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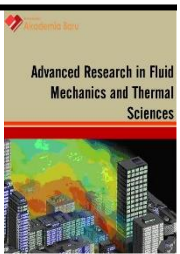

A Qualitative Inter-relation between Drop Impacts on a Solid Surface and the Interaction of a Droplet Placed Inside a Superheated Pool

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ABSTRACT

The phenomenon of drop impacts on a solid surface and the interaction of a cold droplet with a superheated liquid pool are both of great relevance in many practical and engineering situations. Most of the reported research in the literature on these phenomena focus on the impact of a droplet on a solid surface or a liquid surface and there are hardly any study on the interaction of a stationary cold droplet inside a hot pool of liquid, a phenomenon observed quite often. This study reports high speed flow visualization of a drop impact on a Teflon-coated solid surface at different liquid properties and impact Reynolds number. Simultaneously, high speed imaging of the interaction of a cold droplet with the superheated olive oil pool has also been carried out. The images show a striking resemblance between the flow dynamics of the two phenomena. A comparison between the two phenomena is made and suggestions are made for the possible underlying physics.

Keywords:
Drop impact; Vapor explosions; High speed imaging; Splashing; Crown formation

1. Introduction

The phenomenon of drop impacts on a solid surface and the interaction of a cold droplet with a hot liquid are both of great relevance in many practical situations. For instance, the understanding of drop impacts is crucial in multifarious engineering applications such as quenching of metals and alloys, ink-jet printing, spray-assisted cooling of hot surfaces and injection of fuel in engines [1-2]. On the other hand, fundamental studies on droplet – liquid surface interaction can prove useful in the understanding of a myriad variety of industrial processes, such as spray painting, cooling and cleaning. Unlike the process of drop impacts on a solid or a liquid that leads to bouncing, rebound, splashing or jet formation from the pool surface, drop impact on very cold or hot surfaces entails an additional complexity of phase change of the droplet, a phenomenon that has not been explored in

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great detail. Yet, such phase change upon interaction of drop on hot or cold surfaces is of prime importance in many practical applications. For instance, boiling and evaporation assume great importance for fire safety viz. the sprinkler system operation [3], spray deposition and the production of powders by spraying of materials in the molten state into cold liquid mixtures [4], etc. Similarly, phase change applications also include solidification such as icing on airplane wings, fabrication of displays and inkjet droplet soldering [5].

It is expected that the interaction of a cold droplet with a liquid at much higher boiling temperature can lead to nucleate boiling with bubbles forming and collapsing at the interface or to a stable vapor layer between the liquids in contact. However, for an unstable vapor layer, as can be observed in contact of molten metal with a liquid pool or fuel with coolant, vapor explosions may occur resulting in shock waves detrimental to the safety of the equipment or the personnel [6] when it occurs in industry, in nature or even in households. Vapor explosions have been cited as the cause of many explosive accidents in industries, such as in foundries and paper industry [7], nuclear-reactor cooling system failures [8], spillage of liquefied natural gas in seawater and railway tank car explosions [9]. Interactions of molten lava with water is another good example found in nature that relates to such vapor explosions [10]. Finally, cooking fires are one of the leading causes behind household fires, and it has been reported that very often, cooking oil is the culprit behind such cooking equipment fires. Further, water, which is most often used to suppress and combat fires due to its large latent heat of vaporization, and thus the ability to extract heat, cannot be effectively used to suppress cooking oil fires. This is because the application of water to cooking oil may have catastrophic consequences. Although few qualitative studies have been reported on the application of water to cooking oil, hardly any study has been conducted to the application of water to hot olive oils, which is one of the important cooking oils in households [11].

