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DROPLET-DROPLET COLLISIONS ON A SOLID HOT SURFACE

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ABSTRACT

The present study aims to better understand the spray hot-surface complex system. The interaction of two droplets in the presence of a hot surface has been observed under different impact conditions and boiling regimes. The case of droplet-droplet collision on a hot surface has been compared with a single droplet impact on dry and wetted surfaces in order to reveal similarities and differences between these cases. Also presented are some photographs extracted from a high-speed film showing the different regimes and cases countered.

INTRODUCTION

Many engineering areas involve mist or spray cooling, spray-painting, ink jet printing and spray coating. The flow fields of sprays impinging on a solid surface are very complex in nature because of the many factors involved and the droplets' interactions with the surface and each other. Extensive research has been done in the field of single droplet impact on a solid surface [1, 2, 3, 4, 5, 6, 7]. The research addresses low and high impact velocities and dry and wet surfaces [8]. Splashing phenomena such as crown like jets and their propagation are discussed, as well as some additional non-splashing phenomena, like droplet spreading and deposition, receding (recoiling), jetting, fingering and rebounding. Rioboo et al. [9] compared the dry and wet impact cases and showed that the two phenomena are completely different in terms of morphology, spreading behavior and secondary droplet formation. While the impact on a dry surface tends to exhibit only a radially extending lamella, the impact on a wet surface easily causes the formation of a corona expanding vertically and radially. Furthermore, the spreading velocity appears to be slower for impacts on wet than for impacts on dry surfaces. In [10], they reported the experimental results concerning crown formation during liquid droplet impacts on wet surfaces. If the thickness of the film is much larger than the droplet's diameter, the droplet's impact creates a crater in the liquid layer. When this crater recedes, it can lead to bubble entrapment in the liquid and to the formation of an uprising central jet. Such impacts can also lead to splash, when this central jet breaks up and creates a single or several secondary droplets. However, the knowledge obtained by the single droplet tests is not fully or directly applicable to the actual flow fields of spray jet impingement, because it lacks the interaction effects between multiple droplets and the surface [11]. Another complication associated with the fluid flow of impinging droplets is the extreme deformation that a droplet undergoes when it impacts the surface. This deformation occurs in very short time scales and is not yet fully understood.

In cases of low impact velocities, the spreading phenomenon is probably controlled by surface tension, while in cases of high impact velocities compressibility effects strongly affect the outcomes [12].

To the author's knowledge, literature on the subject of droplet-droplet collisions on a solid surface is scarce.

The present study focuses on the characterization of droplet-droplet collisions on a solid surface, as well as a comparison with some single droplet impacts on dry and wet surfaces, for both low and high impact velocities. This study represents a part of a more extensive study on the subject of droplet-droplet collisions on a heated, solid surface. First, experimental data of single droplet impacts on dry and wet surfaces was obtained. We then compared and analyzed the results with droplet-droplet collision results applied for the same surfaces and conditions. An empirical condition for crown splash was also updated to fit with the droplet-droplet collisions.

EXPERIMENTAL SETUP

The experiments performed with water as the tested fluid. The surface material is aluminum. The droplets and the surface are at room temperature. A droplet generator is used to initiate identical droplets. Initial droplets diameter was 3.2 [mm]. Impact velocities range between 0.4 and 2.7 [m/s]. The second droplet collides on a static droplet. Only normal impacts were considered. No significant evaporation takes place between the first and second droplets. The impaction plate's area is about 90 X 80 [mm^2]. High speed CCD camera, having a record rate of 2000 frames per second, is used in order to obtain photographic observations, impact velocity and diameter and height measurements. The measurements are estimated to be accurate within $\pm 5\%$. Data from the high speed camera is transferred to a PC for further analysis. Schematic experimental setup is shown in figure 1.

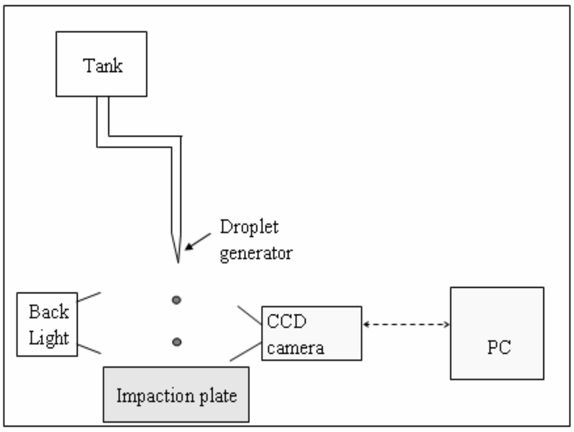

Figure 1: Schematic experimental setup

RESULTS AND DISCUSSION

In this section, the behavior and evolution of the wet diameter, height and shapes of the droplet as it impacts on a surface are discussed in detail and compared with the droplet-droplet collision matching cases. The analysis includes single droplet and droplet-droplet impacts and collisions, low and high impact velocities and dry and wet surfaces.

