UNIVERSIDADE DA BEIRA INTERIOR
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Experimental Study of a Single Droplet Impinging upon Liquid Films: Jet Fuel and Biofuel Mixtures

(versão corrigida após defesa)

Daniela Filipa Santo Ribeiro

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Orientador: Prof. Doutor André Resende Rodrigues da Silva

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Resumo

O presente trabalho foca-se no impacto de uma única gota com um filme de líquido do mesmo fluido. Este estudo particular tem interesse para várias áreas de pesquisa e tem uma grande variedade de aplicações tais como injeção de combustível em motores de combustão interna e processos que envolvem pintura a spray, revestimentos e arrefecimento de sistemas. O Ser Humano começou a procurar novas alternativas para reduzir a poluição e visto que os transportes contribuem com uma porção significativa é extremamente necessário apostar em alternativas aos combustíveis fósseis. A introdução de biocombustíveis no sector da aviação poderia ser um exemplo. O grande desafio passa então por modificar e otimizar motores a pistão de forma a operarem eficientemente com combustíveis alternativos. De forma a alcançar isso, nestes ensaios experimentais foram usadas misturas de Jet Fuel e Biocombustível.

O principal objetivo desta dissertação é visualizar o comportamento dinâmico do impacto de gotas únicas com filmes de líquido com diferentes espessuras relativas, vários resultados são possíveis. Para o obter foram usados quatro fluidos: água (como referência), 100% Jet A-1 e misturas de 75%/25% e 50%/50% de Jet A-1 e NEXBTL, respetivamente, visto que na aviação civil só são aceites misturas com no mínimo 50% de Jet Fuel em volume. Para garantir cálculos precisos as propriedades físicas dos fluidos foram medidas.

Uma montagem experimental foi idealizada e construída. A instalação inclui uma câmara digital de alta velocidade que foi manualmente acionada com um tempo de exposição específico. O local de impacto foi iluminado por uma lâmpada led através de um vidro difusor de forma a fornecer uma luz uniforme de frente para a câmara. Uma bomba infusora foi conectada à agulha e libertava as gotas a uma taxa de bombeamento específica. Um recipiente de perspex conteve o filme de líquido. Foram utilizadas cinco agulhas com diâmetros internos diferentes para produzir cinco diâmetros de gota diferentes para cada fluido. Adicionalmente, foram estabelecidas três alturas de impacto para proporcionar três velocidades de impacto e três números de Weber para cada agulha. Foram consideradas espessuras do filme de líquido de 10%, 50% e 100% do diâmetro da gota.

A existência de splash foi reportada, assim como as suas características. Algumas conclusões sobre a influência das condições de impacto e das propriedades físicas das substâncias foram indicadas. Usando os dados obtidos foram feitas comparações com os limites de splashing disponíveis na literatura.

Palavras-Chave

Impacto de gotas, Estudo Experimental, Jet Fuel, Biocombustível, Filme de Líquido e Splash.

Abstract

The present work is focused on a single droplet impinging upon a liquid film of the same fluid. This particular study is a matter of interest for several research areas and has a wide variety of applications such as fuel injection in internal combustion engines and processes involving spray paints, coatings and systems cooling. The human being started searching for new alternatives to reduce pollution, and since transports contribute with a significant portion, it is extremely necessary to bet on alternatives to fossil fuels. The introduction of biofuels in the aviation sector could be an example. The huge challenge is to modify and optimize piston engines to operate efficiently with alternative fuels. In order to achieve that, in these experiments, Jet Fuel and Biofuel mixtures were used.

The main goal of this dissertation is to visualize the dynamic behavior of single droplets impinging upon liquid films with different relative thicknesses, several outcomes are possible. To accomplish that, four fluids were used: water (as reference), 100% Jet A-1, 75%/25% and 50%/50% mixtures of Jet A-1 and NEXBTL, respectively, since civil aviation only accept mixtures with at least 50% Jet Fuel in volume. To assure the accuracy of the calculations, the fluids physical properties were measured.

An experimental facility was designed and built, and the setup includes a high-speed digital camera that was manually triggered with a specific exposure time. The impact site was illuminated by a led lamp through a diffusion glass to provide uniform back lighting. A syringe pump connected to the needle released the droplets with a specific pumping rate. The liquid film is held by a perspex container. Five needles were used with different inner diameters to yield five distinct droplet sizes for each fluid. Additionally, three impact heights were established to provide three impact velocities and Weber numbers for each needle. The liquid films depths considered were 10%, 50% and 100% of the droplet diameter.

The existence of splash was reported as well as its characteristics. Some conclusions about the influence of the impact conditions and the fluids physical properties were indicated. Using the obtained data comparisons were made with some splashing thresholds available in the literature.

Keywords

Droplet Impact, Experimental Study, Jet Fuel, Biofuel, Liquid Film and Splash.

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Nomenclature

A	Coefficient which depends on the surface roughness
Bo	Bond Number
Ca	Capillary Number
D_0	Droplet diameter
D_{in}	Needle inner diameter
D_{meas}	Measured Diameter
D_{ou}	Needle outer diameter
D_{theo}	Theoretical Diameter
Fr	Froude Number
g	Acceleration due to gravity
h_1, h_2, h_3	Impact heights: $1 - 0.175m$; $2 - 0.500m$; $3 - 1.000m$.
K_L	Splashing/Deposition Limit
l_a	Surface roughness
La	Laplace Number
m_p	Mass of the empty pycnometer
m_s	Mass of the pycnometer full of the substance
Oh	Ohnesorge Number
R_0	Droplet radius
Re	Reynolds Number
R_{in}	Needle inner radius
R_{nd}	Dimensionless parameter related to the surface roughness
U_0	Droplet impact velocity
V_p	Volume of the pycnometer
We	Weber Number
We_c	Critical Weber Number

Greek Symbols

δ	Thickness of the liquid film
δ^*	Relative thickness of the liquid film
θ_{stat}	Static contact angle
μ	Dynamic Viscosity
ν	Kinematic Viscosity
ρ	Density
σ	Surface Tension
τ	Time after impact

Subscripts

0	Related to the droplet
in	Related to the needle
L	Limit

List of Acronyms

fps	Frames per second
HVO	Hydroprocessed Vegetable Oil
JF	Jet Fuel
NEXBTL	Neste Renewable Diesel

Chapter 1

Introduction

This dissertation is devoted to the experimental study of the dynamic behavior of a single droplet impinging upon a liquid film with various relative thicknesses using Jet Fuel and Biofuel mixtures. The outcomes of these impacts provided different phenomena which will be studied and compared with splashing thresholds available in the literature.

This first chapter was divided into four sections. In the first section, the motivation to develop this study is explained. A literature review (section 1.2) was made to present the actual state of knowledge about this theme, including several studies which are considered in the plan and execution of these experiments. In the third section, the objectives of this dissertation are listed and explained. Lastly, in the last section, the general outline of the document is summarized.

1.1 Motivation

Fortunately, the human being has already started to be environmentally concern 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 fossil fuels. 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 introduction of alternative fuels becomes more important since the fossil fuel resources are scarce and not renewable. So, studies were needed to optimize the mixture preparation and also to study the phenomena created by the spray impingement in the interposed surfaces. In order to achieve that, the present work is focused on a single droplet impinging upon a liquid film of the same fluid. The study of single droplets is important to help develop numerical spray models.

However, this particular study is a matter of interest for several research areas and has a wide variety of applications such as fuel injection in internal combustion engines, processes involving spray paints, coatings, and cooling of electronic equipment. In several of these applications the droplets impinged upon a dry surface, but quickly a thin liquid film was formed by the preceding droplets. This is the reason for the investigation of the dynamic behavior of single droplets impinging upon liquid films.

The current legislation only allows fuel mixtures with at least 50% Jet Fuel in volume, for that reason only mixtures with 50% or less of Biofuel were studied since the objective of this work is to be able to be implemented immediately in civil aviation. The biofuel chosen is the NEXBTL (Pizziol, 2017), an hydroprocessed vegetable oil.

1.2 Literature Review

The droplet impingement on the literature was reported for various cases, mainly upon dry and wetted surfaces. When the impact is on a dry wall, the surface could be smooth or rough, heated or angled, and it can even be influenced by a crossflow. When the impact is upon a liquid film, the surface underneath can be smooth or rough, the thicknesses of the liquid films can be thin or really thick, and heat could also be applied.

In the following subsections, the impingement governing parameters, as well as, the impact regimes will be presented and explained. Some considerations about the droplet impinging upon wetted surfaces will be detailed. In the fourth subsection, an experiment's background will be provided including the conclusions of several authors regarding the impact upon liquid layers. Finally, some splashing thresholds will be considered and clarified.

1.2.1 Impingement Governing Parameters

Many studies encompass the dynamic behavior of droplets impinging upon dry and wetted surfaces. The resultant phenomena of these impacts were always difficult to understand, due to its complexity but also to the number of parameters involved. In order to group some of them, the dimensionless numbers were usually used by the researchers. Bai and Gosman (1995) described two of them: the droplet Weber number and the droplet Laplace number. The Weber number is the ratio between the inertial and surface tension forces, so it is the relation between the droplet kinetic energy and surface energy. The equation to calculate the Weber numbers is presented below:

$$We = \frac{\rho D_0 {U_0}^2}{\sigma} \qquad (1.1)$$

where ρ is the density of the droplet fluid, D_o is the droplet diameter, U_o is the droplet impact velocity and σ is the surface tension of the droplet fluid. The Laplace number is a measure of the surface tension and viscous forces acting on the liquid and it is defined by the equation 1.2.

$$La = \frac{\rho \sigma D_0}{\mu^2} \qquad (1.2)$$

where μ is the dynamic viscosity of the droplet fluid. However, more dimensionless numbers were used in the study of droplet interactions, and Yarin (2006) [20] described some more. The

Reynolds number is the ratio between the inertial and viscous forces and it is defined in the equation 1.3.

$$Re = \frac{\rho D_0 U_0}{\mu} \qquad (1.3)$$

The Ohnesorge number is also often times used, it relates the viscous forces to the inertial and surface tension forces and can be equated relating the Weber and Reynolds numbers, as can be seen in equation 1.4.

$$Oh = \frac{\mu}{\sqrt{\rho \sigma D_0}} = \frac{\sqrt{We}}{Re} \qquad (1.4)$$

Other dimensionless numbers are the Bond, the Froude, and the Capillary numbers. The Bond number is a ratio between the body (gravitational) forces and the surface tension forces, it characterizes the gravity-related effects and is presented in the equation 1.5. The Froude number is the ratio between the inertial and the gravitational forces and it is presented in the equation 1.6. Lastly, the Capillary number is the ratio between the viscous and the surface tension forces and can be seen in equation 1.7.

$$Bo = \frac{\rho g {D_0}^2}{\sigma} = \frac{We}{Fr} \qquad (1.5)$$

$$Fr = \frac{U_0}{\sqrt{g D_0}} \qquad (1.6)$$

$$Ca = \frac{\mu}{\sigma} U_o = \frac{We}{Re} \qquad (1.7)$$

However, these three dimensionless numbers will not be used in this dissertation since Yarin (2006) said that in the phenomena obtained by the droplet impacts, the gravity effects were normally not significant.

It is through the impact conditions that the dimensionless numbers were calculated, thus parameters such as the droplet size and impact velocity also governed the outcomes of the droplet impact. The relative thickness of the liquid film is a crucial parameter and it will be explained in section 1.3.3.

The wettability of the surface also governs the droplet/wall interactions. According to Rioboo et al. (2001), the wettability is defined as the ability of a fluid to spread out on a solid surface and it is quantified by the static contact angle (θ_{stat}), as can be seen in Figure 1.1.

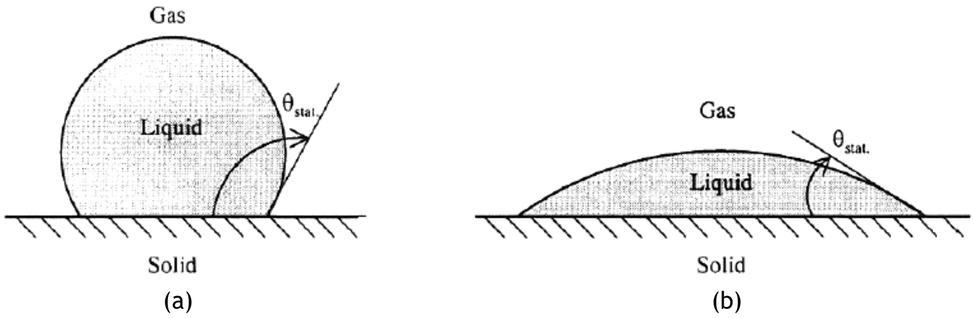
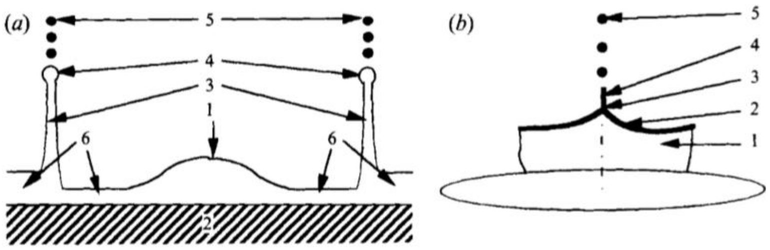


Figure 1.1: Definition of the static contact angle by Rioboo et al. (2001): a) non-wetting system; b) highly wetting system.

For example, a smooth perspex surface and pure water are a non-wetting system, while a smooth perspex surface and 100% Jet A-1 are a highly wetting system.

Understanding the different components evolved in the droplet impingement is essential to comprehend the content of this dissertation. In this way, over this document some of the nomenclature used are proposed by Yarin and Weiss (1995) and can be seen in figure 1.2. Through this image it is possible to clearly identify what are those components, such as the crown sheet, the rim, the cusp, the secondary atomization, etc.



