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Short communication

On the interaction of a liquid droplet with a pool of hot cooking oil[☆]

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Abstract

An experimental study is presented for distilled water droplets impacting on a heated pool of cooking oil. The impaction process was recorded using a high-speed digital camera at 1000 frames per second. The initial droplet diameter was fixed at 3.1 ± 0.1 mm and all experiments were performed at room temperature (20°C). The impact Weber (*We*) number of the water droplets was fixed at 200. As the water droplet impacted the hot peanut oil pool, it fragmented, and ultimately produced a vapor explosion. Experiments were also performed applying methoxy-nonafluorobutane $C_4F_9OCH_3$ (HFE-7100) to hot peanut oil with similar impact *We* number. Dramatic differences were observed when HFE-7100 droplets were used. At peanut oil temperatures above ≈ 180°C, HFE-7100 droplets did not result in a vapor explosion.

1. Introduction

Cooking fires remain the leading cause of household fires within the United States [1]. Fire statistics collected by the National Fire Protection Association reveal that 30% of residential fires start in the kitchen [1]. Injuries sustained from household cooking fires remain on the rise, 4500 in 1980 and up to 5013 in 1997 [1]. The hazards of cooking fires are not limited to the United States. Fire data complied in the city of Alberta, Canada revealed that from 1988 to 1992, cooking equipment accounted for

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Nomenclature

D	initial droplet diameter
P	pressure
T	temperature
t	time
V	impact velocity
We	Weber number

Greek symbols

ρ	density
σ	surface tension

Subscripts

crit	critical
sl	superheat limit

30% of all fires within the city [2]. It was reported that cooking oil was the culprit in 69% of these cooking equipment fires.

Water is most often used to combat and ultimately suppress fires [3]. The thermal properties of water, in particular, the large latent heat of vaporization, allow it to be an effective agent to extract heat [3]. Yet, application of water to a cooking oil fire is known to be catastrophic. A thorough literature review revealed that studies are available regarding cooking oil fires (e.g. [2,4,5]), yet, no quantitative description was found as to the exact mechanism for the danger in applying water to an oil fire. The explanations that were frequently mentioned were only qualitative in nature, such as "if water, which has a boiling point of 100°C is introduced, it first sinks, then becomes superheated and explodes to steam" [2], and do not provide insight into the exact mechanism for an explosion.

To this end, the collision dynamics of a single water droplet impinging on a high-temperature pool of peanut oil were investigated using a high-speed camera at 1000 frames per second. Single droplet studies have historically been used in an effort to understand more complex spray phenomena [6]. Peanut oil was selected since it is a typical oil used for preparing food in the United States [7]. In addition to water, methoxy-nonafluorobutane $C_4F_9OCH_3$ (HFE-7100) droplets were applied to hot peanut oil. HFE-7100, which is currently being screened as a potential fire suppressant [8], has a normal boiling point of 61°C. Since the normal boiling point of HFE-7100 is considerably lower than water, it was speculated that differences in the collision dynamics would be observed between application of water and HFE-7100 droplets to hot oil.

Although droplet interaction with a liquid surface has been studied in some detail, [9–24] to the authors' knowledge, no study has investigated single droplet impingement on a high-temperature cooking oil pool relevant to fire suppression applications.

2. Experimental description

Fig. 1 is a schematic of the experimental setup. All droplets were generated using a syringe pump programmed to dispense the liquid at a rate of 0.001 ml/s. The droplet was formed at the tip of the needle (22 gauge), and detached from the syringe under its own weight. The temperature of the impinging droplets for each solution was fixed at 20°C. A commercial peanut oil was used for all experiments. The peanut oil was stored in a cylindrical dish, 45 mm in diameter. Such a small diameter container was selected to minimize the amount of hot oil that would be ejected to the surroundings. The depth of the peanut oil pool was maintained at 10 mm for all experiments. The peanut oil was heated by placing the container on a copper block with two miniature cartridge heaters embedded within it. The peanut oil temperature was measured using a thermocouple placed within the oil pool. The temperature was

