (Bernardin & Mudawar 1999). As pointed out by Bernardin & Mudawar (1999), the uncertainty in the dropletevaporation lifetime is greatly reduced by averaging over several experiments. Thus, the measured temperature of the surface and the temperature interval used to obtain the evaporation lifetime are believed to be the dominant factors influencing the measurement uncertainty. With the surface temperature controlled to within 1"C and using a 5°C interval, the uncertainty in determining the Leidenfrost temperature and temperature for departure from nucleate boiling was estimated to be ± 12 "C.

A complication when working with solids dissolved in aqueous solution is the presence of solid residue, formed when attempting to measure the evaporation time (King *et al.* 1997). The total evaporation lifetime was defined in a manner similar

to King *et al.* (1997) as the time the solid residual droplet appeared minus the time the droplet was placed upon the surface.

For surface temperatures less than the boiling point of 30% sodium acetate trihydrate, droplet impact will result in evaporation without boiling. An estimate of the normal boiling point (104 "C) for the 30% sodium acetate trihydrate solution was determined from the literature (Horvath 1985). From figure 2, the minimum evaporation time occurred at 230 "C. Nucleate boiling is expected for surface temperatures from the normal boiling point, 104 "C, up to 230 "C. The Leidenfrost temperature for 30% sodium acetate trihydrate was measured to be 320 "C. Transition boiling will occur from 230 to 320 "C, with film boiling above the Leidenfrost point (320°C).

Results obtained for 30% sodium acetate trihydrate were compared with those of pure water. Figure 2 also displays the measured evaporation lifetime as a function of surface temperature for water droplets with an initial diameter of 2.7 ± 0.1 mm. Qualitatively, the curve is similar to water droplets containing 30% sodium acetate trihydrate. For surface temperatures lower than the normal boiling point of water (100 °C), droplet impact should result in evaporation without boiling. From figure 2, the surface temperature for departure from nucleate boiling was 230 °C. Nucleate boiling is expected for surface temperatures from the boiling point, 100 °C, up to 230 °C. The Leidenfrost temperature for water was 330 °C. This is close to the value (310 °C) obtained by Xiong & Yuen (1991) for impact on a stainless-steel surface.

It is interesting to note that the addition of 30% sodium acetate trihydrate to water resulted in a similar Leidenfrost temperature for both solutions. The surface temperature corresponding to departure from nucleate boiling was same for both fluids as well, namely 230 "C.

For surface temperatures below *ca.* 140 "C, the evaporation lifetime of water droplets was considerably shorter than those containing 30% sodium acetate trihydrate (see figure 2). This result is in qualitative agreement with previous work (King *et al.* 1997; Cui *et al.* 2001). Increased salt concentration results in increased mass-transfer resistance, thus reducing the amount of water released from the droplet (King *et al.* 1997; Cui *et al.* 2001).

(b) Droplet impact dynamics

Figure 3 displays temporally resolved images of 30% sodium acetate trihydrate droplet impingement upon a stainless-steel surface at 20 "C for an impact Weber number of 15. Several experiments were performed at each temperature, with repeatable collision dynamics at each condition. Since each experiment displayed the same qualitative trends, results of three consecutive experiments were used for data analysis. The liquid density for **30%** sodium acetate trihydrate (1158kg m⁻³) was obtained from Söhnel & Novotný (1985). Since the surface tension could not be found for solutions of sodium acetate trihydrate in the literature, the surface tension was directly measured using a CSC Scientific Du Nouy 70535 tensiometer. The value of surface tension obtained for 30% sodium acetate trihydrate was 0.068 ± 0.002 N m⁻¹ (mean plus or minus standard deviation). As seen in figure 3, the droplet was observed to spread after impact with the surface. The spreading of the droplet was a consequence of the high pressure induced after impact. The liquid droplet must stretch radially outward upon impact to relieve this pressure (Chandra & Avedisian 1991).

Impact at the normal boiling point (104 "C) (see figure 3) resulted in few differences compared with impact at 20 "C. The structure of the liquid film was more circular

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Figure 3. Time-elapsed images of 30% sodium acetate trihydrate droplet impingement upon a stainless-steel surface at We = 15.

at $104^{\circ}C$ compared with that at $20^{\circ}C$ and began to contract 10ms after impact. Contraction of the film was due to faster evaporation *at* $104^{\circ}C$ *than at* $20^{\circ}C$.