For the case of low impact velocity, droplet-droplet collisions can be compared to single droplet impacts on a dry solid surface [12], as described and shown in figures 2, 3 and 4. Single droplet, low velocity, impact on a dry surface is described by several stages of evolutions such as deposition, spreading, receding and oscillation stages. When a droplet having low velocity collides with a static droplet on a solid surface, as shown in figure 2, the wet diameter on the surface doesn't change, at first, until the resulting diameter is greater than the first, original droplet's equilibrium diameter and the droplets are merged [12].

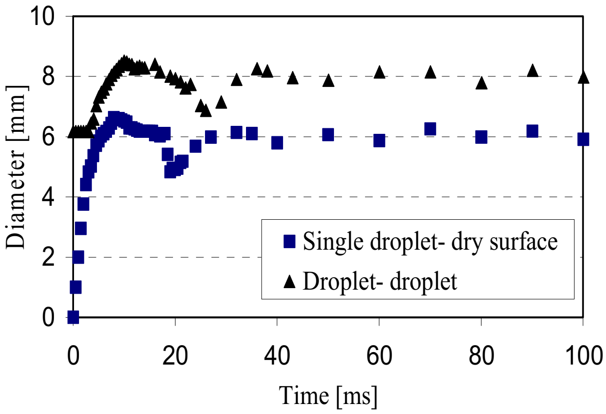

Figure 2: Diameter evolution of a droplet impact on a dry surface and a droplet-droplet collision on a solid surface, at low impact velocity (0.45 [m/s])

Afterwards, the wet diameter expands on the surface (spreading period) since another liquid mass having a certain amount of energy has reached the surface and the system is no longer in equilibrium. In the case discussed, the impact velocity is low, so the collision is not violent and the droplets are able to merge gently. The wet diameter increases to a maximum spread diameter and then recedes to a minimal value (receding stage), after which an oscillation period develops till system stabilization is reached and a new equilibrium diameter is formed. As far as the height is concerned, it's evident from figure 3 that the overall behavior of a droplet-droplet low velocity collision is very similar to a single droplet impact on a dry solid surface. The height first decreases during droplet deposition and spreading, increases through the receding phase to a local maximum and then oscillates until equilibrium height is reached.

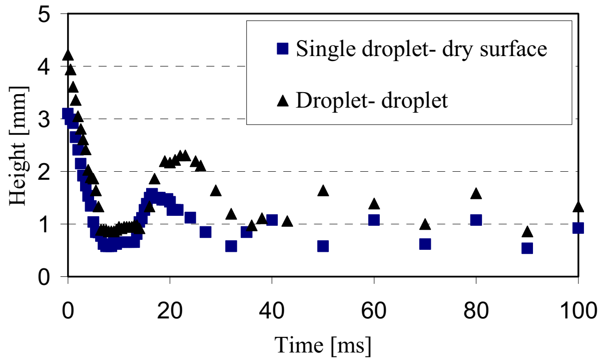

Figure 3: Height evolution of a droplet impact on a dry surface and a droplet-droplet collision, at low impact velocity (0.45 [m/s])

Figures 2 and 3 indicate that the case of a droplet-droplet low velocity collision on a solid surface is very similar to a single droplet impact on a dry, solid surface case with some exceptions. The exceptions have to be taken into account if one would like to use such single droplet impacts in order to model droplet-droplet collisions or when trying to modify or update single droplet models or correlations to match with the droplet-droplet cases.

The main exceptions found are: Diameter behavior during deposition phase, time delay between the cases and difference in evolution values. Droplet-droplet collision tends to develop a time delay in its spreading and receding phases (for both diameter and height evolutions) mainly because of the viscous and surface tension effects caused by the presence of liquid on the surface from the onset of spreading of the second droplet. For both the diameter and height of the droplet-droplet collision case, the time delay developed is not constant but increases with time and evolution throughout the spread, recede and part of the oscillation periods. The main difference between the single droplet impact and the droplet-droplet collision cases is seen in absolute values of the diameter evolution, in the case presented, when a 3.2 [mm] diameter droplet collided with a 3.2 [mm] diameter droplet and the actual difference in equilibrium diameter was at about 2 [mm] or 33% increase for twice the liquid mass. The most significant difference for the height is the local maximum height value at the end of the receding stage.