(a) *1 – residual top of the droplet; 2 – wall; 3 – section of crown-like sheet propagating outwards;* 4 – cross-section of free rim; 5 – secondary droplets formed from the cusps of free rim; 6 – liquid layer on wall;
(b) 1 – crown-like sheet; 2 – free rim at its top edge; 3 – cusp; 4 – thin jet emerging at cusp; 5 – secondary droplets formed on the breakup of the jet.

Figure 1.2: Impingement representation by Yarin and Weiss (1995): (a) splashing mechanism; (b) free rim and secondary droplets magnified.

1.2.2 Impact Regimes

Along with the great amount of parameters that govern the droplet impact upon a dry or wetted surface, a set of possible phenomena can happen depending on the different impact conditions. It is important to identify these regimes as well as understand their differences. Several authors tried to define these phenomena and their opinions are not always unanimous.

The definitions change according to the authors, so the definitions used in this dissertation will be presented as well as others that were found important. A definition of the different phenomena involved in the droplet impact upon both dry and wetted surfaces will be given below.

Stick was defined as when the droplet adheres to the surface in a spherical-like form (figure 1.3), which happen normally at very low Weber numbers (Bai and Gosman, 1995). This phenomenon appears typically for impacts upon dry surfaces.

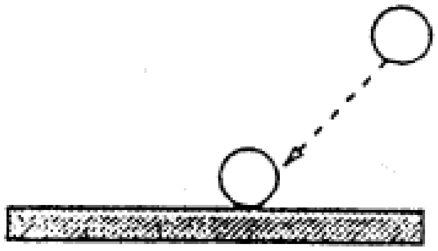


Figure 1.3: Stick regime according to Bai and Gosman (1995).

Spread (figure 1.4), also called deposition was defined as all the process when the droplet deformed and stayed at the surface, without any droplets ejected (Rioboo et al., 2001). By Bai and Gosman (1995) it was reported that spreading happens when the impinging droplet merges with a pre-existing film or spreads out and forms a liquid film on a dry surface. These two definitions were basically the same, and spread or deposition occurs commonly for low impact energies.

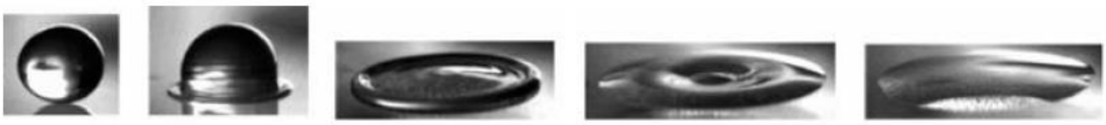


Figure 1.4: Deposition regime according to Rioboo et al. (2001).

When a droplet impinges upon a dry surface or liquid film with high Reynolds and Weber numbers a number of fingers are formed radially. The droplet spreading can have instabilities at the outer rim of the liquid lamella that can be called fingering. These fingers grow as result of these instabilities (Marmanis and Thoroddsen, 1996), images will be presented ahead. Some authors called these “fingers” jets and identify this phenomenon as jetting, but this description will not be adopted in this dissertation and the phenomenon considered as jetting will be explained ahead.

Prompt splash occurs when the impact energy is high enough for the droplet to disintegrate in the first moments after impact, according to Rioboo et al. (2001). Very tiny droplets are ejected from the periphery of the liquid lamella while the crown is still rising or advancing (figure 1.5).

Rioboo et al. (2001) wrote that prompt splash is only observed in the impact with rough surfaces, however, this is not the case since in the literature there are reports of this phenomenon with a whole range of surface topography and also in the impact with liquid films. Therefore, it is clearly influenced by the surface structure.

Figure 1.5: Prompt splash regime according to Rioboo et al. (2001).

The crown splash phenomenon is widely described in the literature and it is also called corona splash or delayed splash (figure 1.6). Crown splash occurs after the stage of maximum expansion and encompasses the break up of the crown fluid sheet and is really common in the impact with liquid films.

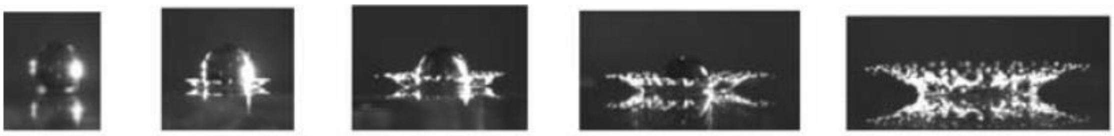


Figure 1.6: Crown splash regime according to Rioboo et al. (2001).

The rebound or partial rebound occurs only when a receding phase is observed (the droplet recoils towards the impact point). This phenomenon was also called jetting and that is the nomenclature used in this dissertation. Shortly, when a droplet impinges upon a dry surface or a liquid film, sometimes after the crown collapses, a vertical extension of fluid, called “jet”, rises from the center of the impact site and droplets are ejected, continuing its upward movement and then falling by gravity forces. Rebound can only happen for the impact upon dry surfaces, as can be seen in figure 1.7.

Figure 1.7: Complete rebound regime according to Rioboo et al. (2001).

The partial rebound can happen in both dry or liquid surfaces (figure 1.8). Again, in this dissertation, since the impact is upon liquid films, this phenomenon will be called jetting.

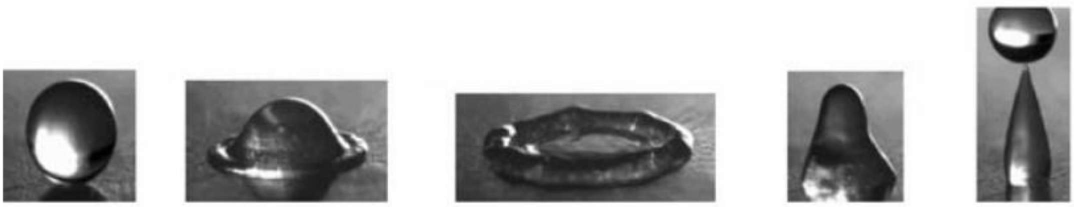


Figure 1.8: Partial rebound regime (or jetting) according to Rioboo et al. (2001).

The last phenomenon which is important to mention regarding this study is the bubbling, reported by Macklin and Metaxas (1976) as an event where a crown was formed and started to close forming a dome or a bubble.

The occurrence of bubbling normally just happen for liquid films with higher relative thickness, such as deep pools ($\delta^* > 10$). Images of this phenomenon will be presented ahead.

1.2.3 Wetted Surfaces

The most important characteristic of the liquid films is their thickness, to simplify the comparison between the authors, it is often described as a relative thickness or as a dimensionless thickness (δ^*) and can be calculated by the ratio between the thickness of the liquid films (δ) and the droplet diameter (equation 1.8).

$$\delta^* = \frac{\delta}{D_0} \qquad (1.8)$$

Several studies reported that the relative thickness of the liquid film influences the droplet impact outcomes. According to the value of the relative thickness, it can be divided into categories as suggested by Tropea and Marengo (1999):

- Thin film: relative thickness of the liquid film between $l_a/D_0 < \delta^* < 3{R_{nd}}^{0.16}$, the impact depends on the surface topography;
- Medium liquid film: relative thickness of the liquid film between $3{R_{nd}}^{0.16} < \delta^* < 1.5$ the droplet impact still depends on the surface topography, but its influence becomes weaker;
- Shallow pool: relative thickness of the liquid film between $1.5 < \delta^* < 4$ the impact does not depend on the surface topography, but only on the thickness of the liquid film;
- Deep pool: relative thickness above 4 ($\delta^* \gg 4$) the impact does not depend either on the surface topography or the thickness of the liquid film.

Other authors made other divisions. For example, Vander Wal et al. (2006b) considers thin films when $\delta^* \approx 0.1$, thick films when $1 \leq \delta^* \leq 10$ and deep pools for $\delta^* \gg 10$. In that way, along this dissertation and due to the range of relative thicknesses of the liquid films ($0.1 \leq \delta^* \leq 1$), it will be considered that the film with $\delta^* = 0.1$ is a thin liquid film, the films with $\delta^* = 0.5$ is a shallow liquid film and the film with $\delta^* = 1$ is a thick liquid film. Therefore, it will be easier to address the different thicknesses of the liquid films. In the next subsection the influences of these liquid films will be reported by the experimental work of several authors.

1.2.4 Experiment's Background

Macklin and Metaxas (1976) experimentally tested the impact of water droplets upon liquid films ($0.4 < \delta^* < 50$). They observed the general characteristics of splashing upon thin and thick films. For thin films, the cavity (illustrated in figure 1.9) was cylindrical and the wave swell seemed negligible. In contrast, when the thickness of the liquid film increased, the cavity presented a more hemispherical form and the wave swell was more pronounced.

Through their experiments, they also reported that both the crown height and the ejected droplets decreased while the thickness of the liquid film increased, however, the height of the jet formed increased. It is interesting to mention that for nearly all the impacts upon deep pools, bubbling did not occur. Lastly, they reported that for deep splashing ($\delta^* \geq 1.5$) the bottom of the container did not affect the splashing, and for shallow splashing ($\delta^* \leq 0.1$) the cavity was nearly cylindrical. As can be seen, their division of the thicknesses of the liquid films were different than the presented by Tropea and Marengo (1999).

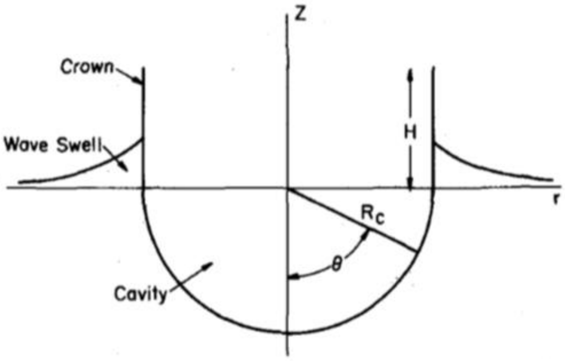


Figure 1.9: Splash model and the coordinate system used by Macklin and Metaxas (1976).

The Chandra and Avedisian (1991) experiments were essentially upon dry solid surfaces. Nonetheless, they also performed impacts upon a preexisting liquid film as a result of the impingement of previous droplets. They reported that due to the liquid film the spreading of the droplet changed significantly.

Range and Feuillebois (1998) focused their work on the droplet impact upon dry rough plates but also with shallow pools for comparison, in both cases a crown was formed and broke-up into small droplets. The biggest difference between this two is that for thin liquid films the splashing happens for smaller Weber numbers. In both cases, there were perturbations in the crown and later the crown disintegrated.

The radius of the droplet can be calculated by the equilibrium between the gravity and the capillary forces that act in the droplet/needle interface (equation 1.9). Multiplying the equation 1.9 by two, the equation for the theoretical droplet diameter can be found (equation 1.10).

$$R_0 = \left(\frac{3R_{in}\sigma}{2g\rho}\right)^{1/3} \qquad (1.9)$$

$$D_0 = \left(\frac{6D_{in}\sigma}{g\rho}\right)^{1/3} \qquad (1.10)$$

They verified the accuracy of the formula by measuring 100 water diameters samples with a $R_{in} = 0.535mm$ needle. They let the droplet fall $1m$ because stroboscopic measurements shown that after $1m$ of free fall the droplet is perfectly spherical. The oscillations in the separation between the droplet and the needle were damped out during the fall and do not affect the precision of the measurements (precision of 1%). They also calculated the theoretical velocity through the equation of motion.

Using fixed radius of the droplets ($R_o = 1.94 \pm 0.05mm$), they verified that for their impact conditions, in the impact with dry rought surfaces, the viscosity (has a weak influence) can be neglected in the description of the splashing limits. They also reported that the splashing mechanims of a droplet impinging upon a shallow film is quite similar to the droplet impact upon a dry rough surface. Both splashing and perturbations appearances are highly dependent on the surface tension and the solid surface material.

It is important to declare that they were really careful with the cleaning of the tip of the needle before every test while others authors did not have the same caution. Using a wet needle to produce a droplet causes liquid accumulation that separates in a non-uniform way. This behavior originates a hysteresis in the droplet diameter distribution. They covered the tip of the needle with wax to avoid wetting.

Coghe et al. (1999) measured the crown characteristics of a single droplet splashing upon thin liquid films. Their main conclusions were about the crown diameter which was found independent of the impact velocity and relative thickness of the liquid film. The crown maximum height is reached at a time after the impact and depends on the Weber number. The crown thickness grew in time and it was independent of the thickness of the liquid film and also on the impact velocity. Lastly, they spotted that the number of protruding jets from the crown rim decreases with time.

Cossali et al. (1999) used photographic techniques to measure some components of the droplet impact upon a liquid film: crown diameter, crown height, jets elongation, and secondary atomization diameter. They disclosed that the elongation of the protruding jets was independent on the thickness of the liquid film and impact velocity. Also, they noticed that the higher the Weber numbers the smaller the secondary droplets.

Lindgren and Denbratt (2000) found several numerical models in the literature and classified them as very distinct. Some of them were really simple while others were complex. The differences between them were due to the different impact conditions (temperature, the thickness of the liquid film, surface characteristics, etc).

Rioboo et al. (2000) 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 on impact: the crown formation was typical for wetted walls, even with low impact velocities and high viscosities.

For droplet impacts upon dry surfaces, the crown formation only happened for liquids with low surface tensions, however, the most common outcome was a radially extended lamella. For a fluid with higher viscosity, the droplet seemed to deform, and neither crown or lamella was formed. The higher the impact velocity the faster the spreading, despite many physical mechanisms dominating the evolution of this process. The viscosity played an important role in the impact upon dry surfaces and also in delaying spread. For wetted surfaces, only tiny variations in the droplet evolution were spotted while the viscosity increased.

The Wang and Chen (2000) experiments were centered about the splashing impact of a single droplet upon very thin liquid films. For this reason, they proposed a new method to produce very thin liquid films with good accuracy ($\delta^* < 0.1$). They also verified that the critical Weber number (the Weber number necessary for splahsing to occur) was influenced by the thickness variation of the liquid film.

They also noticed that for $\delta^* < 0.1$ the critical Weber number gets close to the minimum value. The minimum critical Weber number depends on the fluid viscosity and on the surface characteristics underneath the liquid film. They reported that the splashing dynamic is different between the thin liquid films and the thicker ones.