As far as fundamental studies related to the current study are concerned, a notable review by Yarin [1] is worth pointing out. In this review, Yarin [1] divided the drop impact phenomenon into two categories: substrate deposition and splashing. Further, the substrate deposition dynamics of drops (discussed in the current work) is generally described by the Reynolds number ($Re = \rho D_0 U_0/\mu$) and the Weber number ($We = \rho D_0 U_0^2/\sigma$), , where μ, σ, ρ, U_0 and D_0 are the dynamic viscosity, surface tension coefficient, density, pre-impact velocity and diameter of the liquid drop, respectively. Very few studies have explored the influence of the pool temperature on the dynamics of cold droplet interaction [3, 11-14]. To cite an example, the experiments of Manzello and Yang [11] focused on the interaction of hot peanut oil pool with cold distilled water or coolant HFE-7100 at fixed values of We of the drops. However, in all these studies, the observed dynamics results from a combination of the effects due to velocity as well as phase change. None of the prior studies have looked at the interaction of a stationary cold droplet with a superheated liquid pool. In summary, although a lot of different researchers have already studied the phenomenon of drop impacts, there are hardly any studies focusing on the dynamics of interaction of a cold droplet with a superheated liquid pool. Most of the reported studies (for instance, [15]) entail the actual impact of a moving droplet with the pool and the association of a cold stationary droplet with a hot pool of liquid has hitherto not been taken up. Further, to the authors' best knowledge, there is no study that focuses on the comparison of the dynamics of the two phenomena. Thus, in the present study, we present some experimental findings on the visualization the dynamics of flows under these two situations and present a comparative analysis of the two.

2. Experimental Setup and Methodology

Two distinct sets of experiments are carried out to visualize the phenomenon of drop impacts on solid surface (DISS experiments) on a solid surface and the interaction of a cold droplet with a hot liquid pool (DIHLP experiments). Figure 1(a) shows the experimental setup used in DISS experiments: It includes system for injecting drops, a Teflon impact surface, a pair of high-intensity LED light source as the illumination system, a high speed camera for image acquisition. For the drop injection, a precision syringe is used along with needles of various sizes. The syringe is attached to a mount so that it can be moved vertically allowing for different drop velocities. The drops are produced using a mixture of water and Glycerine and the different conditions at which DISS experiments are conducted are similar to the conditions reported by prior literature (for instnace, [2], [16]) and are listed in Table 1 below. To eliminate surface imperfections and to ensure a perfectly flat impact surface, a thin silicone oil ($\nu = 10^{-5}\ m^2/s, \rho = 930\ kg/m^3$) layer is applied on the Teflon surface. Further, to maintain the same surface condition, a fresh surface is prepared before every impact experiment. Two high-intensity continuous LED light sources are used for illumination.

As shown in Figure 1(b), for the DIHLP experiments, the olive oil is heated on a heating element leading to different temperature ranges of the liquid pool (T_p) as controlled by the heater. All our experiments are conducted for olive oil temperatures greater than 100°C. A cold stationary 0.5 mm water droplet at room temperature is placed on the surface of the pool. Two high-intensity continuous LED light sources are used to illuminate the flow and a high speed camera is used with a 105 mm Nikkor lens at a magnification of 2.5 is used to image the flow dynamics at a frequency of 3kHz. It is observed that the repeated heating of the oil causes the darkening of its color, and may be related to deterioration in its quality or alteration in its chemical composition. To maintain uniformity in fluid properties, the oil is regularly changed whenever a slight variation in its color is observed. The properties of both water and the olive oil used in our experiments are enlisted in Table 2.

