Dynamic Behaviour of Single Droplets Impinging upon Liquid Films with Variable Thickness: Jet A-1 and HVO Mixtures

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Abstract

Fortunately, the human being has already started to be environmentally concerned and the search for new alternatives to reduce pollution increased. Transports are responsible for a significant portion and it is extremely necessary to bet on alternatives to oil. The introduction of biofuels in aero-engines could be an example. In order to modify and optimize piston engines and gas turbines to operate efficiently with alternative fuels, this work used Jet Fuel and Biofuel mixtures. The focus of these studies was to visualize the dynamic behavior of single droplets impinging upon liquid films with variable thickness. The existence of splash as well as its characteristics were reported and the differences and similarities between the outcomes according to the impact conditions and the fluid properties were catalogued.

To achieve that an experimental facility was designed and built. Four fluids were tested: water (as reference), 100% Jet A-1, 75%/25% and 50%/50% mixtures of Jet A-1 and HVO (Hydro-processed Vegetable Oil), respectively, since civil aviation only accept mixtures with at least 50% Jet Fuel in volume. The fluid properties were measured to ensure accuracy. The liquid film depths considered were 10%, 50% and 100% of the droplet diameter. A high-speed digital camera was used to image acquisition and the droplet was released by a syringe pump connected to the needle at a specific pumping rate. The impact surface was a perspex container filled with fluid. Five needles with different inner diameters and three impact heights were employed to provide a variety of Weber and Reynolds numbers.

Keywords: Droplet Impact, Experimental, Jet Fuel, Biofuel, Liquid Film, Splash

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1. Introduction

The droplet impingement is important for a wide variety of areas and it has many applications: fuel injection in internal combustion engines, spray cooling, spray painting, coatings, among others. Many studies encompass the dynamic behaviour of these impacts and the resultant phenomena are quite difficult to understand due to its complexity but also to the great amount of parameters involved. In order to group some of these parameters and also to provide a comparison between studies, the dimensionless numbers are commonly used [1]. In this study, the Weber (We), Reynolds (Re), Laplace (La) and Ohnesorge (Oh) numbers were used.

A set of possible phenomena can happen depending on the impact conditions. Several authors tried to define them and their classification are not always unanimous. Rioboo et al. [2] defined deposition, prompt splash, crown splash, rebound, partial rebound, among others. There are many other but the most relevant for this study are these.

In this study, it was tested the impact of single droplets upon liquid films. The most important characteristic of the liquid films is its dimensionless thickness (δ^*) described by the ratio between the thickness of the liquid film (δ) and the droplet diameter (D_0). According to its dimensionless thickness, the liquid films can be classified as thin, intermediate and thick films or shallow and deep pools [3]. In these experiments, three relative thicknesses were considered and identified as thin ($\delta^* = 0.1$), intermediate ($\delta^* = 0.5$) and thick ($\delta^* = 1$) liquid films.

Many experimental and numerical studies were reported in the literature. The droplet impingement study is primarily divided into two parts: upon dry or wetted surfaces. Identify the differences in the droplet hydrodynamic behaviour depending on the presence of a liquid film was a concern. In that way, Chandra and Avedisian [4] reported that the spreading of the droplet changed significantly due to the liquid film. Later, Rioboo et al. [5] focused their work on distinguishing the spreading behavior between the impact on dry and wetted surfaces. They showed that maintaining all the impact parameters constant except the surface conditions resulted in completely different morphologies of impact.

Studies focused on the impact upon wetted surfaces were widely performed. It was necessary to identify the resultant components of the impact and understand how they evolve with time. One of the first studies was performed by Macklin and Metaxas [6] from thin liquid films to deep pools. They observed the general characteristics of splashing and the behaviour of the crown height and the ejected droplets with the dimensionless thickness variation. Lastly, they reported that for deep splashing the bottom of the container did not affect the splashing. Although they had a wide range of liquid film thicknesses, the fluids used were water, ethanol and glycerol.

Coghe et al. [7] and Cossali et al. [8] measured some components of a single droplet splashing upon liquid films, both for water. The crown diameter, thickness and maximum height were evaluated. They also noticed that the higher the Weber number the smaller the secondary droplets. A few years later, Cossali et al. [9] focused their work on the time evolution of the crown of water droplets impinging upon thin liquid films. They reached to several conclusions related to the crown horizontal size, the non-dimensional crown height, the mean secondary droplet size, among others. However, since they use only one fluid it is not possible to identify if their conclusions could be extended to other fluids.