Moita and Moreira (2003) showed that the wettability depends strongly on the mean roughness of the surface. This suggests that a non-wetting system is composed of a surface with a very low mean roughness possibly combined with a fluid with low surface tension.

Vander Wal et al. (2006b) studied the droplets splashing upon liquid films of different depths. As mentioned by other authors, they reported that thin liquid films decreased the critical Weber number. They found that the splashed products size and number depended on the presence and thickness of the liquid film. For thicknesses between $0.1 \leq \delta^* \leq 1$ both prompt and crowm splash were spotted. For $1 \leq \delta^* \leq 10$ the liquid film limited the prompt splash and inibited the crown splash.

Both viscosity and surface tension affected the number and size of the splashed products. The number of ejected droplets during prompt and crown splash decreases while its mean size increases with the increase of the surface tension and viscosity.

They also reported that an increase in the viscosity leads to a delay of both prompt and crown splash, and correlated more significantly with the decrease of the number and size of the splashed products.

Their final conclusions were: in the impact with dry surfaces, viscosity promoted splashing, while in thin liquid films the role reverted. The surface tension role appeared to be consistent between all the fluids used by them. Lastly, they reported that high surface tension inhibits splashing both in dry or wetted surfaces.

Vander Wal et al. (2006c) combined the influence of a rough surface and a thin liquid film upon the splashing limit and dynamics. Through their experiments, they recognized that both a thin liquid film and a rough surface changed the splashing limit and dynamic substantially. A rough surface decreased drastically the critical Weber number.

On the impact with a rough surface, the topography of the surface overlaps the importance of the others parameters that govern the outcomes, especially in the splashing regime. Considerable differences between the surface tensions and the viscosities became less significant in the splashing limit and dynamic, and made the outcomes very similar.

The splashing behavior of a rough surface covered by a thin liquid film was a combination of the impact upon a rough surface and upon smooth surface covered by a thin liquid film. In that way, the splashing limit was determined first by the surface characteristics and then by the impact conditions and fluid physical properties.

Zhao et al. (2011) focused their work around the droplet impingement on deep pools and analyzed the transition between spreading and jetting. They noticed that both low viscosity and surface tension fomented the formation of an unstable crown and also high central jet, however low viscosity and high surface tension enhanced the break-up of the jet. They presented two models for the spreading/jetting transition.

Zhang et al. (2017) centered their work on the numerical simulation of a droplet impacting upon films of varied liquid properties. They investigated the relative influence of the viscosity and surface tension on the droplet impact and on the prompt splashing regime.

They found that a decrease in the fluid viscosity and surface tension increased the crown heigh while the crown thickness decreased. They also reported that the Weber number plays an important role in the dynamic behavior of the droplet when the Weber number increased, the impact process quickened and the number of splashing products increased.

1.2.5 Splashing Thresholds

The occurrence of splash was always an important concern for the researchers. The desire to predict the droplet impact outcomes originated the development of empirical correlations. The authors realized essays and used that data, as well as, data presented in the literature to obtain equations which can establish a boundary between the splash and the deposition regime.

Several correlations were presented in the literature. There were boundaries available for the impact with dry surfaces as well as with wetted surfaces. These boundaries were crucial for the implementation of numerical models. Some splashing thresholds were presented above along with a few considerations related to their development.

Bai and Gosman (1995) derived three regime transition criteria in order to create a spray impinging model. First, they developed a criterium for the transition between spread and splash for dry walls using the data of Stow and Hadfield (1981) (equation 1.11). Then they developed an empirical correlation for the transition between rebound and spread, in this case for wetted walls (equation 1.12).

$$We_c = A \cdot La^{-0.18} \quad (1.11)$$

$$We_c \approx 5 \quad (1.12)$$

The coefficient A in the equation 1.11 depends on the surface roughness. They also provided a table with the values of the coefficient for some surface roughness. Lastly, they developed a threshold between spread and splash for wetted walls trough the equation created for the dry walls assuming that a wetted wall behaves as a very rough dry surface. This assumption was made based on some studies where the authors considered the behavior between rough surfaces and liquid films similar. The equation 1.13 shows the deposition/splashing boundary for wetted walls:

$$We_c = 1320 \cdot La^{-0.18} \quad (1.13)$$

Cossali et al. (1997) also proposed a splashing threshold for droplets impinging upon wetted solid surfaces. In their experiments, they varied the droplet diameter between $2.00mm$ and $5.50mm$, the impact height between $0.05m$ and $2.00m$ and the maximum terminal velocity was found to be $6.5m/s$. They used a liquid film thickness superior to $250\mu m$.

To achieve a wide range of Ohnesorge numbers, pure water and four mixtures of water-glycerine were used. Their empirical correlation is described by the equation 1.14. In the description, they said that this deposition/splashing threshold is appropriate for $0.1 < \delta < 1$ and $Oh > 7 \cdot 10^{-3}$ and also for $Oh = 2.2 \cdot 10^{-3}$ for pure water but only for $\delta < 0.2$.

$$K_L = (Oh^{-0.4} \cdot We)_L = 2100 + 5880 \cdot \delta^{*1.44} \quad (1.14)$$

They also reported that a decrease in the Ohnesorge number decreases the splashing limit.

According to Lindgren and Denbratt (2000), the impingement was divided into two cases by Senda et al. (1999). One for low impact energies and another for high impact energies. They established that the first case was for $We < 300$ and the droplet-droplet interaction was studied. For the second case, $We > 300$ and a deposition/splashing boundary was developed. The boundary was represented by the equation 1.15.

$$We = (2164 + 7560 \cdot \delta^{*1.78}) La^{-0.2} \quad (1.15)$$

As can be seen, this empirical correlation is quite similar to the Cossali et al. one.

Vander Wal et al. (2006a) also determined an empirical correlation for the splash/non-splash boundary for both dry surface and thin liquid films. The liquid thickness used was $0.2mm$ and the droplet diameter was $2.0mm$ since with that diameter, the liquid kept the spherical form during the free-fall, excluding concerns with uneven impacts. They used different fluids and impact velocities to expand their outcomes.

They noticed a dramatic change in the splashing limit by the introduction of the thin liquid film. Based on the obtained results they tested some combinations with Ohnesorge, Reynolds, Weber, and Laplace numbers, but only the power-low correlation between Oh and Re gave a clear boundary between the two regimes. This correlation is presented in equation 1.16.

$$Oh \cdot Re^{1.17} = 63 \quad (1.16)$$

They also reported that the presence of a liquid film controls the splashing limit, and the viscosity assumed a secondary role, in opposition to the dry impacts, where viscosity was determinant. Through their analysis, the dependency of the impact velocity for thin liquid films was stronger than for dry impacts, reflecting the assumption that splashing occurs for lower Weber numbers than for dry impacts.

Huang and Zhang (2008) realized several essays of a droplet impacting upon liquid films. They compared their results with transition criteria available in the literature, and since these correlations did not fit properly with their data, they also proposed three correlations to predict the transition between rebound, deposition, jetting and splashing. Their empirical correlation for the deposition/splashing limit is presented in equation 1.17:

$$(We \cdot Re)^{0.25} = 25 + 7 \cdot \delta^{*1.44} \quad (1.17)$$

They used different needles which provided a range of droplet diameters between $1.8mm$ and $4mm$. The fluids used were water and oil with moderate viscosity. To determine this correlation the relative thicknesses of the liquid films varied between 0.3 and 1.3.

Looking at these criteria, it is noticeable that there are several differences between them. That fact was also mentioned by Lindgren and Denbratt (2000). The models presented in the literature were mostly validated for the data which originated them and normally depend on the impact conditions of the essays considered to create them.

Table 1.1 shows in resume the splashing thresholds considered in this dissertation, presenting their experiments, comments and empirical correlations.

Table 1.1: Summary of the splashing thresholds presented in the literature and used in this study.

Reference	Authors	Experiments	Conclusions	Empirical Correlations
[6]	C. X. Bai and A. D. Gosman (1995)	They derived three regime transition criteria in order to create a spray impinging model: • Spread/splash transition for dry walls using available data. • Rebound/Spread, in this case for wetted walls. • Spread/Splash threshold for wetted walls assuming that a wetted wall behaves as a very rough dry surface.	Their spray impingement model can recognize the different regimes using the transition criteria developed.	**Dry Walls:** Spread/Splashing: $We_c = A \cdot La^{-0.18}$ **Wetted Wall:** Rebound/Spread: $We_c \approx 5$ Deposition/splashing: $We_c = 1320 \cdot La^{-0.18}$
[8]	G. E. Cossali, A. Coghe and M. Marengo (1997)	They performed several essays of a droplet impacting upon liquid films and with their results proposed an empirical correlation. They used a range of droplet diameters between $2.00mm$ and $5.50mm$, impact heights between $0.05m$ and $2.00m$ and the maximum terminal velocity was found to be $6.5m/s$. They used liquid film thicknesses superior to $250\mu m$. The fluids used were water and four mixtures of water-glycerine.	They proposed an empirical correlation for the deposition/splashing boundary which holds for $0.1 < \delta^* < 1$ and $Oh > 7 \cdot 10^{-3}$ and also for $Oh = 2.2 \cdot 10^{-3}$ for pure water but only for $\delta^* < 0.2$. They also reported that a decrease in the Ohnesorge number decreases the splashing limit.	Splashing threshold: $K_L = (Oh^{-0.4} \cdot We)_L = 2100 + 5880 \cdot \delta^{*1.44}$
[15]	R. Lingren and I. Denbratt (2000)	They reported that Senda et al. (1997) divided impingement into two cases. One for low impact energies ($We < 300$) and another for high impact energies ($We > 300$) where the deposition/splashing boundary was developed.	They noticed that the models presented in the literature for the splashing threshold were quite different and these differences were originated by the impact conditions of the data used to produce them.	Splashing threshold: $We = (2164 + 7560 \cdot \delta^{*1.78})La^{-0.2}$

Table 1.1: Summary of the splashing thresholds presented in the literature and used in this study. (continued)

Reference	Authors	Experiments	Conclusions	Empirical Correlations
[21]	R. L. Vander Wal, G. M. Berger and S. D. Mozes (2006a)	Determined empirical correlations for the splash/non-splash boundary both for dry surface and thin liquid films.	They noticed a dramatic change in the splashing limit by the introduction of the thin liquid film. Power-laws correlations between *Oh* and *Re* gave a clear boundary between the two regimes. They verified that the thin liquid film and the viscosity were the most significant governing parameters of the splashing limits for wet and dry walls, respectively.	Splashing threshold: $Oh \cdot Re^{1.17} = 63$
[26]	Q. Huang and H. Zhang (2008)	They realized several essays of a droplet impacting upon liquid films, compared their results with transition criteria available in the literature and also proposed an empirical correlation. They used a range of droplet diameters between $1.8mm$ and $4mm$. The fluids used were water and oil with moderate viscosity. To determine this correlation the relative thicknesses of the liquid films varied between 0.3 and 1.3.	In the impact with liquid surfaces, the transition criteria that they used fitted their data for the oil outcomes but not for the water outcomes, so they proposed a new splashing threshold.	Splashing threshold: $(We \cdot Re)^{0.25} = 25 + 7 \cdot \delta^{*1.44}$

1.3 Objectives

As can be seen, by the literature review, many studies were made about the droplet impact upon liquid films. However, none is known to use mixtures with Jet Fuel and Biofuel. Thus, the main objective of this study is to determine the influence of the physical properties of the fuels in their dynamic behavior. To achieve it, these objectives were established:

- Design, build and validate an experimental facility to study these phenomena;
- Measure the physical properties of the fluids used and report the main differences between them;
- Visualize the outcomes obtained by the tests, divide them into splash or non-splash and describe all the phenomena observed;
- Report the major differences and similarities between the outcomes of the fuels and relate them with the impact conditions, as well as, the fluids physical properties;
- Compare the outcomes of the fuels with water, which will be utilized as a reference since its properties were well defined in the literature;
- Compare the experimental data with some splashing thresholds available in the literature.

1.4 Organization

This dissertation is divided into four chapters: Introduction, Experimental Procedure, Results and Discussion, and Conclusions and Future Work.

In this first chapter, the motivation to develop this study was explained. A literature review was given to present the actual state of the knowledge about this theme and also to describe the most important studies made in the area. The objectives of this dissertation were listed and explained and lastly, the general outline of the document was summarized.

In the second chapter, the experimental procedure will be presented in detail. The experimental arrangement will be shown, as well as, their components and specifications. The fluid property characterization will be presented. The work methodology will be detailed, including the two phases presented in the experiments. Lastly, the measurements techniques and methodologies used to process the data will be explained.

In the third chapter, the results of this study will be presented. First, the impact characterization will be made, where the droplet diameters, the impact velocities, the dimensionless numbers and the thicknesses of the liquid films will be calculated. In the second section, all the phenomena visualized will be showed and described. Then, in the third section, a detailed study of the dynamic behavior of the droplet will be made. Lastly, in the last section, the data acquired in this study will be compared with splashing thresholds available in the literature.

The last chapter of this dissertation will be divided into two sections where the conclusions and suggestions for future work will be presented.

Chapter 2

Experimental Procedure

In this second chapter, all the important features related to the experimental procedure will be presented in detail. The experimental arrangement will be shown as well as all their components and their specifications. Then, the fluids and their properties characterization (density, surface tension and viscosity) will be presented. After that, the work methodology will be detailed, including the two phases of the experiments. Finally, the measurement techniques will be explained such as the methodologies used to process the data.

2.1 Experimental Arrangement

An experimental facility was designed and built for these experiments and can be seen in figure 2.1. The experimental arrangement was essentially composed of four important parts: the image acquisition, the impact surface, the droplet dispensing system and the impact site illumination. All these four parts will be described in detail in the following subsections. To assemble all the parts a structure was built, the iron beams hold all the components except the high-speed camera. There are also holes in the iron beams that permit to change the impact velocity through the height variation of the dispensing needle.