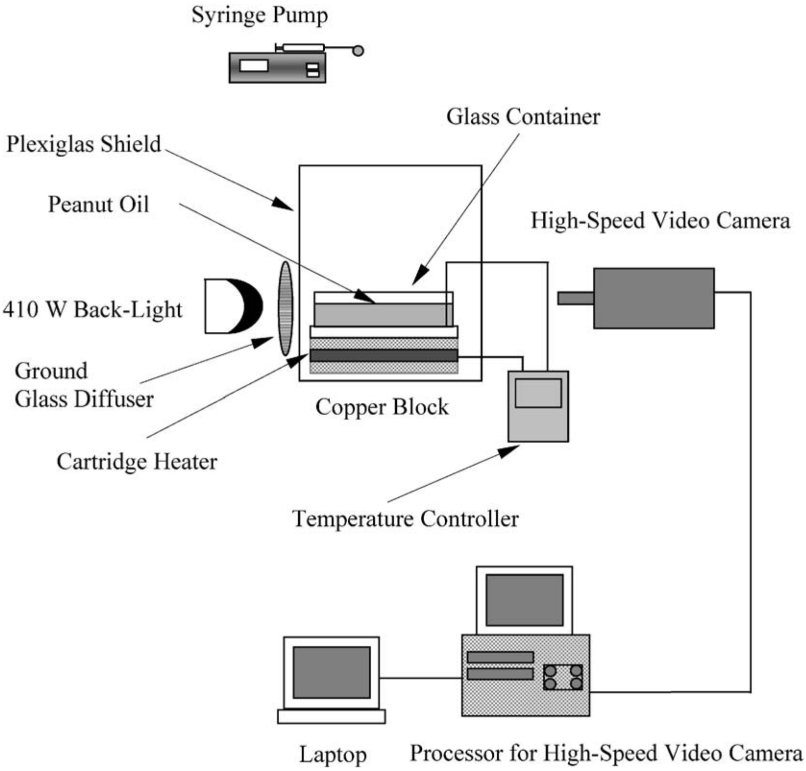

Fig. 1. Schematic of experimental setup showing the droplet generator, peanut oil pool, and digital high-speed imaging system.

controlled within ±1°C using a temperature controller. To mitigate the ejection of hot oil to the ambient, the entire apparatus was encased in a rectangular Plexiglas protective shield with dimensions of 20 × 10 × 10 cm.

Droplet impingement was imaged using a Kodak[1] EktaPro 1000 HRC Digital High-Speed Camera at 1000 frames per second with shutter speed set to 50 μs. The Kodak High-Speed Camera was fitted with a Nikon 60 mm micro-lens to obtain the required spatial resolution to capture droplet impingement. The field of view of the camera was selected to simultaneously monitor both subsurface and surface phenomena that ensued from droplet impact. The entire process was back-lit using one 410 W light source (see Fig. 1). The impact velocity was measured by tracking the location of the droplet centroid 2 ms prior to impact using an image processing software. The initial droplet diameter was determined 2 ms prior to impact. Details of the image processing methodology can be found elsewhere [23].

3. Results

Fig. 2 displays temporally resolved images of distilled water droplet impingement upon a pool of peanut oil maintained at 220°C at an impact *We* number of 200. To simulate the overheating of cooking oil, an oil temperature of 220°C was selected. This is below the smoke point of peanut oil (230°C) [2], but above the typically recommended cooking oil temperature of 190°C for frying. The *We* number, which is the ratio of kinetic energy to surface energy of the impinging droplet, is defined as