Fedorchenko and Wang [10] studied experimentally and theoretically the region of the fully develop splashing. They used water but also a 70% glycerol-water solution. They develop a model for the central jet formation at the cavity collapse. Several considerations were made about viscosity and surface tension of the fluids related to the cavity, the central jet and the crown ejection. Understand the role of the fluid physical properties is essential to understand how they influence the impact regimes. For example, Range and Feuillebois [11] reported that the splashing is highly sensitive to the fluids surface tension.

A parameter truly important is the dimensionless thickness of the liquid film and its influence in the droplet dynamic behaviour. Vander Wal et al. [12] studied droplets splashing upon liquid films of different depths. They reported that thinner liquid films decreased the critical Weber number. They also found that the size and number of the splashed products depend upon the presence and thickness of the liquid film, and also on the viscosity and surface tension. For $\delta^* < 1$ both prompt and crown splash happened but for $\delta^* > 1$ the prompt splash was limited and the crown splash inibited. Moreover, the number of ejected droplets decreased while its mean size increased with the increase of the surface tension and viscosity. In addiction, an increase in the viscosity leads to a delay of both prompt and crown splash. Their final conclusions were: in the impact with dry surfaces, viscosity promoted splashing, while for thin liquid films the role reverted. Lastly, high surface tension inhibits splashing both for dry or wetted surfaces.

Over the years, researchers wanted to produce thinner liquid films and study these particular impacts. In that way, Wang and Chen [13] experiments were centered about the splashing of a single droplet upon very thin liquid films. They verified once again that the critical Weber number and the splashing dynamic was influenced by the thickness of the liquid film. They also noticed that for $\delta^* < 0.1$ the critical Weber number gets close to the minimum value which depends on the fluid viscosity and surface characteristics underneath the liquid film. In the study of wetted surfaces is important to understand if the surface underneath influences the outcome. With that in mind, Vander Wal et al. [14] combined the influence of a rough surface and a thin liquid film upon the splashing limit and dynamics. They recognize that both cases changed the splashing limit and dynamic substantially. A rough surface decreased drastically the critical Weber number, the surface topography overlaps the importance of the other governing parameters, especially in the splashing regime. For example, considerable differences in the surface tension and viscosity became less significant and made the outcome very similar. The splashing behaviour of a rough surface covered by a thin liquid film was a combination of both cases.

Boundaries between the different impact regimes are common and widely reported. Lindgren and Denbratt [15] found several empirical correlations in the literature which establish boundaries between the different impact regimes and classified them as very distinct. The main differences were due to the distinct impact conditions.

Most recently, Zhang et al. [16] centered their work on the numerical simulation of a droplet impinging upon films with different fluid properties. They found that a decrease in the fluid viscosity and surface tension increase the crown heigh while the crown thickness decrease. They also reported that when the Weber number increase the impact process quickened and the number of splashing products increase.

Other study concerns the droplet impact upon immiscible liquid films, similar to the work performed by Che and Matar [17]. They reported that the immiscibility induces completely different hydrodynamic behaviours and they also studied the influence of some parameters such as the Weber and Ohnesorge numbers, the viscosity ratio and the dimensionless thickness of the liquid film. Recently, Burzynski and Bansmer [18] studied the droplet splashing on a thin moving film only for high Weber numbers. They reported that the liquid film velocity affects the crown geometry considerably.

In addition to the described above many other research have been developed [19]: multiple droplet impacts, impact upon heated surfaces, impact upon inclined walls, among many others.

There was an absence in all these studies. The most common fluids used were water, glycerol, ethanol or solutions with different fluids. Since one of the applications is the fuel injection in internal combustion engines seems legit that fuels should be used. The main goal of this work is to make efforts for the implementation of biofuels in the aviation sector. In this way, the working fluids were 100% Jet A-1 and two mixtures with 75%/25% and 50%/50% of Jet A-1 and NEXBTL (Neste Renewable Diesel), respectively. Pure water was also used as a reference. To visualize the outcomes an experimental facility was design and build. The outcomes were then identified and divided into splash and non-splash and a qualitative study of the secondary atomization was made.