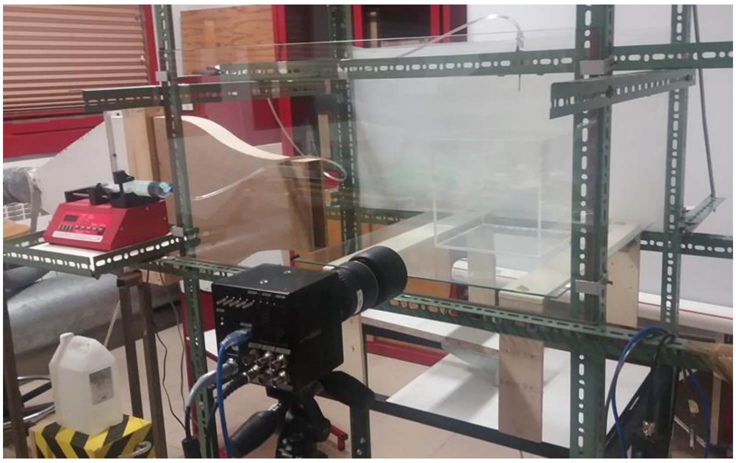


Figure 2.1: Experimental Facility.

The high-speed digital camera that made the image acquisition was manually triggered and it was positioned in front of the impact site that was illuminated by a led lamp through a diffusion glass to provide uniform backlighting. The droplet dispensing system is composed of a syringe pump connected to the needle and operated from the computer to release the droplets with 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's numbers.

2.1.1 Image Acquisition

The image acquisition is essential in these studies. A high-speed digital camera was used to allow the droplet impact visualization. Since quality and precision were important features, the camera used was a Photron FASTCAM mini UX50 with 1.3 Megapixel image resolution at frame rates up to 2,000fps and frame rates up to 160,000fps at reduced image resolution. The lens used was 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. Figure 2.2 presents the camera and the lens.

Figure 2.2: Photron FASTCAM mini UX 50 and the Macro Lens Tokina AT-X M100 AF PRO D.

The high-speed digital camera was manually triggered. The image resolution was 1280x1024, the exposure time was set at 1/5120s and the frame rate at 2,000fps which means that there are 0.5ms between pictures. These features were established at the beginning of the experiments. When the second part of the tests began there was a need to change them to allow better visualization. The frame rate was switched to 2,500fps and the exposure time to 1/6125s, by doing this, the image resolution changed to 1280x800.

2.1.2 Impact Surface

The droplet impinges upon a liquid film, therefore to hold the liquid film a perspex container was used. The material, perspex, was chosen due to its transparency and its smooth surface. The container was dimensioned for these experiments. In order to define the dimensions, tests were made with the pixel size and the distance between the camera and the impact site, to assure the minimum required dimensions to observe the phenomena. Since these were quite low, the side of the container was defined as about 40 times larger than the largest droplet diameter. The dimensions of the topless perspex right-angled container are 200x200x200mm (figure 2.3).

Figure 2.3: Perspex container 200x200x200mm.

To create the liquid film, the volume of fluid was calculated to fill all the container with the required height. It was then deposited in the container with a syringe. Since the thickness of the liquid film was really small it was quite difficult to produce the thinner liquid films, especially for water. The perspex is a hydrophobic surface, so when the volume of water correspondent to the thinner thicknesses was placed into the container, the area was not completely covered. To solve this, the volume of water was stipulated, and all the five needles were tested for the same volume of fluid, originating different relative thicknesses for every droplet diameter. For the other relative thicknesses (shallow and thick), that problem did not exist. For the other fluids, it was possible to produce the film for all the relative thicknesses.

2.1.3 Droplet Dispensing System

Creating the droplets and releasing them was an important part of the experimental arrangement. To release the droplets a syringe pump NE-1000 was used (figure 2.4). This syringe pump has an operational capacity of 1.459µl/hour with a 1ml syringe and 127.2ml/min with a 60ml syringe. In this case, a 50ml syringe was employed and the pumping rate used was 0.5ml/min. The syringe pump with the 50ml syringe can be seen in figure 2.4. This syringe is connected to the needle through a cable. One of the advantages of using the syringe pump, beyond the precision enhancement due to the controlled pumping rate, is the fact that it can be operated from the computer, which is much more practical.

Figure 2.4: Syringe Pump NE-1000.

To produce the droplets with the different diameters, five stainless steel needles were used. Their inner diameters were: 1.50mm, 0.84mm, 0.51mm, 0.25mm and 0.10mm. These needles have straight tips which improve the droplet formation, as can be seen in figure 2.5. To avoid contamination there was a set of needles for each fluid.

Figure 2.5: Stainless steel needles. Left to right the correspondent inner diameters are: 1.50mm, 0.84mm, 0.51mm, 0.25mm and 0.10mm.

Due to the use of different needle inner diameters, it was possible to have a wide range of impact conditions. In the following table, the range of values used in these experiments will be presented, including the droplet diameter, the impact velocity, the thickness and the relative thickness of the liquid films and the dimensionless numbers. In this case, the dimensionless numbers considered were: Reynolds, Weber, Ohnesourge, and Laplace numbers. The values in table 2.1 correspond to the minimum and maximum value used or obtained in these experiments. These values will be specified for every case in Chapter 3.

Table 2.1: Impact conditions range of the experiments.

D_0 [mm]	1.73	4.03
U_0 [m/s]	1.78	4.21
δ [mm]	0.17	4.03
δ*	0.1	1
Re	1411	16889
We	103	1622
Oh $\cdot 10^3$	1.863	9.593
La	27986	288100

2.1.4 Impact Site Illumination

The last part that composes the experimental arrangement is the illumination. To take the images, all the lights in the room were turned off and the windows were closed, providing a dark room. The only light source was a *20W* led lamp positioned in front of the camera. A diffusion glass was used between the impact site and the led lamp to provide uniform lighting.

The led was parallel to the droplet falling plane and the distance to the impact site was 18cm. The distance between the camera and source of light were 58cm. Others sources of light were tested but the one used provided the best illumination.

2.2 Characterization of the Fluid Properties

In this work, four substances were used. First, water since its properties (density, surface tension and viscosity) are reported in the literature and are well defined. The other three substances were 100% Jet Fuel and two mixtures with 75% and 50% in volume of Jet Fuel and the remaining volume of a Biofuel. The Jet Fuel chosen was Jet A-1 and the Biofuel was HVO (Hydroprocessed Vegetable Oil). Since one of the goals was to determine the influence of the different parameters in the dynamic behavior of the droplet with the best accuracy it appeared to be important to work with the right properties.

Consulting the literature (Handbook of Aviation Fuel Properties, 1983) the properties of Jet A-1 and HVO were presented even for a range of temperatures. However, as expected there is no information about the specific mixtures and it wasn't possible to stipulate them. It was then decided that the properties would be measured. Before presenting the tests and the results it is important to note that all the properties were measured in a controlled environment, under the following conditions: Temperature: 22ºC ± 1ºC; Humidity: 50%. To point out that although only the Jet A-1 and the two mixtures were used in this study, the properties of the HVO and the mixture of 25% in volume Jet A-1 and 75% HVO were also measured.

2.2.1 Density

The density (ρ) is defined as the ratio between the mass and the volume of a homogeneous object/solution at a specific temperature. The pycnometer method was used to determine the density (figure 2.6). This method can be applied both to solids or liquids and it is very precise.

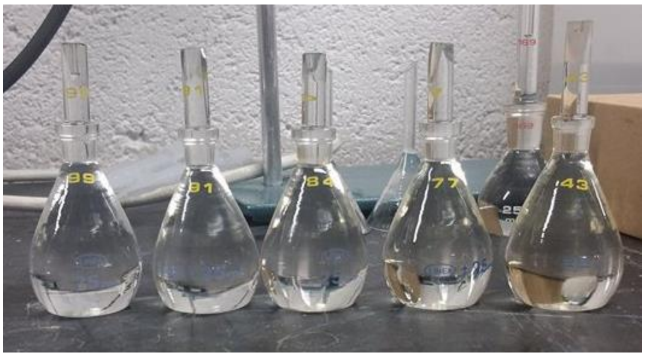


Figure 2. 6: The pycnometers with the different substances. Left to right: 100% Jet A-1, 75% Jet A-1 – 25% HVO, 50% Jet A-1 – 50% HVO, 25% Jet A-1 – 75% HVO and 100% HVO.

The density can be calculated by the following equation:

$$\rho = \frac{(m_s - m_p)}{V_p} \qquad (2.1)$$

where m_s is the mass of the pycnometer full with the substance, m_p is the mass of the empty pycnometer and V_p is the volume of the pycnometer. The instrument used to measure the masses was a Mettler Toledo PB303 DeltaRange balance, the error is $\pm 0.01g$. The results are presented in the next table:

Table 2.2: Realized essays in order to obtain the density of every fluid.

Substance	*Essay*	$m_p\,[g]$	$m_s\,[g]$	$m_s - m_p\,[g]$	$\rho\,[g/ml]$	$\rho\,[kg/m^3]$	
Jet-Fuel (100%)	1	23.4425	43.3928	19.9503	0.7980	798.0	798.3
	2	23.4425	43.4064	19.9639	0.7986	798.6	
JF (75%)-HVO (25%)	1	23.4425	43.3117	19.8692	0.7948	794.8	795.0
	2	23.4425	43.3205	19.8780	0.7951	795.1	
JF (50%)-HVO (50%)	1	23.4425	43.2471	19.8046	0.7922	792.2	792.4
	2	23.4425	43.2548	19.8123	0.7925	792.5	
JF (25%)-HVO (75%)	1	23.4430	43.1909	19.7479	0.7899	789.9	790.0
	2	23.4430	43.1921	19.7491	0.7900	790.0	
HVO (100%)	1	23.4430	43.0520	19.6090	0.7844	784.4	785.2
	2	23.4430	43.0900	19.6470	0.7859	785.9	
H_2O (values reported in the literature)						1000.0	

As can be seen, the density decreases while the percentage of Jet Fuel decreases. The Jet-Fuel exhibits the higher value but the difference between the different fluids are relatively small.

2.2.2 Surface Tension

The surface tension (σ) is defined as the specific free energy of a liquid surface at the interface with another fluid according to the Springer Handbook of Aviation Fuel Properties (1983). Usually, the surface tension values are given when the liquid is in contact with air and in this measurements too. The equipment used was the Data Physics – OCAH200 using the pendant droplet method (figure 2.7), recently calibrated and its accuracy is 0.6%.

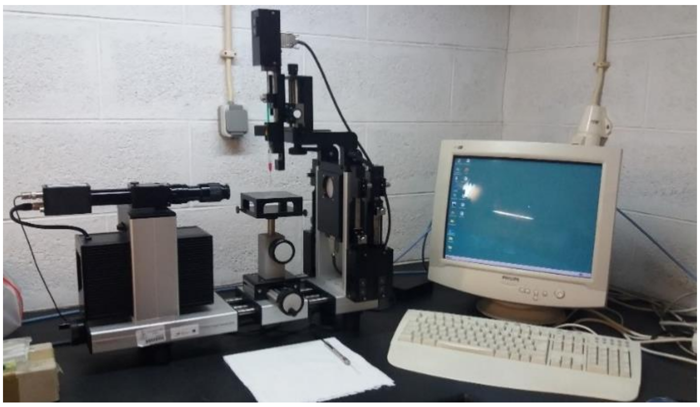


Figure 2.7: Data Physics – OCAH200 used to measure the surface tension.

Three essays were performed for each substance and the mean value was calculated. The results are presented in the next table:

Table 2.3: Realized essays to obtain the surface tension of every fluid.

Substance	*Essay 1* $[mN/m]$	*Essay 2* $[mN/m]$	*Essay 3* $[mN/m]$	σ $[mN/m]$
Jet-Fuel (100%)	25.49	25.49	25.13	25.37
JF (75%)-HVO (25%)	25.55	25.54	25.51	25.53
JF (50%)-HVO (50%)	24.60	24.58	24.73	24.64
JF (25%)-HVO (75%)	26.61	26.58	26.59	26.59
HVO (100%)	26.54	26.61	26.62	26.59
H_2O (values reported in the literature)				71.97

As can be seen, the surface tension of the five fluids is really small, about one-third of the water and doesn't follow a uniform variation with the quantity of the substances. However, considering the small variation of this physical property in the three fluids used in the experiments, the surface tension can be considered as almost constant. Therefore, it will be expected that the surface tension will not have a crucial role in the variation of the outcomes. This will be evaluated in the third chapter.

2.2.3 Viscosity

The viscosity (μ) is defined as a measure of the fluid internal resistance to motion caused by cohesive forces among the fluid molecules according to the Springer Handbook of Aviation Fuel Properties (1983). There are two types of viscosities: dynamic and kinematic. To measure the fluids viscosities it was used a Brookfield DV3TRVCP Rheometer with a cone and plate geometry for small samples as showed in figure 2.8. This instrument measures the dynamic viscosity and its accuracy is ±1.0% of the range.

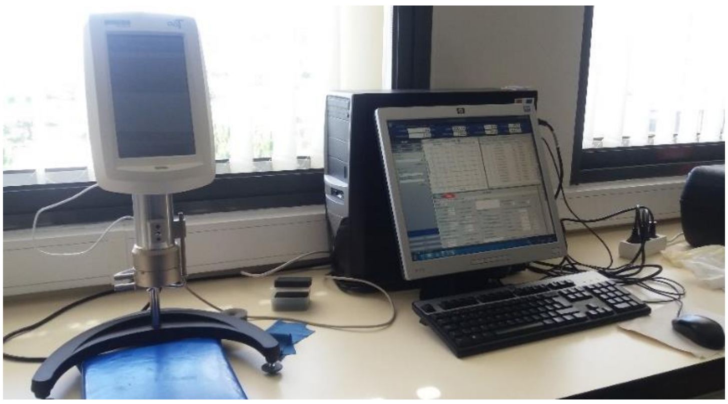


Figure 2.8: Brookfield Rheometer with a cone and plate geometry for small samples.