$$We = \frac{\rho V^2 D}{\sigma}. \tag{1}$$

The water droplet impacted and formed a hemispherical crater within the oil pool. Similar to other investigations of water droplet impingement on liquid surfaces [20,21,23], the crater ultimately reached a maximum depth and fluid began to flow radially inward to fill the crater. A jet was formed at the bottom of the crater and propelled towards the free surface. After the crater rose to the free surface, it was observed that the parent droplet had fragmented into many satellite water droplets (see Fig. 2, ≈60 ms). The water droplets ultimately sank and remained at the bottom of the oil pool. At ≈560 ms, vapor bubbles appeared within the liquid. Ultimately, at ≈1168 ms after droplet impact, a violent explosion resulted that displaced oil in all directions above the oil pool. Qualitatively similar behavior was observed at lower peanut oil temperatures, albeit the time for the rapid vapor explosion to occur increased with decreasing oil temperature (e.g. $T_{\text{oil}} = 220°\text{C}$, $t_{\text{explosion}} \approx 1168$ ms; $T_{\text{oil}} = 200°\text{C}$, $t_{\text{explosion}} \approx 2100$ ms).

Collision dynamics are displayed in Fig. 3(a) for HFE-7100 droplet impact on a pool of peanut oil maintained at 220°C for an impact *We* number of 188. To simulate similar initial conditions, the impact *We* number for the HFE-7100 droplets

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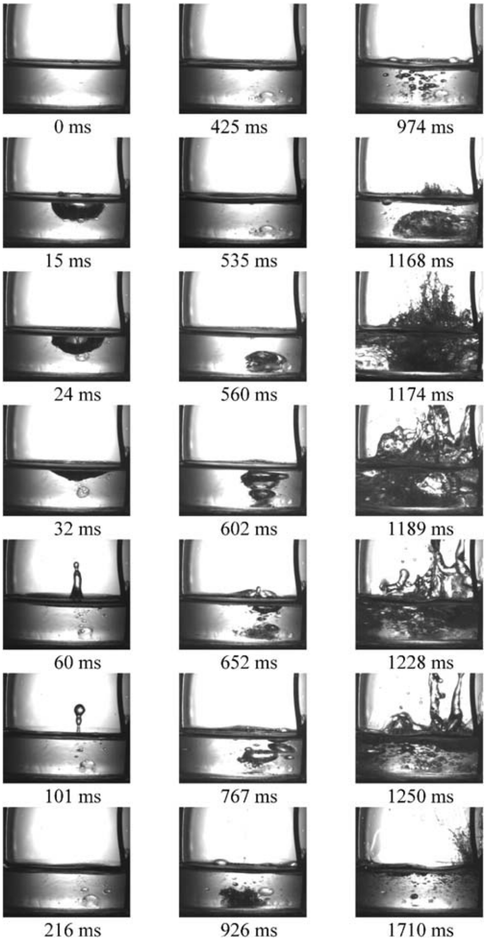
[1] Certain commercial equipments are identified in this paper in order to accurately describe the experimental procedure. This in no way implies recommendation by NIST.