Collision dynamics at the temperature for departure from nucleate boiling $(230 \,^{\circ}\text{C})$ were unlike those at the normal boiling point (see figure 3). At 5 ms after impact,

fluid was ejected from the liquid film. As time progressed, ejection of fluid from the liquid film became increasingly rapid and a residue of the sodium acetate trihydrate was visible on the stainless-steel surface after 17ms.

Figure 3 shows the droplet impact at the Leidenfrost temperature $(320^{\circ}C)$ of 30% sodium acetate trihydrate. Immediately after impact, the droplet was observed to flatten into a disc. With increasing time, the liquid film began to contract and ultimately lifted off the surface at 24 ms. Experiments were performed into the filmboiling regime (340 "C). The collision dynamics were qualitatively similar in film boiling (340 "C) to those at the Leidenfrost point (320°C) (see figure 3).

Figure 4 displays time-elapsed images of 30% sodium actetate trihydrate droplet impingement at 20 "C for an impact We of 80. At higher impact Weber number, the liquid film appeared thinner than at We = 15. The enhanced thinning of the liquid film was a consequence of higher pressure induced after impact due to higher kinetic energy of the impacting droplet. Figure 4 displays collision at 104 "C for an impact We = 80. As observed at 20 "C, the liquid film was thicker at the normal boiling temperature for the higher We impact.

Impact at departure from nucleate boiling (230 "C) for We = 80 was qualitatively similar to that at the same surface temperature for We = 15 (see figure 4). The residue of sodium acetate trihydrate was more visible at We = 80 than at We = 15. The reason for this was the initial impact resulted in more spreading of the liquid film compared with We = 15. Thus, the diameter of the residue left behind was larger at higher impact We.

The collision dynamics at the Leidenfrost temperature, however, were dissimilar at We = 80 compared with those at We = 15 (see figure 4). At We = 80, the droplet impacted on the surface and spread into a thin disc, with several small droplets distributed along the periphery of the disc. At 5 ms, the inner disc began to disintegrate and was completely shattered at 6 ms. Qualitatively similar behaviour was observed (see figure 4) within the film-boiling regime (340 "C) at We = 80: the liquid disc shattered.

Increasing We resulted in differences in impact behaviour compared with collision at We = 80 and We = 15. For collision with the surface at 20 "C for We = 181, the periphery of the liquid film developed ridges, visible 5 ms after impact (see figure 5). At 104 "C for We = 181 (see figure 5), cellular structures were observed within the centre of the liquid film. Such cellular structures are believed to result from surface temperature gradients within the liquid film **as** a result of heat transfer from the heated surface (Chandra & Avedisian 1991). The reason these structures are observed only at the highest We investigated may be that the liquid film is the thinnest for higher We. A thinner layer of liquid would be able to conduct heat more rapidly (compared with a thicker layer of the same liquid), thus allowing visualization of surface tension gradients within the surface.

The liquid film is less stable at the departure from nucleate boiling (230 "C) at We = 181, compared with We = 15 and We = 80 (see figure 5). At 5 ms after impact, the liquid film has begun to disintegrate. For lower impact velocity (We = 80) at 230 "C, the liquid-film diameter was uniform 5 ms after impact. Increased instability of the liquid film was also observed at the Leidenfrost point and the film-boiling regime (see figure 5) at We = 181.

The evolution of the liquid-film diameter with time is necessary to determine the portion of the surface undergoing surface cooling (Bernardin *et al.* 1997*a*). The

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Figure 4. Time-elapsed images of 30% sodium acetate trihydrate droplet impingement upon a stainless-steel surface at We = 80.

temporal variation of the liquid-film diameter was measured as a function of surface temperature for 30% sodium acetate trihydrate and is shown in figures 6–8 for impact Weber numbers of 15, 80 and 181, respectively. The liquid-film diameter



Figure 5. Time-elapsed images of 30% sodium acetate trihydrate droplet impingement upon a stainless-steel surface at We = 181.

at each impact We was measured for three experiments performed at each surface temperature. The diameter was defined as the average of the three measurements, with the error bars representing the standard deviation. This diameter was measured



Figure 6. Measured liquid-film diameter as a function of time for various temperatures for 30% sodium acetate trihydrate at We = 15.

up to the time of liquid film break-up. For We = 15, the liquid-film diameter was measured up to the time the droplet lifted off the surface.