From the values obtained the kinematic viscosity (ν) was calculated by the following equation:

$$Kinematic\ Viscosity = \frac{Dynamic\ Viscosity}{Density} \quad (2.2)$$

Similarly to density and surface tension, all the five fluids were tested and the results of both viscosities are presented in the next table:

Table 2.4: Values of the dynamic and kinematic viscosity of every fluid.

Substance	*Dynamic Viscosity* $[Pa.s]$	ρ $[kg/m^3]$	Kinematic Viscosity $[mm^2/s]$
Jet-Fuel (100%)	0.00112	798.3	1.403
JF (75%)-HVO (25%)	0.00144	795.0	1.811
JF (50%)-HVO (50%)	0.00179	792.4	2.259
JF (25%)-HVO (75%)	0.00267	790.0	3.380
HVO (100%)	0.00340	785.2	4.330
H_2O (values reported in the literature)	0.00100	1000.0	1.000

As can be seen, the viscosities of the five fluids are considered small and the viscosity increases while the percentage of Jet Fuel decreases. The Jet-Fuel exhibits the smallest value and the HVO viscosity is approximately three times higher than the Jet-Fuel.

2.3 Work Methodology

The experiments were essentially divided into two parts. In the first one, the image acquisition was used to measure the diameter and the impact velocity, and from them, the dimensionless numbers that govern splash were calculated. In the second part, the focus was to observe the outcomes and report the important details related to their dynamic behavior. It is important to mention that the majority of the tests were made by night or during the weekend in order to avoid the possible vibrations in the building. Furthermore, as told in the subsection 2.1.4, all the lights in the room were turned off and the windows were covered providing a dark room where the only light source was the led lamp.

In the first phase of studies, the high-speed digital camera was kept parallel to the droplet falling plane. The distance between the tip of the lens and the impact site was $40cm$. The impact surface was the perspex container but it was dry. Basically, the goal of this part was just to record the droplet fall. As soon as the droplet touched the impact surface the remaining images were not considered.

Three heights were established to provide different dimensionless numbers, these heights were $0.175m$ (h_1), $0.50m$ (h_2) and $1.00m$ (h_3). It was taken one image with the background and another with the reference to determine the pixel size before the droplet release. Then, the droplet impact on the dry surface was recorded. The images acquired in this phase of studies were used to determine the droplet diameter and the impact velocity for every needle of every fluid. These results were needed to calculate the thickness of the liquid films that will be used in the second phase of studies.

In the second part, the droplet impinges upon a liquid film. Three relative thicknesses were chosen: 0.1, 0.5 and 1. These relative thicknesses correspond to 10%, 50% and 100% of the droplet diameter. The height was calculated by the diameters obtained in the first phase of studies and as said in the subsection 2.1.2 the volume of fluid was calculated to fill all the container with the required height. Since perspex is a hydrophobic surface it was not possible to produce the thinner liquid films for water. It was then determined a minimum value of volume that allows producing a homogeneous liquid film and the relative thickness was calculated for each droplet diameter. For the other fluids, it was possible to produce the films for all the relative thicknesses, since the perspex surface and the three fluids are highly wetting systems. The tests were made for the four fluids, the three relative thicknesses, the three impact heights and the five diameters.

It was important to mention that in this second part the position of the camera was changed. It was leaned 10º with the horizontal plane. In this way, the visualization improved and the entire crown can be seen. The exposure time and the frame rate were also changed in order to provide better visualization. In these tests, the outcomes were the main goal. From these images, the dynamic behavior of the droplet impact was identified and its characteristics reported.

2.4 Measurement Techniques and Methodologies to Process Data

As mentioned before, the first part of these studies must be analyzed to allow the execution of the second part. The dimensionless numbers determination is essential to evaluate the outcomes and the droplet diameter and the impact velocity must be measured. Also, the droplet diameter measurement is crucial since these values are needed to determine the height of the liquid film for each case.

In this last section, the measurement techniques used will be presented, as well as, the methodologies to process data (image treatment, binarization, etc). The image processing was supported by the information presented in Gonzalez and Woods (2008). Finally, the pixel sizing will be described since the measurements were calculated from the images and pixel is the measurement unit.

2.4.1 Droplet Diameter

Calculating the droplet diameter was an essential step since these results are needed to determine the thickness of the liquid film that should be added to the container. To determine the diameter of the droplets a MATLAB algorithm was written. As mentioned before, in the first phase of studies the images were taken with the camera parallel to the droplet falling plane and these were the images used. To improve precision five tests were made for each needle of the same fluid.

The first thing to do before starting the analysis is to select the ones that will be used. All the frames from the first complete droplet that can be seen until the last frame before impact were considered (around 27 frames). A background image without any droplet was also needed.

An example which includes a background image and a frame with one droplet is showed in figure 2.9.

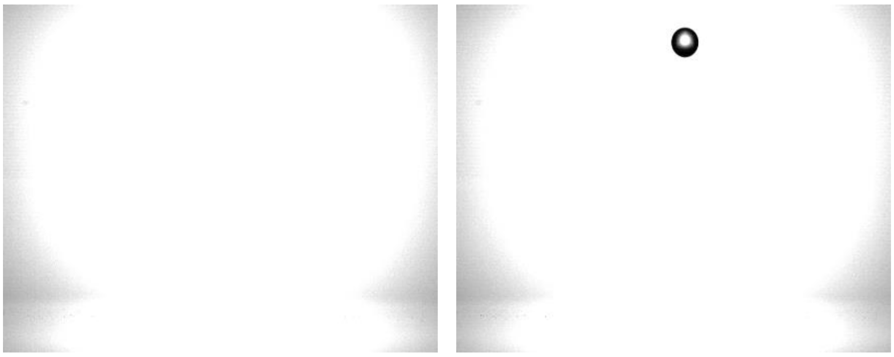
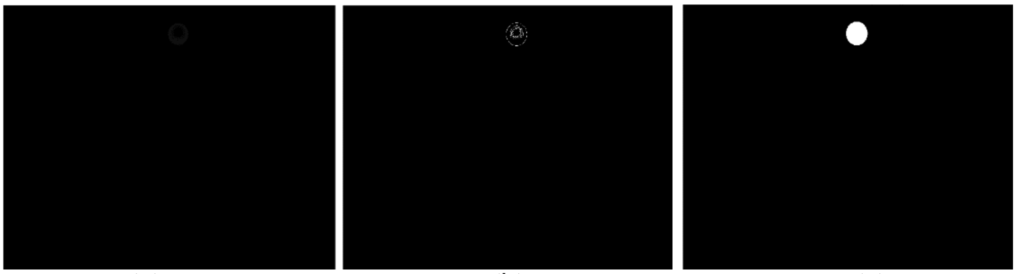


Figure 2.9: On the left an image of the background and on the right an image with the droplet.

Briefly, the algorithm uses an image of the droplet and another of the background and it subtracts the background to the droplet image. At this point, the image only contains the droplet (a). The next step is to transform the image into binary, the pixels are divided into zeros and ones. The zeros correspond to black pixels and the ones to white pixels (b). Lastly, the area within the droplet perimeter is filled (c). The sequence in figure 2.10 shows the process.



(a) (b) (c)

Figure 2.10: Data processing to obtain the droplet diameter: (a) Subtraction between the image of the droplet and the background; (b) Transformation into binary; (c) Fill the area within the droplet perimeter.

It is important to mention that it was also applied a filter to eliminate possible errors such as one or many pixels assuming the value one outside the droplet perimeter. These errors are due to possible dust particles or even to small reflexes. At this point, the image processing is completed and the droplet diameter can now be calculated.

To determine the droplet diameter two measurements were made: the vertical and horizontal maximum length. The reason can be seen in figure 2.11, the droplet shape varies along the trajectory, stretching and contracting. Considering that and with the concern of verifying the spherical form of the droplet, all vertical and horizontal maximum lengths of every droplet, since the first complete droplet that appears in the image until the last one before impact, were considered and the mean values for both vertical and horizontal maximum length were found.

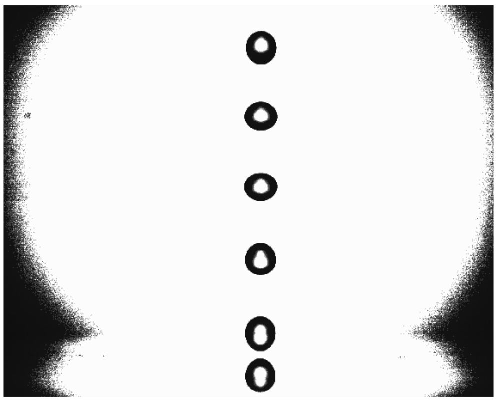


Figure 2.11: Assembly of five frames separated by 5ms to represent the shape-shifting of the falling droplet along the vertical fall.

To measure the vertical and horizontal maximum length, the MATLAB algorithm was also used. The vertical maximum length was calculated with the following process: add the values of all the elements of each column and since the white pixels correspond to ones and the black pixels correspond to zeros, this action basically accounts the number of pixels in each column that are white. Thus, the column with the maximum value of pixels matches the vertical maximum length.

To determine the horizontal maximum length starting from the matrix that was created to calculate the vertical maximum length, the zeros are replaced by ones and the values different from zero are replaced by zeros. Adding all the columns, the number of columns with black pixels were counted and then subtracting that value to the image total horizontal pixels (1280) the maximum value of white pixels was found and that is the horizontal maximum length of the droplet.

As mentioned before, five tests were made and the mean vertical and horizontal maximum lengths of them were calculated. Finally, the higher value between these two lengths was selected for the droplet diameter, mainly the horizontal length. These values were measured in pixels and multiplying by the pixel size, the corresponding length was obtained. The pixel size determination will be mentioned in the section 2.4.3. The fact that the droplet shape varies in three dimensions and the images show just two of them cannot be forgotten and that is why the higher value was considered. It is also important to mention that the differences between the vertical and horizontal maximum lengths never exceed 2% of the droplet diameter, according to this the droplet was then considered spherical in these experiments.

2.4.2 Impact Velocity

In these studies, it is indispensable to calculate the dimensionless numbers such as Reynolds, Weber, Laplace and the Ohnesorge numbers. Having the fluid properties and the droplet diameter, the only element left to determine all these dimensionless numbers is the impact velocity. Similarly to the droplet diameter measurement, the software MATLAB was also employed. Three images were used, the background, the droplet right before impact and the droplet 5ms before impact. The figure 2.12 shows an assembly with the two droplets used to determine the impact velocity, where the droplet traveled distance in $5ms$ can be seen, the third droplet seen in the figure corresponds to the shade of the droplet right before impact, which is cut from the image to facilitate the measurements.

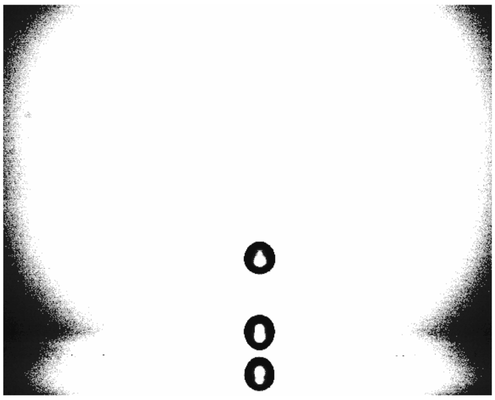


Figure 2.12: Assembly of two frames containing a droplet $5ms$ before impact and the last one before impact.

To calculate the impact velocity, the centroid position of both droplets were found and the distance between them was divided by the time between the two frames. To choose the gap between the two droplets the literature was taken into consideration, values of 5ms and 6ms were normally used. In order to define the value of the gap, a small study was made. In this study, the impact velocity of the same droplet was calculated for gaps between 5ms and 1ms. It was verified that the differences were quite small ($\pm 0.009 m/s$), so $5ms$ was used.

Regarding image treatment, the process is in part identical to the droplet diameter. The algorithm subtracts the background to the droplet image, transforms it into binary and fills the droplet perimeter. After that, the droplet centroid position is given and a cross is marked into the image to provide its location visualization, as can be seen in figure 2.13.

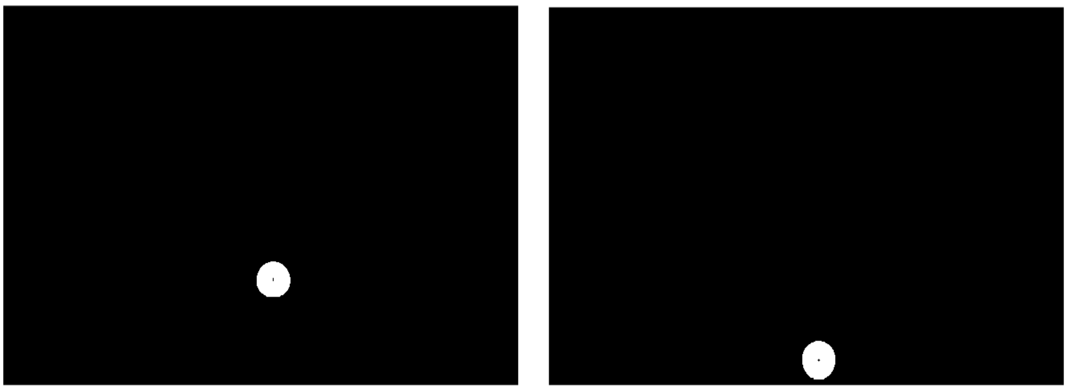


Figure 2.13: Two frames used to calculate the impact velocity, both droplets with a black cross that represents the droplet centroid.

Finally, multiplying the distance between the two centroids for the pixel size, which will be mentioned in section 2.4.3, the droplet traveled distance was determined and dividing by $5ms$

the impact velocity was obtained. Similarly to the droplet diameter case, five tests were made and the mean value of them was used as the impact velocity.

2.4.3 Pixel Sizing

All the measurements in this work were made using the images acquired by the high-speed digital camera. Scaling them becomes crucial. To establish the size of the pixel, in every test made an image with a reference was taken. To improve precision the reference used was one of the needles, figure 2.14. Its outer diameter was 1.82mm (figure 2.14).