Figure 3 shows that the local maximum height of the droplet-droplet collision is greater than that of the single impact case. Also, an equilibrium height difference exists between the cases but this difference is less significant than for the equilibrium diameter. For both cases (droplet-droplet collisions and single droplet impacts), the height evolution precedes the diameter's.

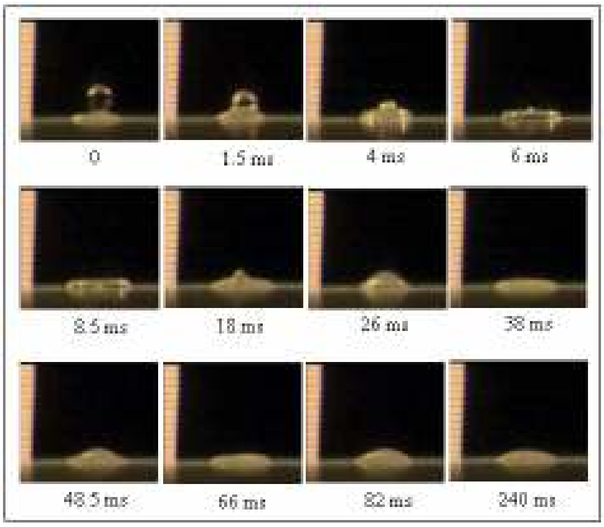

Figure 4: Droplet- droplet collision at low impact velocity- 0.45 [m/s], millimeter scale

Next, we'll deal with the high impact velocity cases. For these cases there is no similarity between the droplet-droplet collision and the single droplet impact on dry surface outcomes. Instead, the droplet-droplet outcome resembles to the single droplet impact on a wet surface. A high velocity impact of a single droplet on a wet surface generally produces deposition stage, crown like formation propagation or splash and an uprising of a central liquid jet that could also breakup and splash, [8, 11].

When a droplet-droplet, high velocity collision takes place as described and shown in figures 5, 6 and 7, a high pressure zone is created around the incoming droplet [11, 13], resulting in a liquid crown-like shape that emerges from the static droplet upwards and outwards. It seems that most of the crown is composed of liquid originates in the first, static droplet.

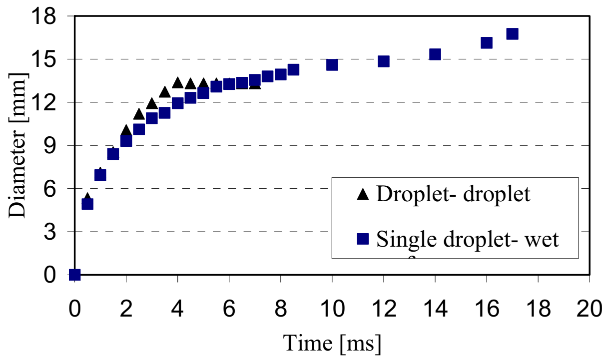

Figure 5: Diameter evolution of a droplet impact on a wet surface (film thickness-1 [mm]) and a droplet-droplet collision at high impact velocity (2.6 [m/s])

The crown's expansion radially outwards (and upwards) increases the wet diameter on the surface. The diameter growth rate decreases with time as the system's energy is reduced by viscosity, surface tension and gravity.
Tiny secondary droplets (an order of magnitude less than the colliding original droplets) are expelled from the rim at the top of the crown during its formation. Finger-like liquid jets are formed at the rim of the crown and evolve during the crown expansion (figure 7). These fingers may eventually break off to form a secondary droplet splash or may stay attached to the crown's top. The crown reaches to a point at which the wet diameter does not expand any more on the surface (see figure 5). Although the lower part the liquid has ceased to expand, its upper section continues to expand outwards (not upwards) until the crown collapses due to instability and lack of support. In figures 5 and 6, the last point indicated is just before the collapse of the crown (so the actual moment of collapse is not indicated in these figures for the droplet-droplet collision). The collapse of the crown is directed outwards. As can be seen from figure 5, the early part of the diameter evolution for both the droplet-droplet, high speed collision and the single droplet, high speed impact on the wet surface is similar. The deposition part and the early part of the formation of the crown are similar for the two cases mentioned. The separation between these two cases starts from the crown's later evolution and thereafter. The crown in the droplet-droplet collision case develops a bit quicker than that in the single impact case and shortly afterwards its expansion on the surface stops, resulting in a constant diameter. However, the crown in the single droplet impact case expands as long as it exists till it descends and dissolves back into the liquid film. The difference in the crowns' expansion behaviors is caused by the fact that the liquid film area and thickness on the surface in the single droplet impact case is much greater than those occupied by the static original droplet in the droplet-droplet collision case. The crown's expansion in the droplet-droplet collision case suffers from boundary effect, unlike the single droplet impact case.