Figure 6 displays the evolution of liquid-film diameter at We = 15. At *ca.* 1 ms after impact, the liquid-film diameter was essentially independent of surface temperature. As time progressed after impact, the surface temperature that resulted in the greatest film diameter was 170° C, corresponding to the nucleate-boiling regime. After reaching a maximum value of 7 mm at 170 "C, the liquid-film diameter decreased. For surface temperature equal to the Leidenfrost temperature (320 "C), the liquidfilm diameter increased rapidly and decreased monotonically with time. The reason for this was simply that the droplet spread, began to recoil and ultimately lifted off the surface (see figure 3). When the droplet lifts off the surface, the liquid-film diameter can no longer be defined. The evolution of the liquid-film diameter with time within the film-boiling regime (340 "C) was qualitatively similar to the evolution at the Leidenfrost temperature (320 "C). A slight difference was that the droplet lifted off the surface at 21 ms after impact within the film-boiling regime as opposed to 24 ms at the Leidenfrost temperature.

The influence of increasing We from 15–80 on the evolution of liquid-film diameter can be seen in figure 7. The magnitude of the liquid-film diameter was greater at all surface temperatures at We = 80. This enhanced spreading is **a** direct consequence of the higher impact velocity. Similar to collision at We = 15, a surface temperature of 170 "C resulted in the largest liquid diameter, 10mm. For temperatures between nucleate and film boiling (170–340 °C), the evolution of the liquid-film diameter cannot be measured past 8 ms, since it becomes unstable at these surface temperatures. With increased surface temperature, the liquid-film diameter became increasingly unstable at We = 80. For example, at 170 °C, the liquid film became unstable at



Figure 7. Measured liquid-film diameter as a function of time for various temperatures for 30% sodium acetate trihydrate at We = 80.



Figure 8. Measured liquid-film diameter as a function of time for various temperatures for 30% sodium acetate trihydrate at We = 181

8 ms, whereas instability occurred at 7 ms and 4 ms, for surface temperatures $230 \,^{\circ}C$ and $320 \,^{\circ}C$, respectively.

Figure 8 displays the evolution of liquid-film diameter at We = 181. Further increases in impact velocity resulted in further increases in the magnitude of the

liquid-film diameter. For nucleate boiling $(170 \,{}^{\circ}\text{C})$, the maximum liquid-film diameter measured was 12 mm. Thus, as We was increased from 15 to 181 the magnitude of the liquid-film diameter increased from 7 to 12 mm. Instabilities, similar to those observed at We = 80, were more severe at We = 181. For example, at a surface temperature of 320 "C, the liquid-film diameter become unstable 1 ms after impact at We = 181.

The increased instability with an increase in impact We is believed to be due to increasing kinetic energy as the impact We is increased. The measurements of the liquid-film diameter as a function of impact We confirm that the liquid-film diameter increases with attendant increases in impact velocity. Thus, from conservation of mass, the liquid-film diameter must be thinner at higher impact We (for a fixed droplet size). As speculated earlier, with a thinner surface of liquid in contact with the heated surface, conduction of heat into the liquid film should be faster at higher impact We. Increased heat transfer into the liquid results in vigorous boiling, which is responsible for the ultimate disintegration of the liquid film.

Comparing the impact of water droplets with those containing additives required matching the impact Weber number in addition to the boiling regimes. Matching the Weber number exactly is difficult, since it is obtained from statistical averages of droplet diameter and impact velocity. The Weber numbers for water impact were equal to 14, 74 and 171. These values are based on properties evaluated at 20 "C. The relative standard uncertainty in determining the Weber number was $\pm 8\%$. Therefore, within experimental uncertainty, the Weber numbers for water-droplet impact may be considered to be similar to those measured for 30% sodium acetate trihydrate droplets.