0 ms 425 ms 974 ms

15 ms 535 ms 1168 ms

24 ms 560 ms 1174 ms

32 ms 602 ms 1189 ms

60 ms 652 ms 1228 ms

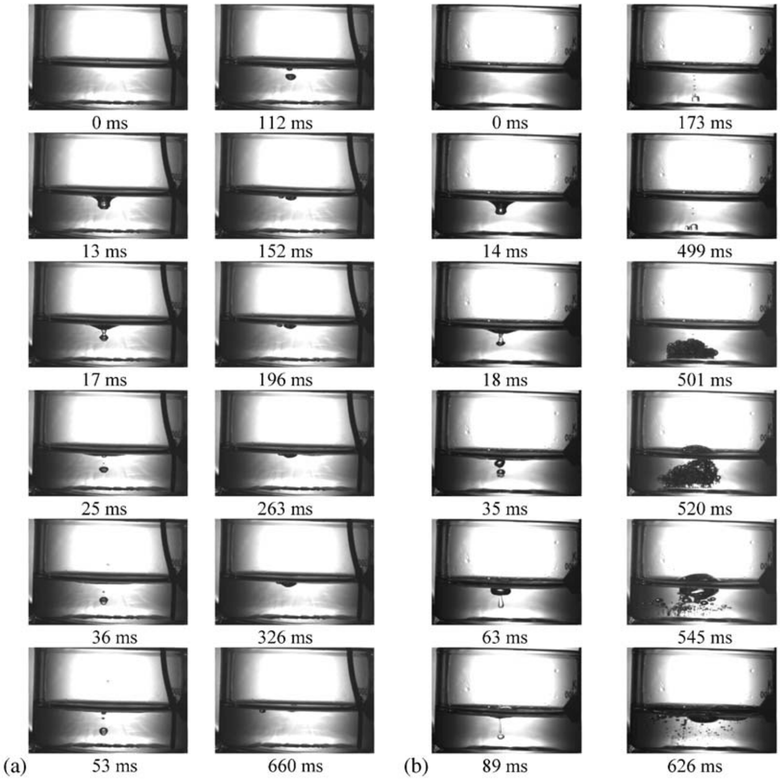
101 ms 767 ms 1250 ms

216 ms 926 ms 1710 ms

Fig. 2. Time elapsed images of distilled water droplet impingement ($We = 200$) on a heated peanut oil pool at 220°C.

was matched to the impact *We* number for the water droplets. Matching the *We* number exactly is difficult since the *We* number is obtained from statistical averages of droplet diameter and impact velocity. The relative standard uncertainty in determining the *We* number was $\pm 8\%$. Within experimental uncertainty, a *We* number of 188 may be considered similar to the *We* number of 200 for water droplet impact.

Similar to water droplet impact at the same oil temperature, a crater was formed within the oil pool after droplet impact. Interestingly, no jet was observed to appear. Yet, the most dramatic difference is that the incipient HFE-7100 droplet did not produce a violent vapor explosion. The HFE-7100 droplet simply impinged upon the hot oil pool and boiled without any violent repercussions.



HFE-7100 Droplet Impact into Peanut Oil 220 °C HFE-7100 Droplet Impact into Peanut Oil 140 °C

Fig. 3. (a) Time elapsed images of HFE-7100 droplet impingement ($We = 188$) on a heated peanut oil pool at 220°C. (b) Time elapsed images of HFE-7100 droplet impingement ($We = 188$) on a heated peanut oil pool at 140°C.

The pool temperature of the peanut oil was lowered in increments of 10°C to see if a vapor explosion would occur for HFE-7100. Application of HFE-7100 droplets to the peanut oil pool above 180°C did not produce a vapor explosion. A vapor explosion resulted for temperatures below 180°C. For illustration, Fig. 3(b) displays HFE-7100 droplet impact at 140°C. Upon impact, a crater formed, and at ≈ 63 ms, the HFE-7100 droplet is seen to descend to the base of the peanut oil pool. The droplet remained at the bottom and an explosive boiling started at ≈ 501 ms.

4. Discussion

When a cold liquid is brought into direct contact with a hot liquid, it is possible that the cooler liquid may vaporize so rapidly that an explosion may occur. These explosions have been termed vapor explosions, explosive boiling, or rapid vapor explosions [25]. For laboratory-scale experiments, such as those reported here, liquid–liquid contact must be present and the hot liquid should be above a minimum temperature, usually the superheat limit of the cold fluid. The following expression may be used to estimate the thermodynamic superheat limit temperature [25]:

$$T_{\mathrm{sl}} = T_{\mathrm{crit}}\left[\left(0.11\frac{P}{P_{\mathrm{crit}}}\right) + 0.89\right]. \tag{2}$$

Under non-explosive conditions, liquid–liquid contact was observed for HFE-7100-peanut oil. The superheat limit temperature at 0.101 MPa was estimated for HFE-7100 to be 146°C using Eq. (2). This suggests that for HFE-7100-peanut oil at 220°C (Fig. 3), the bulk oil temperature was significantly higher than the superheat limit temperature of HFE-7100. In fact, the bulk peanut oil temperature was higher than the critical temperature of HFE-7100, which is 195°C [26]. The absence of an explosion when the bulk peanut oil temperature was significantly higher than the superheat limit temperature of HFE-7100 was in qualitative agreement with rapid vapor explosion experiments [25].