As for the height evolution in the case of droplet-droplet, high speed collision, we can see from figure 6 that, at first, deposition takes place and the height is reduced.

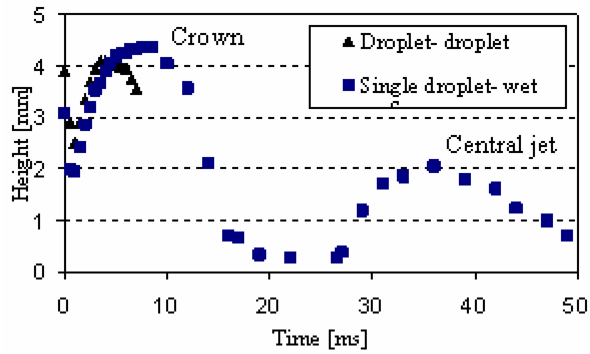

Figure 6: Height evolution of a droplet impact on a wet surface (film thickness-1 [mm]) and a droplet-droplet collision at high impact velocity (2.6 [m/s])

Because of the high impact energy, a crown emerges and quickly takes the leading height, even before the upper part of the incoming droplet reaches the surface or completes its deposition. The height is increased by the crown's development to a certain maximum, after which the crown height starts to decrease until its collapse (refers to the droplet-droplet case). The similarity between the two cases lasts only during the first few milliseconds. The difference in the crown's expansion then sets them apart.

A phenomenon that exists only for the single droplet wet impact case is the uprising of the central liquid jet (Worthington jet) that occurs after the crown disappears. This phenomenon does not take place in the droplet-droplet collision case, because the crown collapses outwards onto the dry surrounding surface and there is almost no energy left in order to get the liquid back into the center of impact and no crater is left open in the central area that needs to be closed. However, in the single droplet wet impact case, when the crown descends, there is still a crater in the liquid film that contributes to the return of liquid to the center of impact and, with the help of surface tension, too much liquid rushes to the center of impact, thus forming the central liquid column jet as a result of its inertia and pressure. This difference is responsible for the fact that the droplet-droplet, high speed collision takes place for less than 8 [ms] while the relevant single droplet wet impact case takes about 50 [ms] to complete (figure 6). Differences in the two cases crowns' behaviors are also expressed by the finger like jets thickness and magnitude. For the droplet-droplet collision case these are very thin and small while for the single droplet wet impact case they are thicker and larger. Another difference is the crown's descent type; in the droplet-droplet collision there is a collapse of the crown, while in the single droplet wet impact case there is no outward directed collapse but a simple descent into the liquid film.

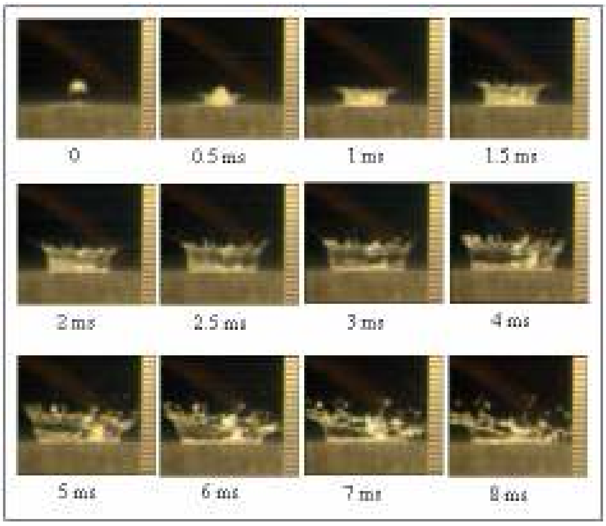

Figure 7: Droplet-droplet collision at high impact velocity- 2.6 [m/s], millimeter scale

Droplet-droplet collision also lowers the crown's splash threshold (for droplets with the same initial diameter). Tropea and Roisman [14] gave an empirical condition for a crown splash as

$$We^{4/5}\,\mathrm{Re}^{2/5} \geq 2800 \qquad (1)$$

This condition is valid for the case of single droplet impact on a wet surface where the thickness of the film and the droplet's diameter are of the same order of magnitude. For the case of droplet-droplet collision, crown splash condition is reached for lower values of collision velocity and therefore is matched as

$$We^{4/5}\,\mathrm{Re}^{2/5} \geq 1600 \qquad (2)$$

An example is shown in figures 8 and 9.