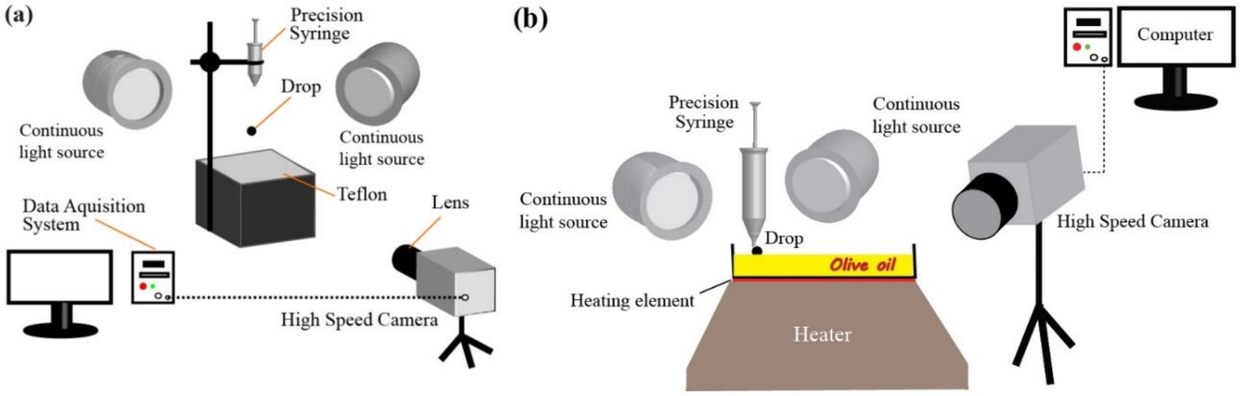

Fig. 1. Experimental Setup for (a) DISS Experiments, and (b) DIHLP Experiments

Table 1
The range of variation of non-dimensional parameters for different drop impact experiments

Mixture Number	Glycerin/Water (v / v %)	*We*	$Re(\times\ 10^3)$	*P*
I	0/100	22-190	0.4-9.5	0.02-0.15
II	10/90	37-247	2.8-7.5	0.15-0.29
III	30/70	87-543	2.5-5.6	0.18-0.54
IV	50/50	73-263	0.9-1.7	0.24-0.70

Table 2
The properties of the liquids used at 20°C

Fluid	Density (kg/m^3)	Viscosity (cP)	Surface tension (mN/m)	Boiling point (°C)	Heat capacity (kJ/kg °C)
Olive Oil	917	84	31.9	700	2.0
Water	997	1	72.9	100	4.2

3. Results and Discussion

We report the dynamical interactions between solid-liquid and liquid-liquid under two distinct sets of experiments, focusing particularly on the different morphologies observed. The purpose of these experiments is to establish a comparative trend between the observed dynamics in both experiments, which may possibly indicate an interrelation with the underlying physics. The first set of experiment pertains to the impact of water-glycerin mixtures on a solid Teflon surface (discussed in section 3.1), followed by the interaction of a cold water droplet placed inside a superheated oil pool (presented in section 3.2) and a comparison between the dynamics observed in these experiments (detailed in section 3.3).

3.1 Drop Impacts on a Solid Surface Experiments (DISS)

The outcome of the drop impact on the solid surface depends upon the impact Reynolds number of the drop. At a sufficiently low *Re,* the drops spread over the surface looking akin to lamellae with visible outer rim. In such a situation, the impact process generally involves four phases as shown in Figure 2: pre-impact, spreading, recoil, and decay.

The pre-impact phase, shown in Figure 2(a), begins at the point of drop release from the syringe and ends with the impact upon the Teflon surface (t = 0ms). As shown in Figure 2(b), the drop spreads radially outwards upon impact, forming a very thin flattened disk that momentarily coming to rest at the point of maximum spreading which is obtained at t = 6ms (shown in Figure 2(c)). Next, the drop recoils inwards and upwards to reach a maximum recoil height at t = 41ms, as presented in Figure 2(d) and 2(e). This is followed by another cycle of downward motion and lateral spreading and recoil. This oscillation gradually decays under the effect of dissipative viscous forces. A lower impact *We* essentially implies that surface tension forces are dominant as compared to inertial forces, thus inhibiting the breakup of a recoiling droplet into individual bubbles. In contrast, at higher impact *We,* inertial forces are much greater than the surface tension, thus facilitating the breakup into individual droplets and splashing is observed to occur. At an intermediate *We,* the competing effects of inertia and surface tension result into the breakup of the recoiling droplet into a few daughter bubbles. Figure 3 shows some interesting features of the impact phenomenon occurring at an intermediate *We.* As the droplet recoils and gains an upward momentum, a bubble can be seen clearly at the center of the droplet (shown in Figure 3(a)). The occurrence of a bubble inside the impacting drop can owe its genesis to several causes such as air entrainment or cavitation, or even to the spreading and retracting motion of the lamella. But, since the occurrence of bubble is observed just 2ms after impact, even before the spreading phase of the droplet, it is quite evident that the presence of the bubble is purely due to air entrainment in our experiments. Figure 3(b) to 3(d) shows that a micro droplet very quickly shoots up before the drop gains a vertically upward momentum and begins to rise. This is again because of the radially recoiling liquid at high velocity, leading to a small pinch-off that ejects at a tremendously greater velocity as compared to the vertical recoil velocity of the rising droplet.