Figure 9 displays water impact at We = 14 for surface temperatures of 20, 104, 230, 330 and 350 "C, respectively. The collision dynamics were qualitatively similar to 30% sodium acetate trihydrate for surface temperatures of 20, 104 and 230 "C. For surface temperatures of 330 "C (Leidenfrost point) and 350 "C (film boiling), however, dramatic differences were observed. As displayed in figure 9, at 4 ms after impact a protrusion was observed on the surface of the liquid film. This protrusion of fluid extended upward and the film ultimately disintegrated into many satellite droplets 5 ms after impact. Similar behaviour was observed within the film-boiling regime $(350 \,^{\circ}\text{C})$ for water impact, albeit with a higher protrusion of fluid rising from the surface. A conjecture for the difference between the collision dynamics of water droplets and those containing 30% sodium acetate trihydrate may be related to the residue left behind by droplets containing the additive. The sodium acetate trihydrate residue may act as a barrier to heat transfer from the stainless-steel surface to the liquid film compared with water impact with no residue present. Since the ability of the liquid film to be able to re-group and recoil is thought to be related to surface tension forces (Bernardin et al. 1997a), reduction in heat transfer for the additivecontaining droplet would result in greater surface tension forces for the 30% sodium acetate trihydrate droplet compared with the water droplet.

Bernardin et al. (1997*a*) reported that water droplets impacted, recoiled and levitated (i.e. break-up was not observed) above the surface for impact *We* of 20 and a surface temperature of 280 "C. In their experiments, 280 "C corresponded to filmboiling conditions, since they performed experiments using a heated aluminium surface. For water, the Leidenfrost point (hence temperatures for film boiling) is known to be a strong function of the material of the impacted surface (Gottfried et *al*.



Figure 9. Time-elapsed images of water-droplet impingement upon a stainless-steel surface at We = 14.

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Figure 10. Time-elapsed images of water-droplet impingement upon a stainless-steel surface maintained at $350 \,^{\circ}$ C for We = 3.

1966; Bernardin & Mudawar 1999). The Leidenfrost temperature generally increases as the thermal diffusivity of the surface decreases (Gottfried *et al.* 1966). Differences between the present experiments and those of Bernardin *et al.* (1997*a*) may be explained in a similar manner to differences between the 30% sodium acetate trihydrate droplets and water droplets. The higher surface temperatures needed for film boiling on a stainless-steel surface result in greater reduction of surface tension forces; thus, this may be the reason why distilled-water droplets break up on stainless-steel surfaces in film boiling for impact W e = 14 and no break-up is observed for similar droplets on heated aluminium surfaces. Figure 10 displays water-droplet impact for a surface temperature of 350 "C at W e = 3. The droplet spread, recoiled and lifted off the surface. Consequently, with attendant reductions in impact W e (increased surface tension forces), the collision dynamics were able to be matched to experiments of Bernardin *et al.* (1997*a*) and those of the 30% sodium acetate trihydrate at W e = 15.

Figure 11 displays water impact at We = 74 for surface temperatures of 20 °C, 100 °C, 230 °C, 330 °C and 350 °C, respectively. The collision dynamics were qualitatively similar to 30% sodium acetate trihydrate at We = 80. Impact at 230 °C resulted in disparities compared with 30% sodium acetate trihydrate. At 3 ms after impact, large satellite droplets began to break away from the periphery of the liquid film. Such behaviour was not observed for droplets containing sodium acetate trihydrate.

The collision dynamics of a water droplet at We = 171 are displayed in figure 12. The stability of the liquid film at the higher surface temperature was reduced with increasing We, similar to impact of the 30% sodium acetate trihydrate droplets. For the surface temperatures considered, the collision dynamics at high We were qualitatively similar to droplets containing the additive.

The 'miniaturization' phenomenon was observed at departure from nucleate boiling (230 "C) for both 30% sodium acetate trihydrate and pure water. The ejection of liquid from the film occurred for both fluids at each impact We considered. Inada & Yang (1993) reported that miniaturization was strongest within the transition-boiling regime but 'miniaturization' was also observed slightly below the transition-boiling regime. Thus, the observations here support their findings, since the departure from nucleate boiling marks the onset of transition boiling.