2. Experimental Procedure

The experimental facility (figure 1) is composed of four main parts: image acquisition, impact surface, droplet dispensing system and the impact site illumination. For the image acquisition, it was used a high-speed digital camera Photron FASTCAM mini UX50 with 1.3 Megapixel resolution at frame rates up to 2,000fps (frame per second) and at reduced image resolution for frame rates up to 160,000fps. It was used a Macro Lens Tokina AT-X M100 AF PRO D with a minimum focus distance of 0.3m, a focal length of 100mm, a macro ratio of 1:1 and a filter size of 55mm. The image resolution at first was 1280x1024, the exposure time was 1/5120s and the frame rate was 2,000fps. Later, these parameters were switched for 2,500fps, the exposure time to 1/6125s and the image resolution to 1280x800. A topless right-angled perspex container was the impact surface and its dimensions were calculated based on the maximum droplet diameter (edge equal to $40D_{0max}$). To release the droplets a syringe pump NE-1000 was used at a pumping rate of 0.5ml/min. To vary the droplet diameter five stainless steel precision tips were used, they have straight tips and their inner diameter were: 1.5mm, 0.84mm, 0.51mm, 0.25mm and 0.10mm. The illumination of the impact site is crucial and the only light source in the room was a 20W LED in front of the camera to provide backlighting. A diffusion glass was put between the impact site and the LED.

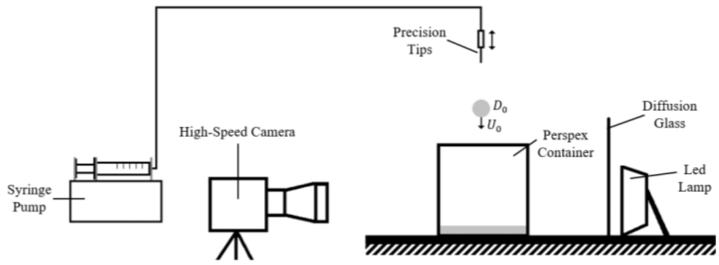


Figure 1 Scheme of the experimental facility.

The physical properties of the three fuels used were measured to increase the precision of the study (density, surface tension, and dynamic viscosity) and can be seen in table 1. Analysing the values it is possible to see that both the density and the surface tension of the three fluids are very similar, the major differences are in the dynamic viscosity values.

Table 1 Physical properties of the substances.

Substances	ρ [kg/m^3]	$\sigma \cdot 10^3$ [N/m]	$\mu \cdot 10^3$ [Pa.s]
H_2O (*literature)	1000.0	72.0	1.00
100% Jet A-1	798.3	25.4	1.12
75% JF – 25% HVO	794.9	25.5	1.44
50% JF – 50% HVO	792.3	24.6	1.79

The work was divided into two parts. In the first one, the camera was kept parallel to the droplet falling plane and the droplet diameters and impact velocities were measured through the impact upon the dry surface to allow the determination of the height of the liquid films. In the second part, the camera was leaned 10º with the horizontal plane to improve the visualization. In this part, the droplet impinges upon a liquid film with dimensionless thicknesses (δ^*) of 0.1, 0.5 and 1. Since the perspex is a hydrophobic surface it was not possible to produce the thinner films for the water, the water and perspex are a non-wetting system. In this way, the thinner films produced for H_2O were defined by the minimum volume that allows the production of a homogeneous liquid film and it was then calculated for every droplet diameter.

To measure the droplet diameter and the impact velocity a MATLAB algorithm was created and through the subtraction of the background and the binarization of the image, the number of pixels correspondent to the droplet diameter were counted. Multiplying by the pixel size, the droplet diameter was then determined. The maximum pixel size was $49.2\mu m/pixel$ providing a maximum error of $24.6\mu m$. For the impact velocity, the image treatment was similar but in this case, it was chosen the last droplet before impact and the droplet $5ms$ before and again by pixel counting the values were determined.

A more detailed description of the experimental work can be seen in Ribeiro [20].

3. Results and Discussion

3.1 Impact Characterization

As mentioned before five different inner diameters were used and the resultant droplet diameter are presented in table 2. As can be seen, the differences between the three fuels were quite reduced and the largest diameters were registered for H_2O. The impact velocity was also determined for the three impact heights used ($h_1 = 0.175m$, $h_2 = 0.5m$ and $h_3 = 1m$) and it is presented in the table 3.

Table 2 Droplet Diameters.