Using the software MATLAB a code was written to solve this topic. Essentially, the code measured the number of pixels that corresponded to the needle outer diameter and later the real value in meters is divided for them. Therefore, the pixel size was determined.

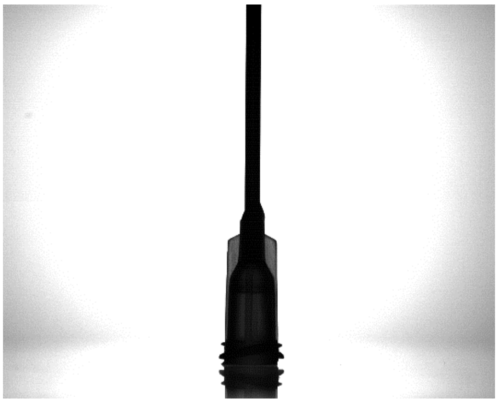


Figure 2.14: Reference used to determine the pixel size $D_{ou} = 1.82mm$.

Respecting to the image treatment, the only alteration to the needle frame was to transform it into binary, mentioned in section 2.4.1. After that, the contour of the needle is well defined in white and the rest of the picture is black. Ten lines of the image were selected at the top and it is asked to the program to give the positions of the elements with the value one, the white pixels. The distance between the two sides of the needle contour matches the outer diameter number of pixels. As mentioned above, dividing the outer diameter by the number of pixels gives the pixel size. Important to notice that ten lines were chosen in order to confirm the vertical position of the needle and to discard any error.

The reference image was taken for every test, although the distance between the camera and the impact site was kept constant. Millimetric differences in the camera position or even in the focus adjustment causes different pixel sizes. In these studies, the reference assumed values between 37 and 40 pixels. So, the minimum pixel size was $45.5\mu m$ and the maximum was $49.2\mu m$. It is also necessary to account the error associated with the droplet diameter and impact velocity measurements. Consulting the Springer Handbook of Experimental Fluid Mechanics (2007), it was confirmed that the measurements of an object length in a digital image with gray values associated to the pixel positions can only be determined with an accuracy of ± 0.5 pixel ($\pm 24.6 \mu m$). It is also relevant to notice that this error corresponds to 1.4% of the smallest droplet diameter and about 0.6% of the highest.

Regarding the impact velocity, its value was calculated with an accuracy of $\pm 0.00492 m/s$, since it was determined by the ratio between half pixel and the time between the two frames used to calculate the impact velocity ($5 ms$).

Chapter 3

Results and Discussion

In this chapter, the results of the experiments will be presented. First, the impact characterization will be made, where the droplet diameter will be determined and compared with the theoretical one. The values of the different impact velocities will be presented and the dimensionless numbers calculated. Then, through the droplet diameter, the thicknesses of the liquid films will also be calculated to allow the second part of the experiments. The second section is dedicated to the visualization. The various phenomena observed will be shown and described to provide a better understanding of the third section.

The third section includes a detailed study of the dynamic behavior of the droplets impinging upon liquid films, the different outcomes will be identified and the similarities and differences between them will be reported considering the fluid properties, the impact velocities, the droplet diameters and the thickness of the liquid films. At the end of the chapter, the focus will be the splashing threshold. Some authors were considered, and the splash and non-splash boundaries defined by them will be compared with the results obtained in this study.

3.1 Impact Characterization

It is an important goal to observe the outcomes of the droplet impact, but before that, it is necessary to know the important features involved. As mentioned before, in the first phase of studies, the droplet diameter and the impact velocities were measured through a MATLAB algorithm. The following subsections present these values as well as the thicknesses of the liquid films, calculated by the droplet diameters, and the dimensionless numbers for every case.

3.1.1 Droplet Diameter

The first results obtained in these experiments were the droplet diameters. The reasons for that and the methodology to determine these values were already been described in subsection 2.4.1. Table 3.1 shows the droplet diameters for all the cases studied, the five needle inner diameters for the four fluids used. As explained before five tests were made for every case and the mean value was used, but it was also verified that the droplet diameter does not change with the impact height. According to this, the values presented in the table 3.1 were mean values of the 15 tests made for the same needle inner diameter with the same fluid, for the three heights.

Table 3.1: The droplet diameters used in the experiments.

Needle Inner Diameter [mm]	H_2O [mm]	100% Jet A-1 [mm]	75% Jet A-1 and 25% HVO [mm]	50% Jet A-1 and 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

As can be seen, the H_2O exhibits the largest diameters. For all the five needle inner diameters, the resultant diameter for H_2O is $0.5mm$ to $1mm$ higher than the other fluids. This fact is due to its higher surface tension and density relative to the other three fluids. The differences between the Jet A-1 and the two mixtures are quite reduced, but it is noticeable that the mixture with 50% Jet A-1 has the largest diameters, then the mixture with 75% Jet A-1 and lastly, the 100% Jet A-1 with the smallest values. The only exception to this trend happens for the needle with $D_{in} = 0.51mm$ where the two mixtures exhibit the same value.

Before starting the experiments, the theoretical droplet size was calculated using the equation 1.9, which Range and Feuillebois (1998) verified the accuracy through the measurements of 100 water droplets. The droplet radius was calculated from the equilibrium between the gravity and the capillary forces acting on the liquid interface between the droplet and the needle. To calculate the theoretical droplet size the equation 1.9 was multiplied by two, originating the equation 1.10.

$$R_0 = \left(\frac{3R_{in}\sigma}{2g\rho}\right)^{1/3} \quad (1.9)$$

$$D_0 = \left(\frac{6D_{in}\sigma}{g\rho}\right)^{1/3} \quad (1.10)$$

Figure 3.1 shows four graphics comparing the measured droplet size to the theoretical droplet size for each fluid.

Looking at the graphics, it is possible to see that the measured diameter, the one that was calculated from the images acquired, is higher than the theoretical. The only exception occurs for the needle with the higher inner diameter. In this case, the theoretical diameter is higher for all the fluids but almost coincident with the measured one. It is also noticeable that the difference between the theoretical and measured diameters decreases while the needle inner diameter increases. It can mean that the smaller the needle inner diameter the higher the difference to the measured diameter.

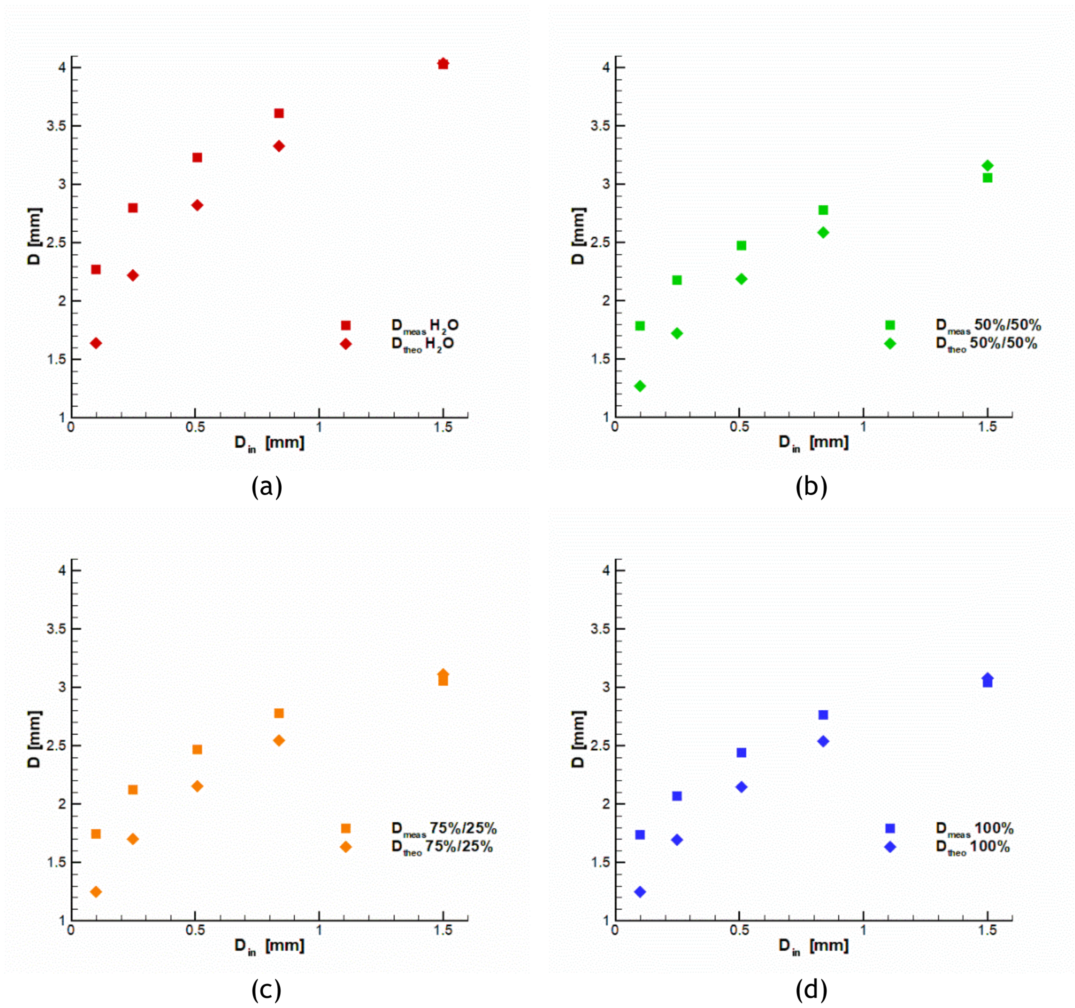


Figure 3.1: Graphics comparing the measured droplet size to the theoretical droplet size: a) H2O; b) mixture of 50% Jet A-1 and 50% HVO; b) mixture of 75% Jet A-1 and 25% HVO; d) Jet A-1.

In fact, Range and Feuillebois (1998) used a needle with an inner radius of $0.535mm$, a diameter of $1.070mm$, to validate this equation. So, maybe this equation should not be used for needle inner diameters under $1.00mm$. However, for the needle inner diameter of $1.50mm$, the results were very close. Moreover, in the Range and Feuillebois (1998) experiments, the impact height was $1m$ since stroboscopic illuminations of the droplet show that after $1m$ of free-fall the droplet was completely spherical. In these experiments, two impact heights under 1m were used, but it was verified that the droplet diameter does not change with the impact height, at least significantly.

From the equations 3.1 and 3.2, it can be seen that the droplet diameter depends on the surface tension but also on the density. The 50% mixture has a higher diameter than the 75% mixture and the 100% Jet A-1 but exhibits the lower surface tension. However, the difference between the values of the surface tension of these three fluids is really small. Still, the density is inversely proportional to the droplet diameter, which means that the lower the density the higher will be the droplet diameter, and that is probably why the 50% mixture has higher droplet diameters than the 75% mixture and consequently the 75% mixture has higher droplet diameters than the 100% Jet A-1.

It is important to point out that Range and Feuillebois (1998) were extremely careful with the tip of their needle while other authors were not. Using a wet needle to produce a droplet causes liquid accumulation that separates in a non-uniform way. From this fluid accumulation results a hysteresis in the droplet diameter distribution. They covered their needle with wax to avoid the wetting.

In these experiments, the tip of the needle was always cleaned before every test to avoid the liquid accumulation. However, no treatment or substance was employed or applied to avoid wetting.

The images presented in figure 3.2 allows visualizing the discrepancies in the droplet size according to the inner diameter of the needle used to produce them.

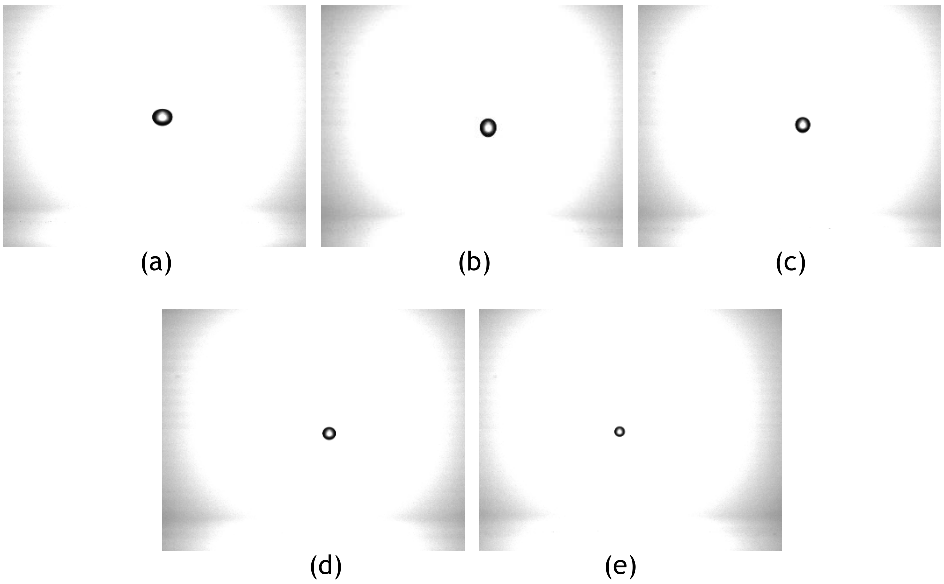


Figure 3.2: The difference between the droplet size according to the inner diameter of the needle used to produce them: a) D_{in}=1.50mm; b) D_{in}=0.84mm; c) D_{in}=0.51mm; d) D_{in}=0.25mm; e) D_{in}=0.10mm.

3.1.2 Impact Velocity

The methodology to calculate the impact velocity was already explained in the subsection 2.4.2. These velocities were calculated for the three impact heights and are presented in table 3.2. For every case, the result showed in table 3.2 was a mean value of the five essays performed. The essays used to measure the impact velocity were the same used to determine the droplet diameter.

Table 3.2: The impact velocities used in the experiments.