The temporal variation of liquid-film diameter was measured as a function of We for water and is displayed in figures 13–15. In a manner similar to measurement



Figure 11. Time-elapsed images of water-droplet impingement upon a stainless-steel surface maintained at We = 74.

of 30% sodium acetate trihydrate impact, the liquid-film diameter was measured up to the time of droplet break-up. Figure 13 displays the liquid-film diameter for various surface temperatures at We = 14. The evolution of liquid-film diam-

On the collision dynamics of a water droplet



Figure 12. Time-elapsed images of water-droplet impingement upon a stainless-steel surface maintained at We = 171.

eter for water displayed differences from 30% sodium acetate trihydrate (see figure 6). Impact at 100 °C resulted in the largest liquid-film diameter. At 20 ms after impact, the liquid-film diameter was still greater at 100 °C. For sodium acetate tri-



Figure 13. Measured liquid-film diameter as a function of time for various temperatures for water at We = 14.



Figure 14. Measured liquid-film diameter as a function of time for various temperatures for water at We = 74.

hydrate droplets, at 20 ms after impact, the greatest liquid-film diameter occurred at 20 °C. Additionally, for surface temperatures of 230, 330 and 350 °C, the liquid film became unstable and disintegrated. Thus, the liquid-film diameter could no longer be measured.



Figure 15. Measured liquid-film diameter as a function of time for various temperatures for water at We = 171.

Figure 14 displays the evolution of the liquid-film diameter at We = 74. The magnitude of the liquid-film diameter at all temperatures increases with an increase in impact We, similar to results for the impact of droplets containing the additive. For surface temperatures of 230, 330 and 350 "C, the liquid-film diameter was less stable compared with the **30%** sodium acetate trihydrate droplets under similar conditions. The liquid-film diameter decreased more rapidly at the normal boiling point for pure water compared with droplets containing the additive.

The liquid-film diameter measured at We = 171 is displayed in figure 15. The collision dynamics of the water and 30% sodium acetate trihydrate droplets became increasingly similar with an attendant increase in impact We. For surface temperatures of 230, 330 and 350 °C, and at We = 171, the liquid-film diameter became unstable 1 ms after impact. For water + additive droplet impact, the liquid film became unstable at 4 ms for 230 "C and 1 ms for 320 "C and 340 "C.

As the impact We was increased, the liquid-film diameter became greater, providing more surface area for surface cooling. These experiments confirm that this observation is valid whether sodium acetate trihydrate or pure water is used. This is important in fire-suppression applications, since droplets impinging on surfaces from sprinklers and pressure nozzles are not expected to have low impact We (Bolle & Moureau 1981). Thus, high We impact may provide a greater degree of surface cooling, even with the addition of salt.

A comparison of the evolution of liquid-film diameter with time was made with existing models of droplet spread on a heated surface. At present, no models exist in the literature for 30% sodium acetate trihydrate. Consequently, comparisons were performed for models validated for water impact.

Within the film-boiling regime, Bolle & Moureau (1981) developed a correlation valid for determining the evolution of liquid-film diameter D_f as a function of time.

The equation is given as

$$\frac{D_{\rm f}}{D} = 1.67(3.1\tau - \tau^2),\tag{3.1}$$

where $\tau = t/t^+ = tV/d_0$, t is time and V is impact velocity. This correlation was obtained based on water-droplet impingement and was valid for time, $0.2t^+ \leq t \leq (1.2 - 1.5)t^+$. The physical meaning of the term t^+ corresponds to the time for the dome on top of the liquid film to disappear. The Bolle & Moureau (1981) correlation was validated using water data of Moureau (1978) and Savic (1958). The data of Moureau (1978) and Savic (1958) considered water impingement for $263 \leq We \leq 1500$.

Another correlation suggested to describe droplet spread within the film-boiling regime is that of Shi & Chen (1983). The correlation has the form

$$D_{\rm f}(t) = 1.6V \left[t - \frac{6.8\sigma}{\rho D^3} V^{0.25} t^{2.95} \right] + D, \qquad (3.2)$$