D_{in} [mm]	H_2O [mm]	100% JF [mm]	75% JF – 25% HVO [mm]	50% JF – 50% HVO [mm]
1.50	4.03	3.04	3.05	3.06
0.84	3.61	2.76	2.77	2.78
0.51	3.23	2.44	2.47	2.47
0.25	2.80	2.07	2.12	2.18
0.10	2.27	1.73	1.74	1.78

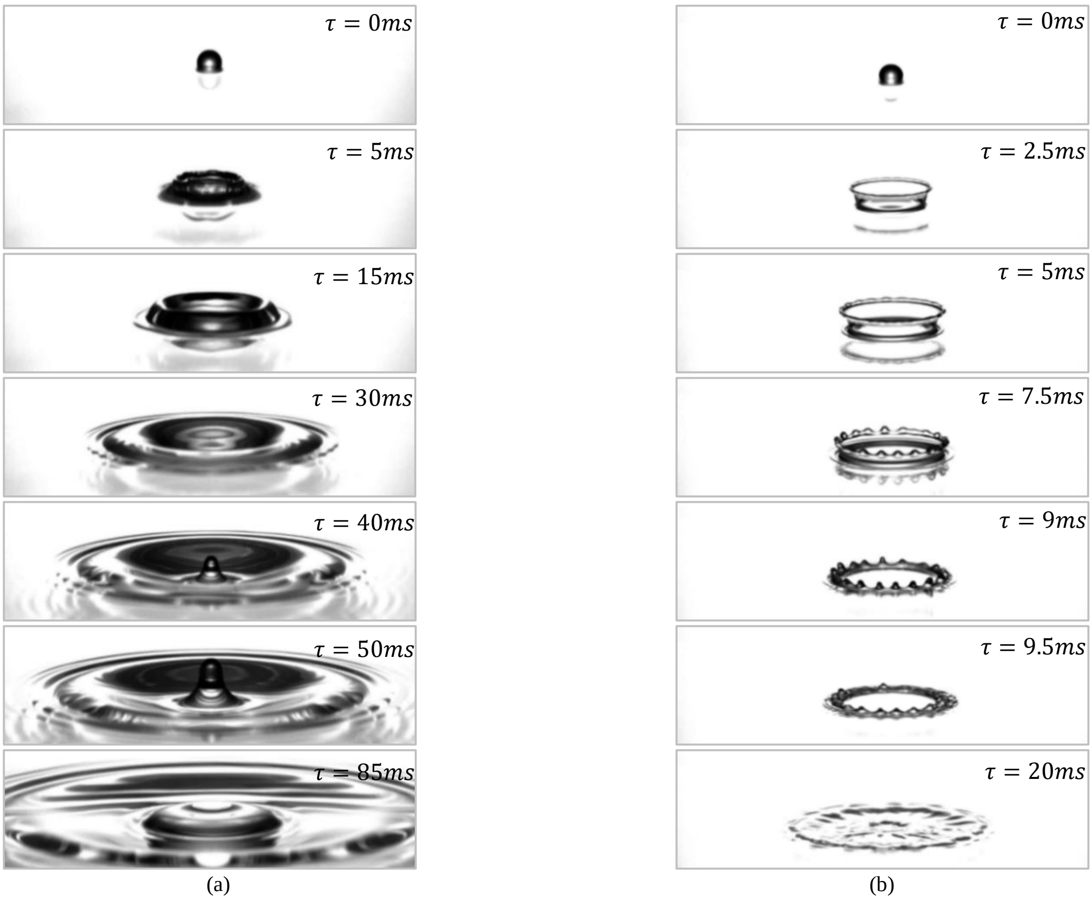
Using the droplet diameter and the impact velocity, as well as, the fluids physical properties, the dimensionless thickness of the liquid film and also some dimensionless numbers (Reynolds, Weber, Laplace, and Ohnesorge numbers), were calculated. Their variation was noticeable and their ranges can be identified: $1411 < Re < 16889$; $103 < We < 1623$; $27987 < La < 288101$; $1.863 \cdot 10^{-3} < Oh < 9.593 \cdot 10^{-3}$.

Table 3 Impact Velocities.

h [m]	D_{in} [mm]	U_0 [m/s]			
		H_2O	100% JF	75% JF – 25% HVO	50% JF – 50% HVO
h_1=0.175	1.50	1.83	1.80	1.80	1.81
	0.84	1.83	1.80	1.80	1.80
	0.51	1.82	1.79	1.79	1.80
	0.25	1.81	1.79	1.79	1.79
	0.10	1.81	1.79	1.78	1.79
h_2=0.50	1.50	3.07	2.97	2.99	3.00
	0.84	3.05	2.96	2.97	2.97
	0.51	3.04	2.93	2.94	2.95
	0.25	3.02	2.90	2.93	2.93
	0.10	2.96	2.88	2.90	2.91
h_2=1.00	1.50	4.21	4.05	4.06	4.06
	0.84	4.18	4.00	4.00	4.00
	0.51	4.15	3.95	3.96	3.96
	0.25	4.09	3.83	3.86	3.89
	0.10	3.98	3.68	3.68	3.78