Impact Heights	Diameters [mm]	U_0 [m/s]			
		H_2O	100% JF	75% JF/25% HVO	50% JF/50% HVO
h_1=175mm	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=500mm	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_3=1000mm	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

The impact velocities vary between $1.78m/s$ and $4.21m/s$. Like the droplet diameter, the highest impact velocities occurred for water. As expected, for the same fluid and the same height, the impact velocity grows while the droplet diameter increases, however for the three fuels this growth was very smooth. Between the 100% JF and the two mixtures the differences were quite reduced. As expected the density is an important physical property governing the impact velocity, the higher the density, the higher the droplet weight, therefore the higher the impact velocity shall be. However, the differences between the density of the 100% Jet A-1 and the two mixtures is tiny. The surface tension and the viscosity also played an important role in the impact velocity.

As can be seen, the higher velocity corresponds to the mixture of 50% JF/50% HVO, then the mixture 75%JF/25% HVO and lastly, the lower impact velocity was obtained for the 100% Jet A-1. There were several exceptions, where the 100% Jet Fuel exhibited higher values than the 75% JF/25% HVO mixture. These differences happened in: h_1: $D_{in} = 0.25mm$ and $D_{in} = 0.10mm$; h_3: $D_{in} = 0.84mm$ and $D_{in} = 0.10mm$. There is also one case where the impact velocity of the 100% Jet Fuel and the 75% JF/25% HVO mixture is the same (h_1: $D_{in} = 0.84mm$). It was also important to notice that the differences were really small and can be due to the precision of the measurements.

It was possible to calculate the theoretical impact velocity through the equation of motion but it was not found relevant for these studies since the accuracy between the equation and several authors data were not reliable.

3.1.3 Liquid Film Thickness and Dimensionless Numbers

One of the main goals of this study is to observe the outcomes of a single droplet impinging upon a liquid film. For that purpose, the relative thicknesses of the liquid films were chosen. A variety of liquid films was wanted. With that in mind, three relative thickness were selected, corresponding to thin ($0.1D_0$), shallow ($0.5D_0$) and thick (D_0) liquid films. Using them provided a wide range of results. Therefore, the thickness of the liquid films were 10%, 50% and 100% of the droplet diameter. The following table presents the thicknesses of the liquid films:

Table 3.3: The thickness of the liquid films used in the experiments.

Impact Heights	δ^*	D_{in}=1.50 [mm]	D_{in}=0.84 [mm]	D_{in}=0.51 [mm]	D_{in}=0.25 [mm]	D_{in}=0.10 [mm]
H_2O	0.1	0.40	0.36	0.32	0.28	0.23
	0.5	2.02	1.80	1.62	1.40	1.14
	1	4.03	3.60	3.23	2.79	2.27
100% JF	0.1	0.30	0.28	0.24	0.21	0.17
	0.5	1.52	1.38	1.22	1.03	0.87
	1	3.04	2.76	2.44	2.06	1.73
75% JF – 25% HVO	0.1	0.31	0.28	0.25	0.21	0.17
	0.5	1.53	1.39	1.24	1.06	0.87
	1	3.05	2.77	2.47	2.12	1.74
50% JF – 50% HVO	0.1	0.31	0.28	0.25	0.22	0.18
	0.5	1.53	1.39	1.24	1.09	0.89
	1	3.06	2.78	2.47	2.18	1.78

To produce these films the following method was used: calculate the required volume to fill the container with the required height and using a syringe place the volume in the container. The associated error was $\pm 0.1ml$ which corresponds to $\pm 2.5\mu m$ in the height of the fluid deposited in the container. It was considered a precise method.

The films were produced without any problems except for the thin relative thickness of water. The smooth perspex is a hydrophobic material (H_2O and the smooth perspex are considered a non-wetting system), thus the volume of fluid put in the container does not spread out. Due to that a minimum volume of water, that could fill the container providing a homogeneous film, was established. Therefore, $35.0ml$ were used to produce the thinner films for all droplet sizes for H_2O. That is why in the following tables the value of the relative thickness for water appears with an asterisk ($\delta^* = 0.1^*$). This fact was taken into account in the analysis of the outcomes, since a direct comparison was not possible between the H_2O and the other three fluids for the thinner liquid films. The table 3.4 presents the values of the relative thickness of the thinner films for H_2O.

Table 3.4: The relative thickness of the thinner liquid films for H_2O.

D_{in} [mm]	δ^*
1.50	0.22
0.84	0.24
0.51	0.27
0.25	0.31
0.10	0.39

In these experiments, four dimensionless numbers were considered: Ohnesorge, Laplace, Reynolds and Weber numbers. Table 3.5 shows their values. A description of these dimensionless numbers was presented in subsection 1.2.1. However, it is important to remember that Ohnesorge and Laplace's numbers were independent of the impact height. They just depend on the fluid properties and on the droplet diameter. On the other hand, Reynolds and Weber's numbers depend on the impact height, therefore they were calculated for every impact height.

There was a wide range of impact conditions, which is one of the primary concerns of this study. Looking at the table, the variations of the dimensionless numbers were noticeable and it was possible to identify their ranges: $1411 < Re < 16889$; $103 < We < 1623$; $27987 < La < 288101$; $1.863 \cdot 10^{-3} < Oh < 9.593 \cdot 10^{-3}$.

Observing the table, it was verified that the highest Reynolds numbers occurred for H_2O, which is understandable since it depends on the droplet diameter, density, dynamic viscosity and impact velocity and H_2O exhibits the highest values for all them except for the dynamic viscosity. However, the dynamic viscosity is inversely proportional to the Reynolds number. As expected both Reynolds and Weber's numbers increase with the impact height, since both depend on it. Ohnesorge number decreases while the droplet diameter increases and Reynolds, Weber and Laplace's numbers increase while droplet diameter increase.

To finish, the tiny differences in the droplet diameters and in the impact velocities become widely significant in the value of the dimensionless numbers. That shows that although these two parameters were very close, the impact conditions were large, therefore a wide variety of outcomes will be expected.

Table 3.5: Dimensionless numbers used in the experiments (Oh, La, Re and We).

				h_1		h_2		h_3	
Fluid	**D_{in}**	**$Oh \cdot 10^3$**	**La**	**Re**	**We**	**Re**	**We**	**Re**	**We**
H_2O	1.50	1.863	288101	7357	188	12343	529	16889	990
	0.84	1.969	257871	6560	167	10966	466	15026	876
	0.51	2.081	230879	5871	149	9770	413	13348	772
	0.25	2.237	199917	5056	128	8405	353	11400	650
	0.1	2.482	162387	4093	103	6702	277	9003	499
100% JF	1.50	4.514	49087	3899	310	6440	845	8780	1570
	0.84	4.735	44596	3536	280	5819	759	7874	1390
	0.51	5.037	39418	3119	247	5106	661	6870	1197
	0.25	5.477	33334	2634	208	4273	548	5631	951
	0.1	5.978	27986	2205	174	3556	452	4546	739
75% JF - 25% HVO	1.50	5.783	49323	3033	308	5051	853	6847	1568
	0.84	6.069	44793	2751	279	4542	760	6121	1380
	0.51	6.437	39813	2441	247	4006	665	5384	1201
	0.25	6.946	34195	2091	211	3425	566	4514	983
	0.1	7.659	28123	1715	172	2792	457	3535	733
50% JF - 50% HVO	1.50	7.328	49338	2445	321	4054	883	5497	1623
	0.84	7.687	44844	2216	290	3649	787	4919	1430
	0.51	8.145	39936	1966	256	3230	692	4338	1249
	0.25	8.681	35160	1729	225	2827	602	3746	1057
	0.1	9.593	28791	1411	183	2293	484	2986	821

3.2 Visualization

To provide a better understanding of the outcomes observed in these experiments, all the phenomena observed were presented in this subsection. Essentially, in these studies, the outcomes were divided into two types: splash and non-splash. However, six different phenomena were found: spreading, fingering, crown splash, prompt splash, jetting and bubbling. The spreading and fingering were part of the non-splash outcomes. The prompt splash and the crown splash, as the names suggest, belonged to the splash outcomes. Only one episode of bubbling was spotted, and the droplet heavily splashes before the bubble formation. Regarding the jetting, the opinions in the scientific community are still divided. This case will be explained further below.

Figure 3.3 a) shows a droplet spreading upon a liquid film. This phenomenon was also called deposition. Usually, spread or deposition occurs for low impact energies. Briefly, spreading happens when the impinging droplet merges with a pre-existing liquid film or spreads out to form a liquid film on a dry surface. In the image sequence, it can be seen that when the droplet impinges the thick liquid film, a smooth crown is formed, and it slowly spreads out in order to end the perturbation created and turn the film homogeneous again.

Figure 3.3 b) shows the fingering created by the impingement of a droplet upon a thin liquid film. The droplet spreading can have instabilities at the outer rim of the liquid lamella that can be called fingering. The liquid lamella is identified in the figure in the frame correspondent to $\tau = 2.5ms$. These fingers grow as result of these instabilities. The example in figure 3.3 b) it is about fingering formed on the droplet spreading, therefore these fingers were also formed when the droplet exhibited splash. Normally, the fingers were formed on the crown and broke up originating secondary atomization.

In the sequence, it is possible to see the formation of tiny fingers which evolved, without any of them breaking into secondary atomization and later collapsing, spreading into the liquid film. The fingers in these images are really tiny due to the fact that when their length is higher normally secondary droplets are ejected.

The other four phenomena visualized encompass the creation of secondary atomization (droplets ejected due to the main droplet impact). By definition, splash consists in the physical separation of fluid from the impact site, and it happens normally for high impact energies. There are two types of splash: prompt and crown splash. Both were spotted in these experiments. It is important to mention that prompt splash is seen in the videos of the droplet impact, but it is hard to see in the majority of the images. The crown splash was easily identified. Both phenomena can happen together but to facilitate the distinction between them, they are presented separately.

Figure 3.3: 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 ($D_{in} = 0.51mm$, $D_0 = 2.47mm$, $h = 175mm$, $\delta^* = 0.1$).

Figure 3.4 shows the prompt splash of a droplet. Prompt splash occurs when the impact energy is high enough for the droplet to disintegrate in the first moments after impact. Very tiny droplets were ejected from the periphery of the liquid lamella while the crown is still rising or advancing.

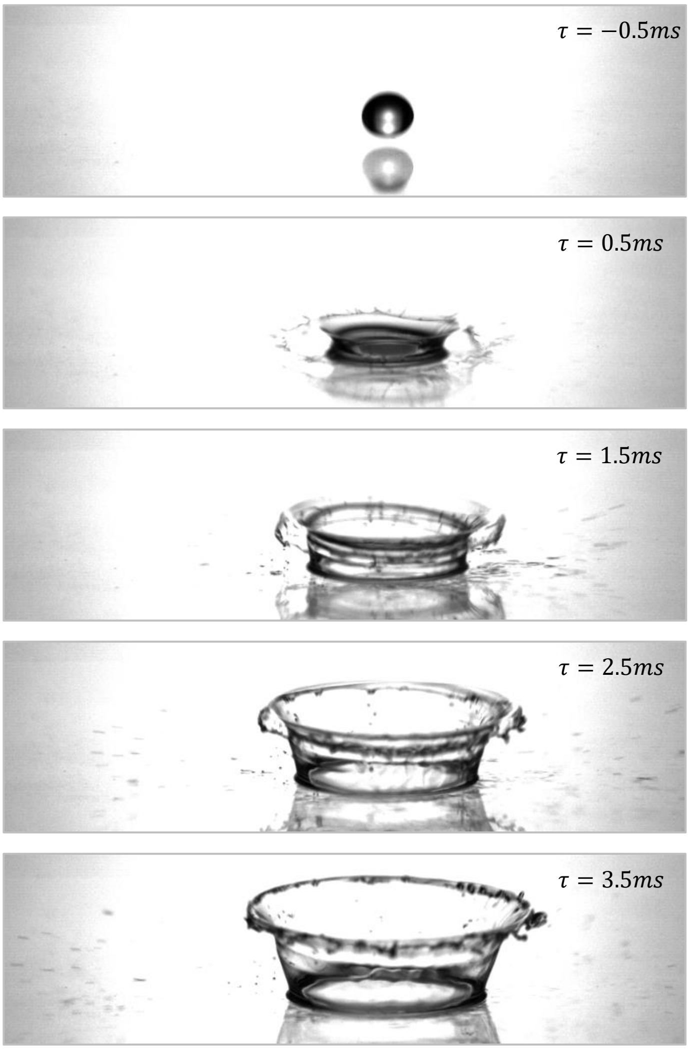
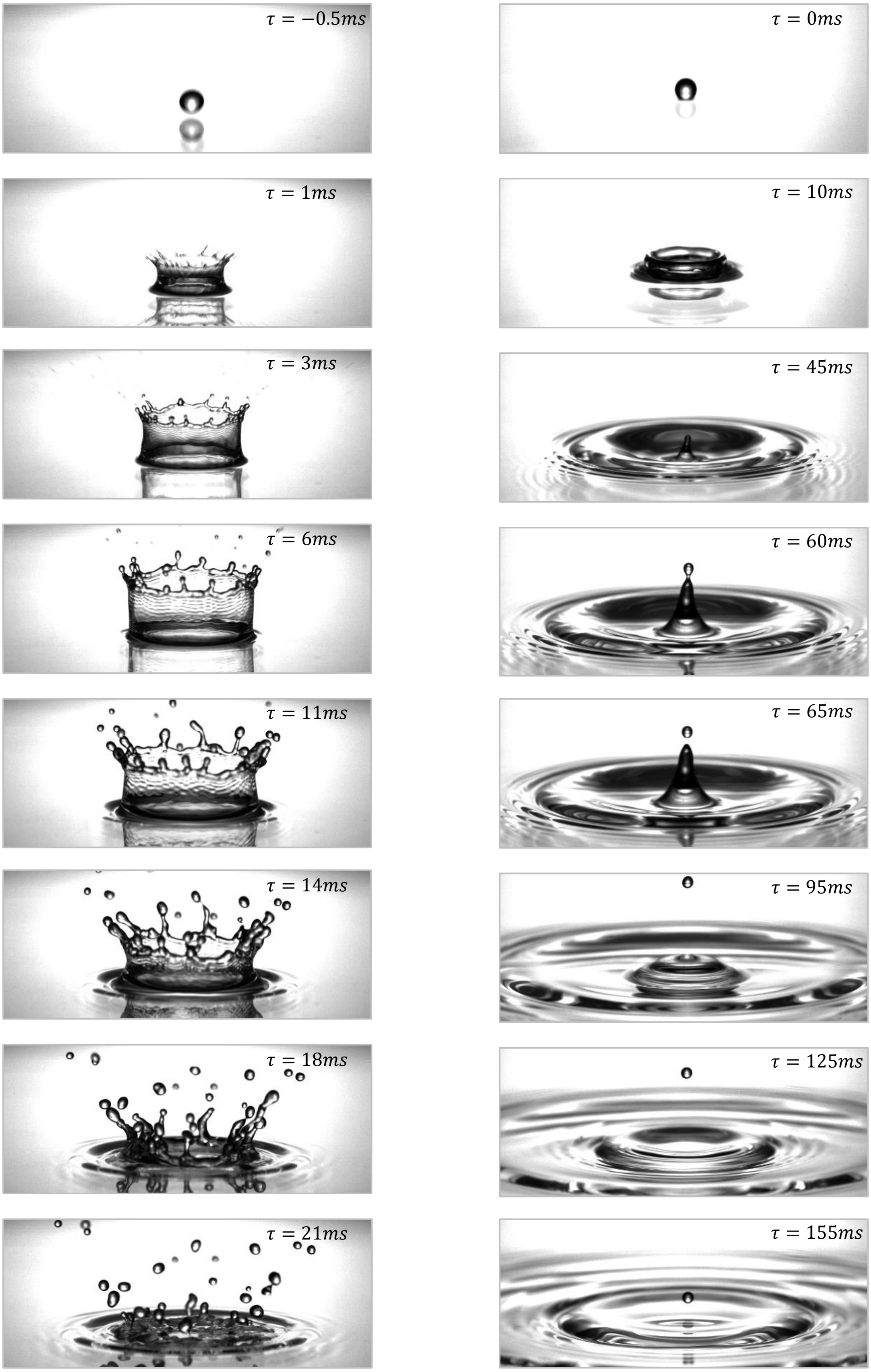