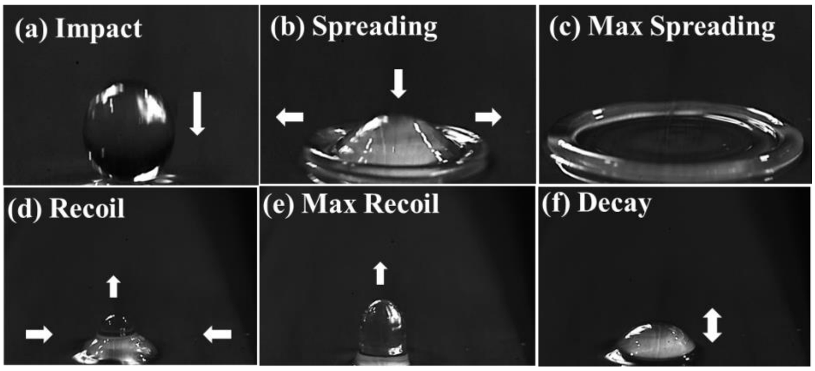

Fig. 2. Drop morphology in DISS experiment for a low impact *We* at (a) *t* = 0ms, (b) *t* = 2.3ms, (c) *t* = 5.7ms, (d) *t* = 27.0ms, (e) *t* = 41.0ms and (f) *t* = 153.7ms

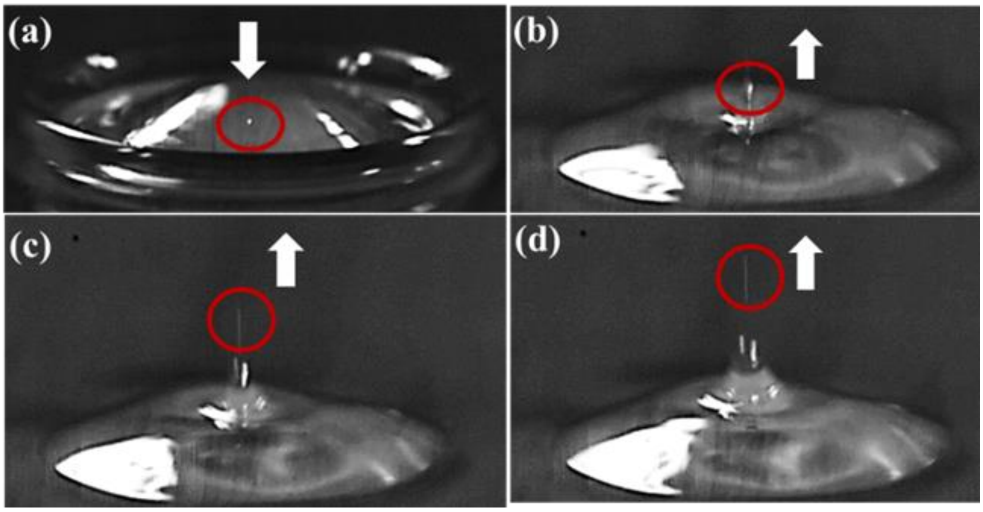

Fig. 3. Drop dynamics in DISS experiment for an intermediate We after impact at (a) t = 2ms, (b) t = 25.3ms, (c) t = 26.0ms, (d) t = 26.7ms