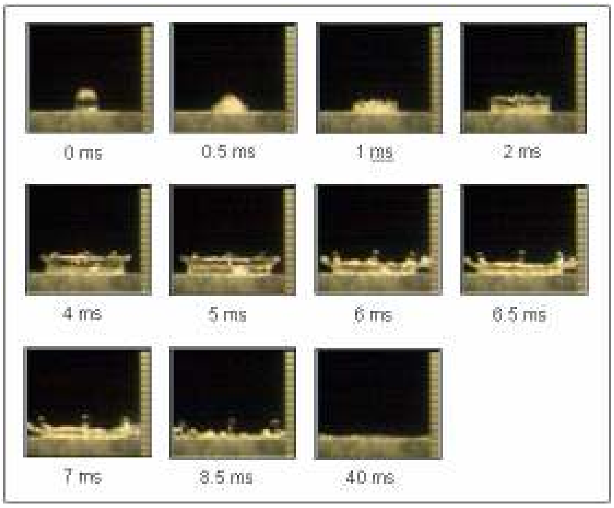

Figure 8: Droplet-droplet collision on a solid surface

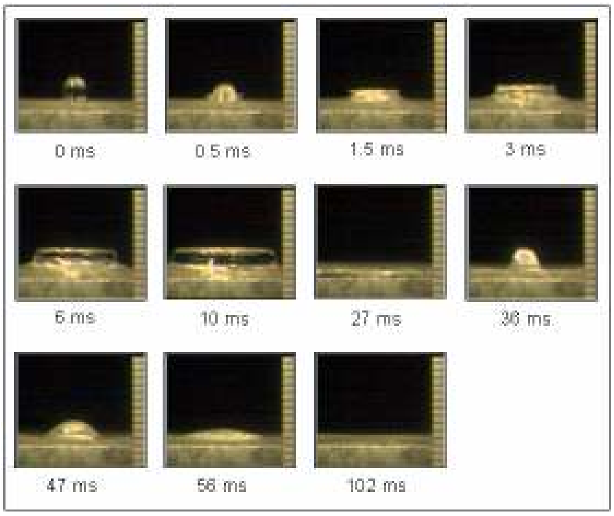

Figure 9: Single Droplet impact on a wet surface

Figure 8 exhibits a droplet-droplet collision on a solid surface where the collision velocity is 1.8 [m/s]. Under these experimental conditions, a crown emerges from the collision and splashing occurs. In figure 9 there is a single droplet impact on a wet surface with the same impact velocity, where the film thickness is 1.5 [mm]. After the impact, a ring shaped liquid emerges from the wet film but finger like jets are absent and no splashing occurs.

After the ring shape liquid descended and disappeared in the wet film, a central liquid jet emerges.

A possible reason for this behavior and trend, that a droplet-droplet collision needs less energy in order to form a crown splash than a single droplet impact on a wet surface, may originate from the wet film features and properties, such as film thickness, shape, uniformity and the liquid properties. These features are different for the two cases mentioned and it is only logical that the consequences will be different as well.

Although the cases of droplet-droplet high speed collision and a single droplet, high speed impact on a wet surface have similarities, there are also some significant differences demonstrating that these two cases are separate phenomena.

CONCLUSIONS

This work compares droplet-droplet collisions on a solid surface, having low or high impact velocities, with single droplet impacts on dry and wet solid surfaces. Droplet-droplet collisions on a solid surface with different collision velocities develop different types of behaviors. For the low collision velocity case, there is no crown formation, the droplets merge, spread, recede, oscillate and act in a way similar to the single droplet impact on a dry surface case with low impact velocity. For the high collision velocity case, the collision forms a crown that propagates to a certain magnitude until it stops and fall outwards. The early part of this behavior is very similar to the high velocity single droplet impact on a wet surface case, while the more advanced part of the collision outcome is quite different from the mentioned single impact case. An empirical crown splash condition was updated to fit with the droplet-droplet collision outcome. The similarities found can assist in obtaining or updating some more correlations that will fit and describe the droplet-droplet collisions' outcomes. The way to enhance spray-modeling accuracy may lie in the ability to form a combined and integrated model that treats the single droplet impact cases as well as the droplet-droplet collision ones.

NOMENCLATURE

Symbol	Quantity	SI Unit
We	Weber number	Dimensionless
Re	Reynolds number	Dimensionless

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