3.2 Phenomena Visualization

In this work six different phenomena were spotted: deposition, fingering, prompt splash, crown splash, jetting and bubbling. In Figure 2 it is possible to see two phenomena without the formation of secondary atomization: a) spreading, when the droplet merges with the liquid film; b) fingering, instabilities were created in the outer rim of the liquid lamella and structures with a finger-like shape grow, normally when the size of the fingers was higher they tend to break up and formed secondary atomisation. The time after and before impact is defined by τ, being $\tau = 0$ the instant of impact.



(a) (b)

Figure 2 Image sequences: a) the spreading of a single droplet in a liquid film for the 75% JF/25% HVO mixture ($D_{in} = 0.84mm,\ D_0 = 2.77mm,\ h = 175mm,\ \delta^* = 1$); b) the fingering of a single droplet in a liquid film for the 75% JF/25% HVO mixture ($D_{in} = 0.51mm,\ D_0 = 2.47mm,\ h = 175mm,\ \delta^* = 0.1$).

It was also spotted prompt splash (Figure 3) when the impact energy was high enough for the droplet to disintegrate in the first moments after impact. Very tiny droplets were ejected from the liquid lamella periphery while the crown is still rising or advancing. Figure 4 shows: a) crown splash and b) jetting.

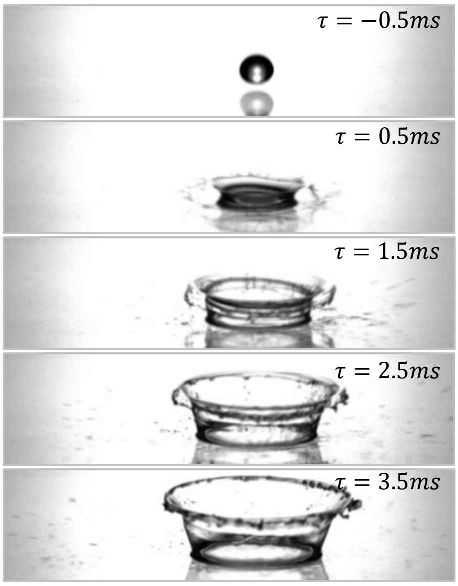
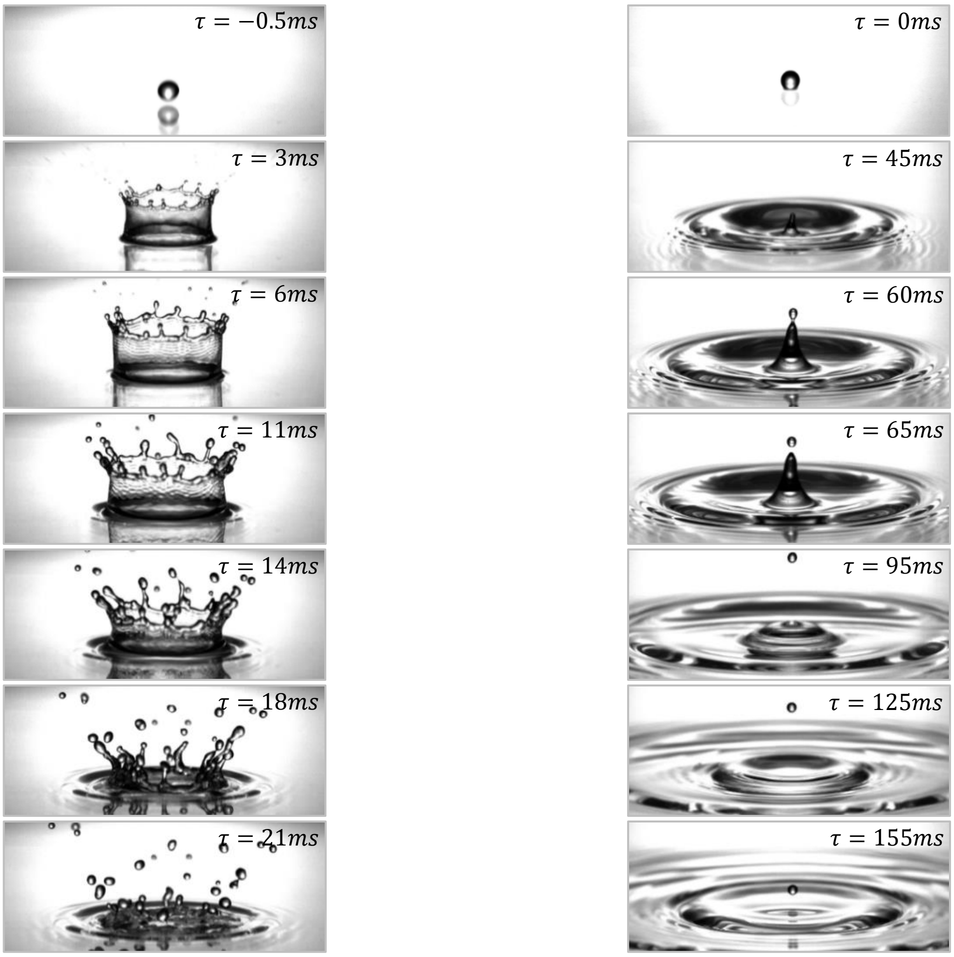