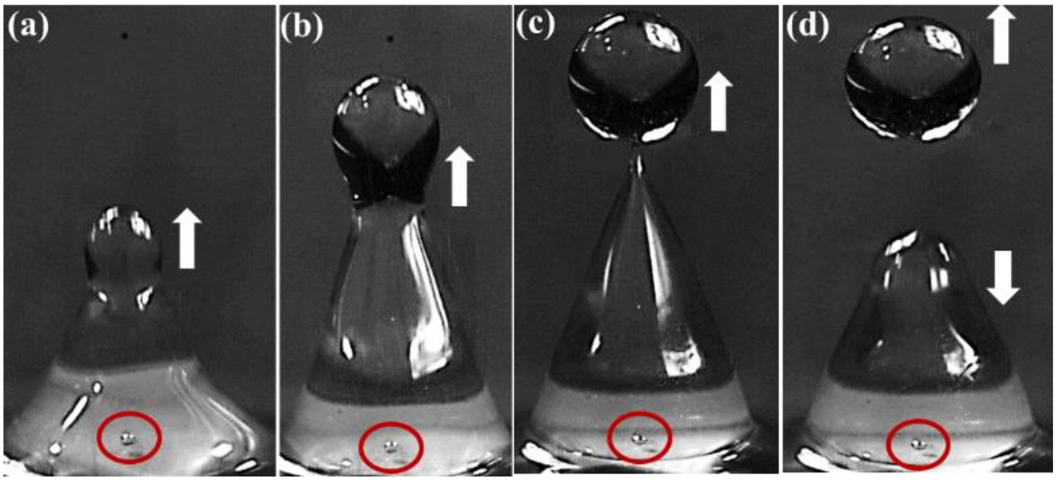

Fig. 4. Drop morphology in DISS experiment for an intermediate We at a duration of (a) 29.7ms, (b) 37.0ms, (c) 47.7ms and (d) 50.0ms after impact

Although the trapped air bubble is not clearly visible in Figure 3(b) to 3(d) and the chances are that this trapped bubble may have a role to play in the swift ejection of the micro-droplet and it is unclear whether these trapped bubbles will necessarily remain inside or get expelled. Figure 4 shows an illustration of the different stages in upward recoil of a drop, and the trapped bubble can be observed to remain at the centre of the drop surface at different stages of the vertical recoil, necking, separation and the final breakup of the droplet from the parent drop.

3.2 Stationary Droplet Interaction with a Hot Liquid Pool (DIHLP Experiments)

Figure 5 shows the drop dynamics at low pool temperature when a cold stationary water droplet is placed inside a superheated olive oil pool at low temperature (> 100°C). As shown in Figure 5(a), the cold water droplet at room temperature, upon sudden contact with the superheated oil undergoes a sudden vaporization, eventually leading to a micro-explosion with a feeble intensity and the chaotic surface of the oil pool is a manifestation of this explosion.

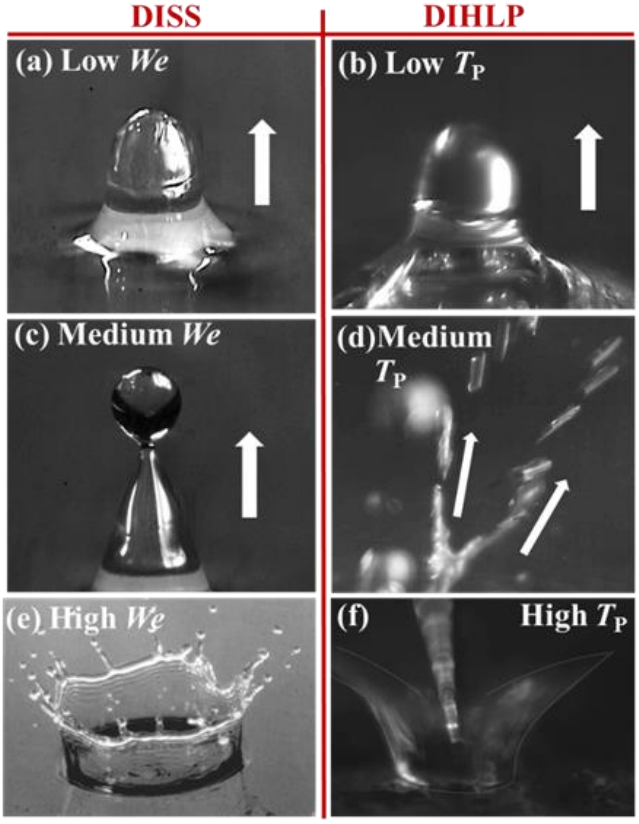

Fig. 5. Comparison of drop morphologies formed in DISS and DIHLP experiments. 5(e) is adapted from [18] with permission and boundaries are outlined in 5(f) to clearly show the former corona