where V is the impact velocity. The empirical correlation suggested by Shi & Chen (1983) was based upon numerical calculations of the transient droplet-spreading process. Shi & Chen (1983) adopted an approximate numerical model to describe the droplet-impingement process. Such an approach was deemed necessary due to the 'extreme difficulty' in solving the multi-dimensional momentum, energy and continuity equations (Shi & Chen 1983). In their approach, a Lagrangian energy analysis was performed that allowed for energy loss due to droplet deformation during impact, with an assumed velocity profile during droplet spread. The shape of the assumed velocity profile was altered based on the type of impact expected (i.e. film evaporation and film-boiling regimes). The impingement process was assumed to consist of two phases. The first phase is where the impinging droplet deforms into a flat disc on the solid surface. The second phase is the ultimate spread of this disc upon the solid surface. Another assumption they made was that, as the impinging droplet deformed, a portion of the kinetic energy was transformed by internal dissipation due to the change in droplet shape. An impact coefficient was defined as the amount of energy loss during deformation. The impact coefficient, however, was based on an empirical fit to data of Toda (1972). Thus, the model of Shi & Chen (1983) may be thought of as being semi-empirical. For further details of the Shi & Chen (1983) model, the interested reader is referred to their work.

Figures 16 and 17 display the measured spread diameter within the film-boiling regime for droplets with additives in conjunction with model predictions. The Bolle & Moureau (1981) correlation consistently over-predicted the final liquid-film diameter. The agreement with the magnitude of the liquid film improved at increased We. In contrast, the semi-empirical correlation of Shi & Chen (1983) under-predicted the liquid-film diameter. In general, better agreement with the experimentally determined liquid-film diameter was obtained with the Shi & Chen (1983) semi-empirical correlation. For example, the change in magnitude of the liquid-film diameter was captured in this semi-empirical correlation. This is mainly due to the fact that the model of Shi & Chen (1983) considers liquid fluid properties. It should be noted that neither Bolle & Moureau (1981) nor Shi & Chen (1983) predict break-up of the liquid film. Rather, the predicted film diameter was calculated up to the maximum film diameter.

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Figure 16. Comparison of the measured liquid-film diameter with model results for film boiling for 30% sodium acetate trihydrate.



Figure 17. Comparison of the measured liquid-film diameter with model results for film boiling for **30%** sodium acetate trihydrate.

Figures 18 and 19 display results of the Bolle & Moureau (1981) and Shi & Chen (1983) correlation for pure water impact at film boiling. For water, poor agreement was realized using both the Bolle & Moureau (1981) and Shi & Chen (1983) correlation. Since these correlations provided poor agreement for water, a fluid that



Figure 18. Comparison of the measured liquid-film diameter with model results for film boiling for water.



they were validated for, it is unreasonable to expect good agreement with additivecontaining droplets. Better agreement may be possible with the Shi & Chen (1983) semi-empirical correlation by judiciously selecting the temperature to evaluate the thermophysical properties. While this may be tractable for pure water, addition of



Figure 20. Comparison of the measured liquid-film diameter with model results within the film-evaporation regime for water.

a salt greatly complicates this matter due to limited thermophysical property data as a function of temperature for various salt additives.

Shi & Chen (1983) have proposed another semi-empirical correlation valid within the film-evaporation regime. The correlation is given as

$$D_{\rm f}(t) = 1.6V \left[t - (10^6 \nu)^{0.1} \frac{4\sigma V^{0.6} t^{2.95}}{\rho D^3} \right] + D, \qquad (3.3)$$

where ν is the kinematic viscosity and the remaining variables are the same as those defined in equation (3.2). The measured and predicted liquid-film diameter for water are plotted in figure 20. The semi-empirical correlation provided good agreement at We = 14. Increased We, however, resulted in poor agreement. Calculations were not performed for 30% sodium acetate trihydrate using the Shi & Chen (1983) correlation within the film-evaporation regime.

Within the film-evaporation regime, expressions are also available in the literature to calculate the maximum liquid-film diameter. The correlation proposed by Kurokawa & Toda (1991) was used to calculate the maximum film diameter for water impact at 20 °C at We = 171. The correlation is

$$\frac{D_{\rm f max}}{D} = 0.96 R e^{0.095} W e^{0.084}, \tag{3.4}$$

where $D_{\rm f\ max}$ is the maximum film diameter and Re the Reynolds number. The Reynolds number was defined as $Re = \rho VD/\mu$, where μ is the dynamic viscosity. The correlation is valid for $150 \le We \le 750$ and $850 \le Re \le 50000$. The correlation was validated based upon water, ethyl alcohol and mercury impact on a glass surface at 20 °C. The calculated maximum film diameter for water impact at We = 171 using this correlation is 9.1 mm. The measured value was 12.3 mm, a difference of 26%.