Figure 3 Prompt splash for the 50% JF/50% HVO mixture ($D_{in} = 1.50$mm, $D_0 = 3.06$mm, h = 1m, $\delta^* = 0.1$).



(a) (b)

Figure 4 Image sequences: a) crown splash in a liquid film for H_2O ($D_{in} = 0.51mm,\ D_0 = 3.23mm,\ h = 1m,\ \delta^* = 0.1^*$); b) Jetting in a liquid film for 100% JF ($D_{in} = 1.50mm,\ D_0 = 3.04mm,\ h = 175mm,\ \delta^* = 1$).

Crown splash normally occurs after the stage of maximum expansion and encompasses the breakup of the crown sheet and it is really common in the impact with liquid films. This phenomenon produces various sizes of splashed products while prompt splash only produces very tiny ones. The jetting as it is shown in the image sequence only happened two times in these experiments. However, it was several times accompanied by prompt and crown splash. Shortly, after the crown collapses, a vertical extension of fluid (jet) rises from the center of the impact site. The jet breakup and one or more droplets were ejected.

There was only one phenomenon left, the bubbling (figure 5). Its occurrence was a surprise since that was only reported for deep pools in the literature [6, 21]. It just occurred for one set of conditions. In this impact, no prompt splash was spotted and a very thin and high crown was formed. Many secondary droplets were ejected and the crown started to close at the top ($\tau = 12.5ms$). Later, the crown is almost closed forming a dome or a bubble and some rotation is imposed to the ejected droplets ($\tau = 35ms$). The crown completely closed and a vortex downwards started forming at the top of the bubble ($\tau = 42.5ms$). The vortex grown downwards and connect to the liquid film ($\tau = 72.5ms$). With time the vortex become thinner ($\tau = 115ms$) and ends up ceasing forming an empty bubble ($\tau = 152.5ms$). Many secondary droplets fall on the bubble but one of them breaks it up ($\tau = 208ms$). In the remaining frames, it is possible to see the collapse of the bubble.