Figure 5(c) shows the presence of two discrete vapour bubbles trapped inside the “recoiling” structure that resulted from the vaporization of the original water droplet. Vapour bubbles grow as they extract thermal energy from the oil pool, leading to a bump in the oil level till a point they collapse again and the oil bump drops down and a momentum decay is observed. However, unlike the drop impact where the decay process is a persistent one and consisted of multiple stages, in this case, the decay process is unusually short. After the initial decay, the stationary water droplet sits on the surface of the oil, and the energy is dissipated in the form of expansion waves in the hot oil pool. Although there are not many prior reports on this phenomena, a recent study by Alchalabi *et al.,* [17] on the vortex-induced vapour explosion of Perfluorohexane drops in superheated soyabean oil, when these drops impact the superheated oil pool at various impact velocities in the range of 1 – 3.5 m/s. Alchalabi *et al.,* [17] identified a specific regime as a function of pool temperature and Weber number, where the vortex-induced vapour explosion was observed. The reason behind the localized explosion was attributed to the rapid boiling of the water enclosed within the hot oil due to initial impact velocity. However, in our study, water drops (of boiling point 100°C) is placed inside the surface of superheated olive oil with a negligible velocity. Therefore, the mechanism of vapour explosion is markedly different in our experiments, and is taken up in the next section.

3.3 Comparison between DISS and DIHLP experiments and the underlying mechanism.

As shown in Figure 5, the mechanism of drop impact dynamics has been well explained and documented in the literature, particularly in the celebrated reviews by Rein [6], Yarin [1] and a more recent review by Josserand *et al.,* [19]. However, since the underlying physics behind DIHLP experiments has not been reported in the literature, a possible mechanism is outlined below. Figure 6 below presents a schematic to illustrate the underlying sequence of events that explain the dynamics observed in DIHLP experiments. The process of bubble formation in DIHLP experiments is due to the vaporization of liquid into a cavity, and since this process occurs at temperatures exceeding the boiling temperature of the liquid, it is called superheating [20]. Heating of a liquid to its superheat limit is facilitated by suppressing the heterogeneous nucleation and ordinary boiling by isolating the volatile liquid from rough solid surfaces containing gas nuclei [21]. In our experiments, this has been accomplished by immersing a more volatile liquid (water) in a less volatile olive oil pool. When the temperature of a liquid droplet in another immiscible liquid reaches its superheat limit, the explosive vaporization of droplet results, thus converting the droplet into a bubble. Since the pressure inside the evaporated droplet is greater than the ambient pressure, the rapid expansion of the bubble makes it overshoot the mechanical equilibrium condition resulting in an oscillation in its size, as shown in Figure 6(a). At an intermediate oil temperature, a surface jet results in the DIHLP experiments, which further may break into one or several droplets [22]. Finally, when the oil is superheated to a much higher temperature, the growing vapour bubbles come out of the free surface, making elongated protrusions on the free surface of the oil, also called corona, as shown in Figure 6(b). These coronae further elongate and expand outward, breaking into thinner jets and smaller droplets. Finally, the mechanism behind the growth of a surface jet is worth noting. Figure 7 presents an illustration behind the creation of a surface jet. In a situation similar to our experiments, a vapour bubble is bounded by the free surface on one side, whereas a solid wall on the other. The study by Rattray [23] suggested that the presence of a solid wall close to a collapse of an initially spherical bubble could cause the formation of a liquid jet directed towards the wall. It was also confirmed by experiments of Benjamin and Ellis [24] that jets form on bubbles collapsing near a solid wall. First, the bubbles become elongated in the direction normal to the wall; then they flatten and form an inward moving re-entrant jet on the side of the bubble opposite to the wall and shatters itself [25]. The velocity of this re-entrant jet is very high, causing the liquid to rush in from all sides, particularly above the cavity where the pressure deficit would be the highest. The incoming liquid collides and can go only up and down. The resulting updraft creates the surface jet. However, such a situation does not arise either at very low temperatures of the oil, since the cavities do not grow large enough to form a strong re-entrant jet. Conversely, at very high temperatures of the oil pool, the vapour cavity may grow so rapidly that it immediately comes outwards, resulting in a corona. However, to substantiate these hypothesis requires more quantitative and systematic experiments to be carried out.