On the contrary, vapor explosions were only observed for HFE-7100-peanut oil and water–peanut oil experiments when liquid–solid contact was present, not liquid–liquid contact. This suggests that rapid vapor explosion literature may not be used to provide insight into the explosive experiments observed in this study. For the HFE-7100-peanut oil experiments, when the oil temperature was reduced, the droplet came to rest on the container surface and ultimately nucleated and exploded. A similar outcome was observed for the water–peanut oil experiments at 220°C. For the water–peanut oil experiments, however, the incipient droplet fragmented upon impact and several droplets were deposited on the container surface.

It is not believed that additional heat was absorbed due to droplet contact with the wall after the droplets came to rest on the bottom of the glass container. Thermocouples were used to monitor the oil temperature and block temperature simultaneously during heating. Both temperatures were the same during the droplet impact experiments. It is believed that the result of the liquid–solid contact upon the surface influenced the nucleation process compared to the HFE-7100-peanut oil experiments at 220°C, where no liquid-surface contact was present.

Indeed, for water–peanut oil experiments, a vapor explosion was observed at a bulk peanut oil temperature of 220°C, well below the measured superheat limit temperature range of water reported in the open literature of 279–302°C [27]. The superheat limit temperature of water used in the present experiments was most likely lower for the following reasons: (1) the water droplets came to rest on the container surface, resulting in liquid–solid contact and it is very difficult to obtain a high degree of superheat when a liquid is in contact with a solid interface [27] (2) water and peanut oil used in these experiments may contain impurities (e.g. dissolved gases) that make it impossible to obtain a high degree of superheat. The homogeneous nucleation temperature of a fluid is known to decrease with increased concentration of dissolved gas [28].

Water is known to be very difficult to superheat to very high temperatures unless it is carefully prepared [29,30]. In the present experiments, such preparation was intentionally not performed. The purpose of these experiments was to use water and peanut oil similar to those that would be found in the home (distilled water was used in these experiments simply for consistency). For home use, and many fire fighting applications, water would not be de-gassed and prepared in such a manner used to determine the superheat limit temperature. Accordingly, the water and the peanut oil used in these experiments may contain impurities that make it impossible to obtain a high degree of superheat.

Prior to the violent explosion in the water–peanut oil experiments at 220°C, small, less chaotic vapor explosions occurred. As the parent water droplet impacted the peanut oil pool, it fragmented and many small water droplets were formed. Close inspection of the images revealed that the cause of the violent vapor explosion was the nucleation of the large water droplet at the bottom of the oil pool. The large water droplet nucleated, produced many small water droplets that were propelled towards the surface, and these small water droplets subsequently nucleated, ejecting oil in all directions.

The relatively non-violent vapor explosions that occurred prior to the large vapor explosion are conjectured to be the result of nucleation of the small, fragmented water droplets. The time scale of the vapor explosions confirms this supposition (e.g. $\approx 500\,\mathrm{ms}$, compared to $\approx 1160\,\mathrm{ms}$ for the large vapor explosion). It would be expected that the temperature would rise faster within a smaller droplet of fluid, compared to a larger one. Thus, the smaller droplets would reach their superheat temperature faster, resulting in a vapor explosion. These small explosions were not observed in experiments with HFE-7100-peanut oil since the parent HFE-7100 droplet did not breakup into many tiny droplets upon impact.

5. Conclusions

An experimental study was presented for distilled water and HFE-7100 droplets impinging upon a heated pool of cooking oil. As the water droplet impacted the hot peanut oil pool, the water droplet was observed to fragment, and ultimately produce a vapor explosion. Dramatic differences were observed when HFE-7100 droplets were applied to hot oil. At oil temperatures above $\approx 180°\mathrm{C}$, HFE-7100 droplets did not result in a vapor explosion.

Acknowledgements

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