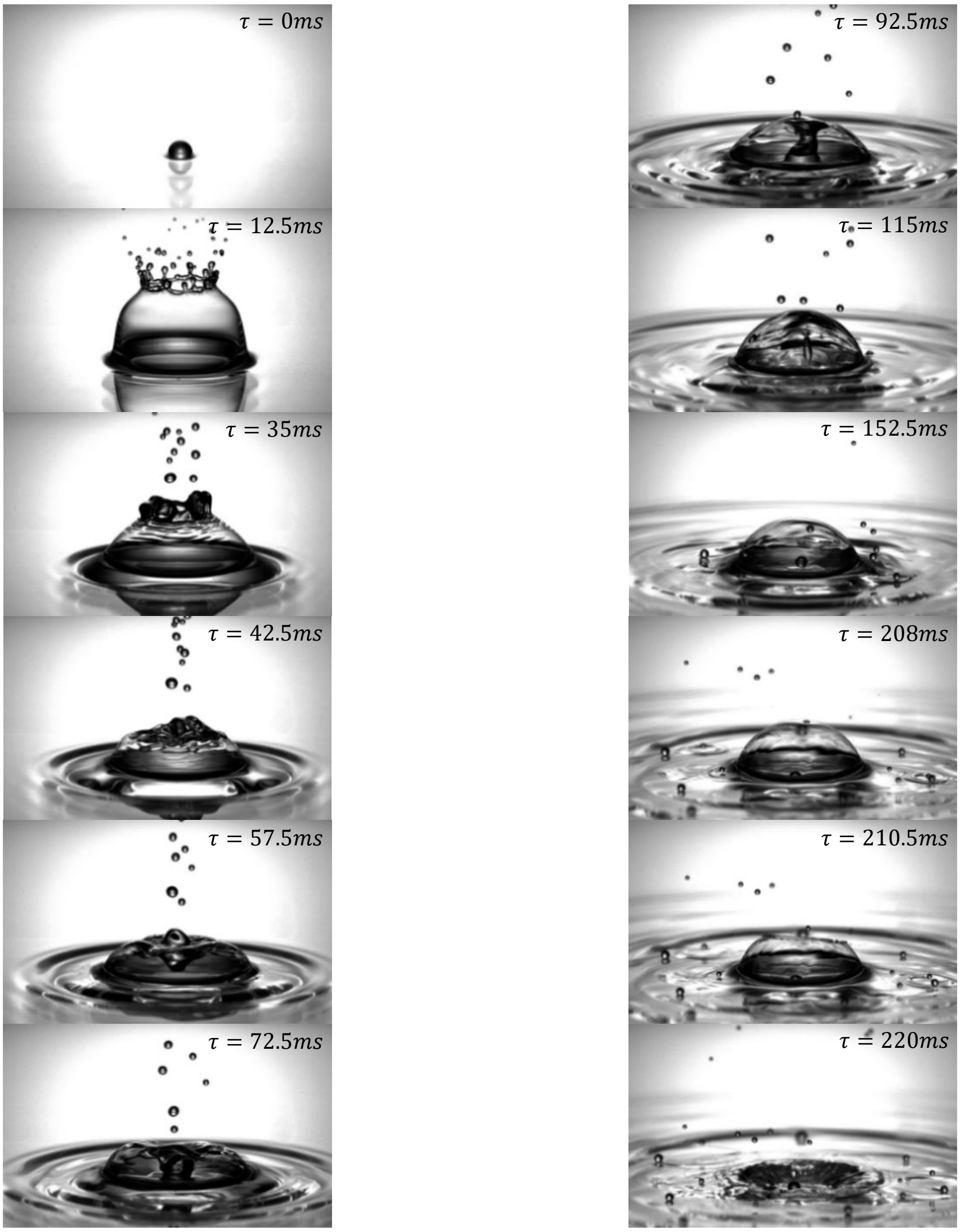


Figure 5 Crown splash follow by bubbling for the 75% JF/25% HVO mixture ($D_{in} = 1.50mm$, $D_0 = 3.05mm$, $h = 1m$, $\delta^* = 0.5$).

3. Outcomes

Regarding the obtained outcomes, first, they were divided into splash and non-splash as table 4 shows. In the table, N means non-splash and Y means that splash has been observed. There were also two cases identified as $N*$, which correspond to jetting without prompt or crown splash happened. Some authors defended that jetting alone should be considered splash but others alleged that splash involves the physical separation from the immediate impact site. Taking that into account, in this study, jetting alone was treated as a special outcome. As can be seen for h_2 and h_3 splash always occurred, but for the lower height the occurrence of splash depended on the fluid physical properties, the droplet diameter and dimensionless thickness of the liquid film.

Table 4 Splash and non-splash outcome identification.

Impact Heights	Needle Inner Diameters [mm]	H_2O			100% JF			75% JF – 25% HVO			50% JF – 50% HVO		
		0.1*	0.5	1	0.1	0.5	1	0.1	0.5	1	0.1	0.5	1
h_1	1.50	N	N	N	Y	N	N*	Y	Y	N*	N	N	N
	0.84	N	N	N	Y	Y	Y	N	Y	N	N	N	N
	0.51	N	N	N	N	N	N	N	Y	N	N	N	N
	0.25	N	N	N	N	N	N	N	N	N	N	N	N
	0.10	N	N	N	N	N	N	N	N	N	N	N	N
h_2	1.50	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	0.84	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	0.51	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	0.25	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	0.10	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
h_3	1.50	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	0.84	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	0.51	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	0.25	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	0.10	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Despite the splash and non-splash division it is relevant to catalogue the phenomena observed for all sets of impact conditions, as well as, identify the differences and similarities between them. Due to the wide amount of impact conditions and to turn the analysis easier schemes will be presented below (figure 6 and 7).