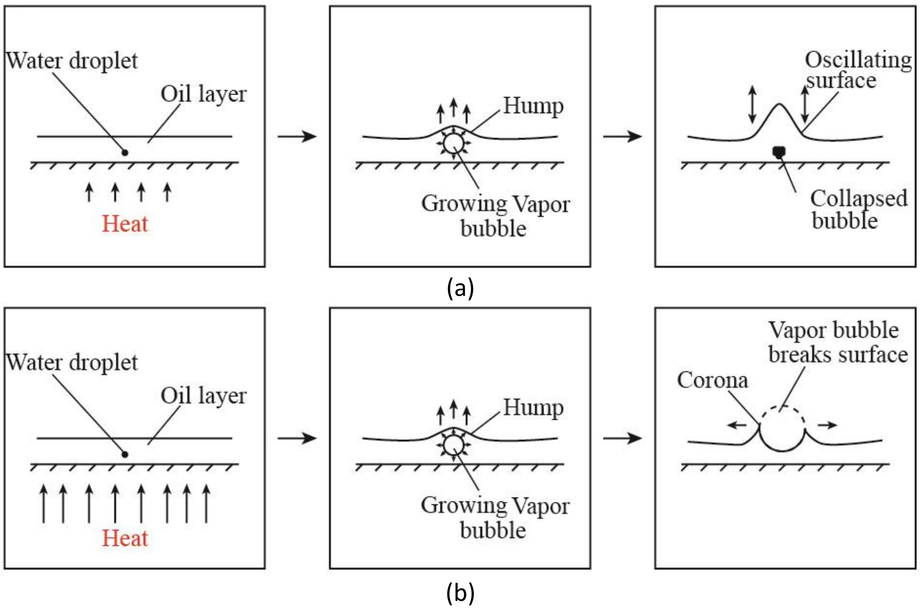

Fig. 6. Schematic to explain the observed phenomena in DIHLP experiments for (a) Low to intermediate Tp and (b) High Tp

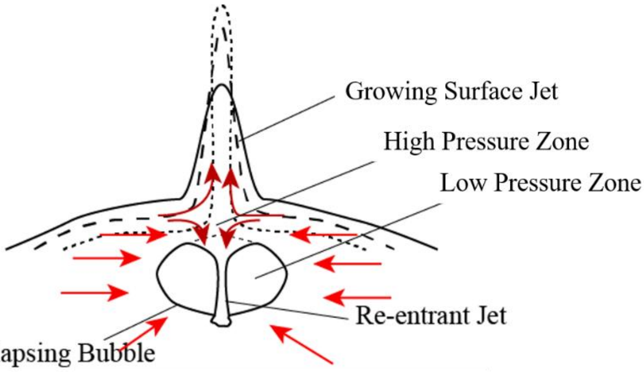

Fig. 7. The mechanism behind surface jet in the DIHLP experiments

4. Conclusions

In the present work, two physically intriguing and industrially important phenomena – drop impact on a Teflon-coated solid surface (DISS) and the interplay of a stationary cold water droplet with a hot olive oil pool (DIHLP) are investigated through high speed imaging. Our studies indicate a close correspondence into the underlying fundamental physics in both the phenomena.

First, the results of DISS experiments are discussed in detail. The outcome of a drop upon impact with a solid surface is seen to depend upon the impact Weber number (*We*). At low *We,* there is a minor recoil from the solid surface. As *We* increases, the inertia forces dominate surface tension and the resulting recoiling jet may break into a daughter individual droplet. Finally, at very high *We,* splashing is expected to occur. In addition, the phenomena of the pinch-off a small micro-bubble during recoil and the entrapment of an air bubble is also pointed out. Next, the results of DIHLP experiments are discussed. At low temperature of oil pool (i.e. low degree of superheating), a drop morphology results that is homologous to the recoiling droplet from the solid surface. As temperature increases, a growing surface jet is seen, and at very high degrees of superheat, a corona splash results. In conclusion, our study indicates that the drop dynamics and the resultant drop morphologies are a result of the total available energy involved in the process, be it the kinetic energy of the impacting drop or the thermal energy of the hot oil pool. However, more quantitative experiments need to be conducted to explore the DIHLP experiments in detail.

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