Such a large difference may be a consequence of the surface, being glass, compared with stainless steel used here.

The Kurabayashi-Yang correlation, given in Yang (1975), also valid within the film-evaporation regime, is

$$\frac{We}{2} = \frac{3}{2} \left(\frac{D_{\rm f}}{D}\right)^2 \left[1 + \frac{3We}{Re} \left(\left(\frac{D_{\rm f}}{D}\right)^2 \ln\left(\frac{D_{\rm f}}{D}\right) - \frac{(D_{\rm f}/D)^2 - 1}{2}\right) \left(\frac{\mu}{\mu_{\rm wall}}\right)^{0.14}\right] - 6, \quad (3.5)$$

where μ_{wall} is the viscosity evaluated at the wall temperature. The Kurabayashi–Yang equation was obtained based on an energy balance between the initial condition and the final, fully spread condition and is valid up to the saturation temperature of pure water. The Kurabayashi–Yang correlation predicts a maximum film diameter for water at 20 "C of 7.5, 10.7 and 12.3mm at We = 14, 74 and 171, respectively. The measured values were 6.2, 9.9 and 12.3mm at We = 14, 74 and 171. Thus, the Kurabayashi–Yang correlation provided good agreement within the film-evaporation regime for water. Calculations were not performed for additive-containing droplets, since the viscosity of the 30% sodium acetate trihydrate solution was not measured. Excellent agreement is also expected, since the maximum film diameter, density and surface tension for 30% sodium acetate trihydrate are similar to water at 20 "C.

The poor agreement overall suggests the limitations of semi-empirical correlations. An empirical correlation could be computed using the present data. However, in light of the above findings, it is of little benefit to do so. It is not surprising that the Kurabayashi–Yang equation provided the best agreement with experimental data. The Kurabayashi–Yang equation predicts the maximum film diameter under simplified, non-boiling conditions. Thus, in attempting to determine the temporal evolution of liquid-film diameter under boiling conditions, a detailed numerical model with experimental validation would be beneficial. Droplet-collision dynamics have been modelled by solving the complete Navier–Stokes equations (Fukai *et al.* 1995; Healy *et al.* 2001). While these models are limited to the film-evaporation regime, it is anticipated that more complicated models, including boiling, will be developed. It is desired that the present data may be used for such future model validation.

4. Conclusions

For surface temperature below *ca.* 140 "C, the evaporation lifetime of water droplets was considerably shorter than those containing 30% sodium acetate trihydrate. This result was in qualitative agreement with previous work (King *et al.* 1997; Cui *et al.* 2001). Increased salt concentration results in increased mass-transfer resistance thus reducing the amount of water released from the droplet (King *et al.* 1997; Cui *et al.* 2001). Addition of 30% sodium acetate trihydrate resulted in the same temperature as water for the departure from nucleate boiling.

The presence of 30% sodium acetate trihydrate influenced the collision dynamics greatly at low impact *We* but, as the impact *We* was increased, the presence of the salt appeared to have less influence. This result suggests that, for high velocity impact, knowing the evolution of the liquid-film diameter for water impact may be sufficient to determine the amount of surface cooling. This is important in fire-suppression applications, since droplets impinging on surfaces from sprinklers and pressure nozzles are not expected to have low impact *We* (Bolle & Moureau 1981). Additionally, high *We* impact may provide a greater degree of surface cooling compared with low

We impact, due to the increase in liquid-film diameter as the impact *We* is increased. This increase in liquid-film diameter with increased impact *We* diameter occurred for both pure water and additive-containing droplets.

Correlations of liquid-film diameter in the film-boiling regime resulted in poor agreement when compared with additive-containing droplets. In fact, film-boiling correlations provided poor agreement when compared with pure water, a fluid for which these correlations were validated. Excellent agreement was realized using the Kurabayashi–Yang equation within the film-evaporation regime for water. This result is discouraging since, for fire-suppression applications, the surface temperature within the proximity of a fire may not be below 100°C. In attempting to determine the temporal evolution of liquid-film diameter under boiling conditions, a detailed numerical model with experimental validation must be devised.

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