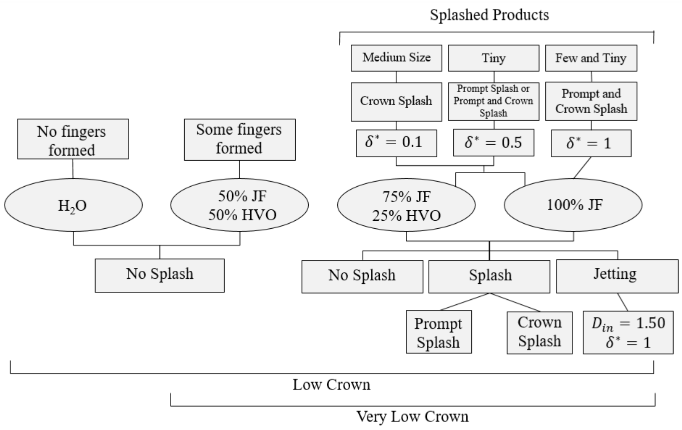


Figure 6 Scheme with the description of the outcomes for the lower impact height ($h_1 = 0.175m$).

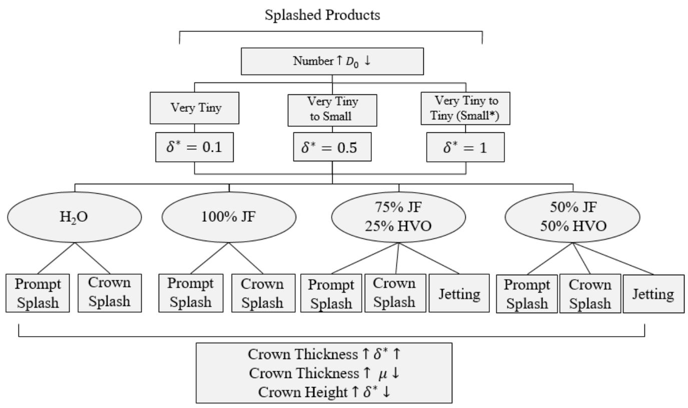


Figure 7 Scheme with the description of the outcomes for the second impact height ($h_2 = 0.5m$).

In h_1 both for H_2O and the 50%/50% mixture non-splashed happened for all the impact conditions, therefore the mixture had finger formation. The 100% JF and the 75%/25% mixture showed both splash, non-splash and jetting. Jetting just happened for one set of impact conditions ($D_{in} = 1.50mm$; $\delta^* = 1$). Analysing the outcomes through the dimensionless thickness of the liquid films it is possible to see that both fuels had splash for the thin and intermediate liquid film but only the 100% JF showed splash for the thicker. For the thinner liquid films only crown splash were spotted and the size of the secondary droplets were considered medium. For the intermediate liquid films happened prompt splash or prompt and crown splash together. Finally, for the thicker films, the ejected droplets were few and tiny. In this height, the crown was considered low and even very low for the fuels.

For h_2 splash was always spotted. Prompt and crown splash occurred for all the fluids and sometimes followed by jetting for the two mixtures. Regarding the secondary atomization, for the thin liquid films was very tiny, for the intermediate was very tiny to small and for the thick was very tiny to tiny with some episodes of small. It was possible to identify some behaviours such as the increase of the crown thickness with the increase of the dimensionless thickness of the liquid film and with the decrease of the viscosity. It was also noticed that the crown height increased when the dimensionless thickness decreased.

For h_3 the behaviour was similar to the observed for h_2 but crown splash happened for all the impact conditions and there were episodes of jetting for all the fluids. Bubbling was spotted for the 75%/25% mixture. One of the major difference to the outcomes of h_2 was the fact that there were more and larger ejected droplets.

4. Summary and Conclusions

The goal of this experimental study was to determine and evaluate the outcomes of a single droplet impinging upon liquid films with different dimensionless thicknesses. Moreover, analysing the influence of the parameters involved in the dynamic behaviour of the droplet, such as the fluid physical properties, the droplet diameter and impact velocity, and the relative thickness of the liquid film.

To achieve that an experimental facility was validated and it has been concluding that the droplet diameter and impact velocity were clearly influenced by the fluids physical properties. Additionally, the different outcomes were clearly influenced by the fluids physical properties as well as by the relative thickness of the liquid film. It was also found that the size and number of the splashed products changed with the relative thickness of the liquid film and also with the impact energy. It was spotted that bubbling can occur with shallow liquid films. Globally, the behavior of the 100% JF and the 75%/25% mixture was very similar, the major differences were spotted for the 50%/50% mixture.

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