Figure 3.4: Prompt splash of a single droplet in a liquid film for the 50% JF/50% HVO mixture ($D_{in} = 1.50mm$, $D_0 = 3.06mm$, $h = 1m$, $\delta^* = 0.1$).

Since the images correspond to an impact height of $1m$, the impact velocity is really high, therefore in the first frame of the impact, the impinging droplet cannot be seen. For that reason, a frame $0.5ms$ before the impact was inserted in the image sequence to help scale it. The phenomenon lasts for $3.5ms$ after impact and consequently is hard to spot. Point out that these images are the ones where prompt splash is better noticeable. Several very tiny droplets were almost instantly ejected from the periphery of the liquid lamella.

Figure 3.5 shows two image sequences, the crown splash (a) and the jetting (b). Crown splash occurs after the stage of maximum expansion and encompasses the break up of the crown fluid sheet and it is really common in the impact with liquid films.



(a) (b)

Figure 3.5: Image sequences: a) crown splash of a single droplet 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 ($D_{in} = 1.50mm$, $D_0 = 3.04mm$, $h = 175mm$, $\delta^* = 1$).

As can be seen, in crown splash, fingers can be formed and broke up into secondary atomization. This type of splash produces various sizes of splashed products while prompt splash just produces very tiny ones. At the beginning ($\tau = 3ms$) just very tiny droplets were produced (barely seen). In this case, fingers were formed and the crown was thin and high, so during the crown collapse, secondary droplets continued to eject. The secondary droplet size increased with time.

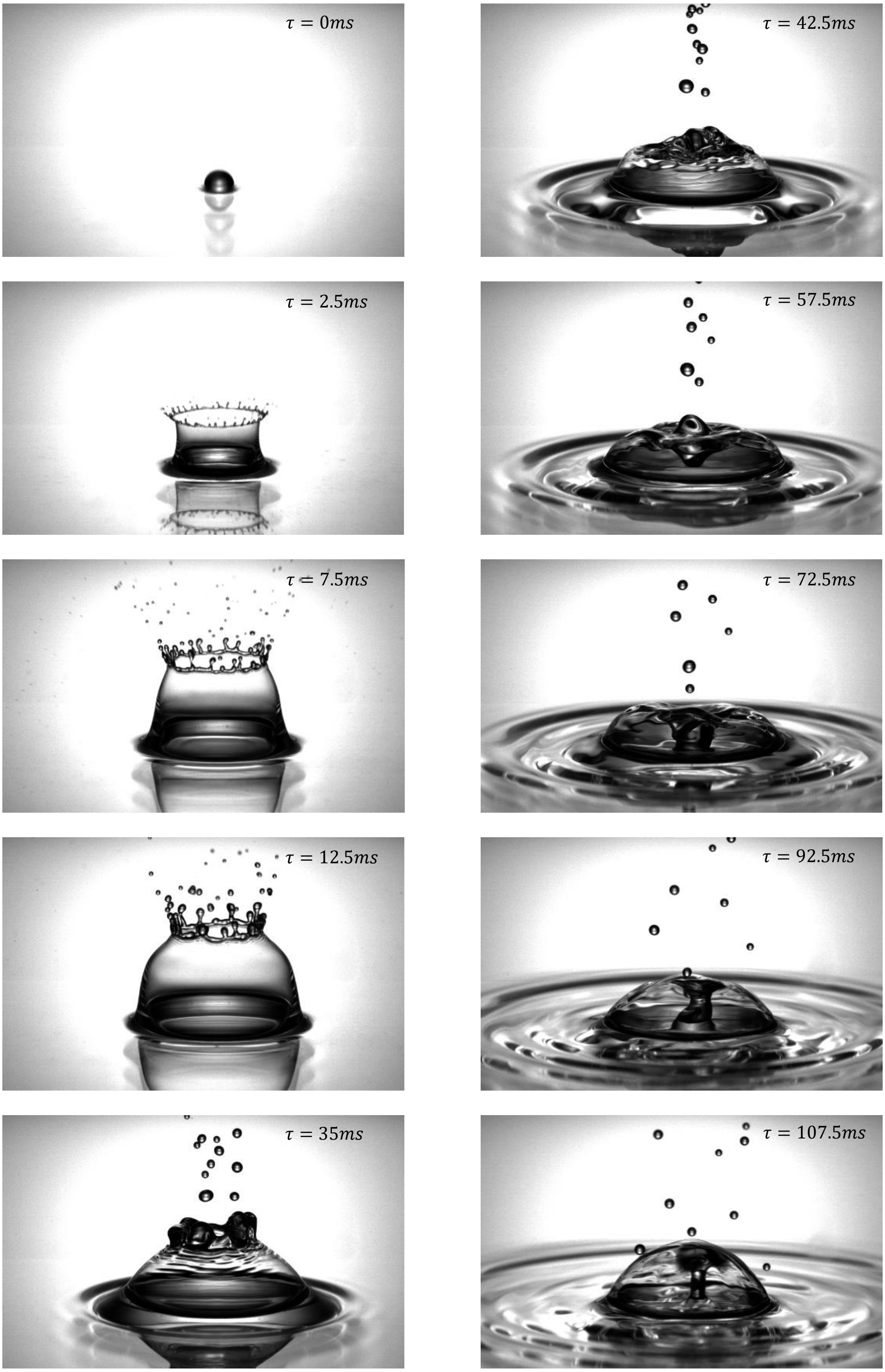
Regarding jetting, the images presented in figure 3.5 b) only happen two times in the experiments. Sometimes, after the crown collapses, a vertical extension of fluid (jet) rises from the center of the impact site, this phenomenon is called jetting. Many jets were formed after the crown collapse, but only two of them were formed without prompt or crown splash happen. This is the case presented in the figure.

Looking to the second frame ($\tau = 10ms$) a smooth crown is formed, and when it collapses a jet grows ($\tau = 45ms$), and rises and a droplet with nearly half the size of the impinging droplet is ejected. The ejected droplet continues its upward movement and then falls by gravity forces.

The definition of splash said that there is a physical separation of the fluid, therefore jetting, without prompt or crown splash should be considered splash. Some authors defended this theory, however, others allege that splash involves a physical liquid separation from the immediate impact site. Taking that into account, in this study, jetting will be treated as a special outcome. It will not be classified as splash or non-splash.

There is just one phenomenon left, bubbling. Just happened for one set of impact conditions. It is described in figure 3.6. Observing the droplet impact, no prompt splash happened and a crown was formed ($\tau = 2.5ms$). The crown was very thin and high, many droplets were ejected ($\tau = 7.5ms$). The crown started to close ($\tau = 12.5ms$) forming a dome or a bubble, some rotation is imposed to the ejected droplets ($\tau = 35ms$). The crown closed and a vortex downwards started forming at the top ($\tau = 42.5ms$). The vortex grown downwards and connected to the liquid film ($\tau = 72.5ms$). The vortex becomes thinner with time ($\tau = 107.5ms$) and ends up ceasing ($\tau = 152.2ms$) forming an "empty" buble. Many secondary droplets fall on the dome but one of them breaks it up ($\tau = 208ms$). In the remaining frames it is possible to see the collapse of the dome.

The occurrence of bubbling was a surprise in these experiments since normally bubbling just happen for liquid films with higher relative thickness, such as deep pools ($\delta^* > 10$). The fact that it was spotted for a shallow liquid film should be investigated. Moreover, there is few avaiable information in the literature about this phenomenon.


$\tau = 0ms$
$\tau = 2.5ms$
$\tau = 7.5ms$
$\tau = 12.5ms$
$\tau = 35ms$
$\tau = 42.5ms$
$\tau = 57.5ms$
$\tau = 72.5ms$
$\tau = 92.5ms$
$\tau = 107.5ms$

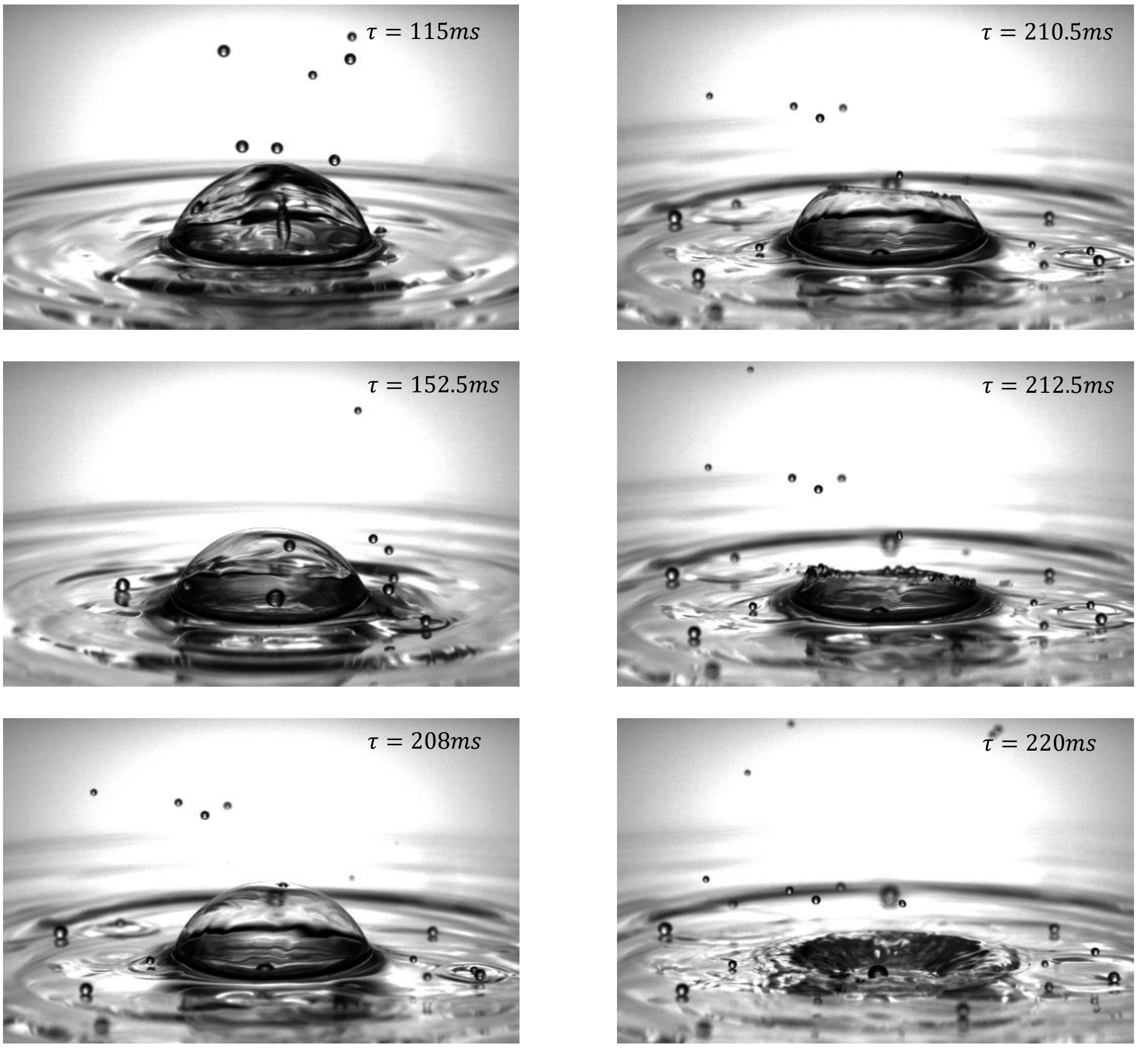


Figure 3.6: Crown splash follow by bubbling for the 75% JF/25% HVO mixture ($D_{in} = 1.50mm$, $D_0 = 3.05mm$, $h = 1m$, $\delta^* = 0.5$).

3.3 Outcomes

This subsection will be dedicated to the outcomes identification and description. First, they will be divided into splash or non-splash as table 3.6 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, as mentioned before.

It was verified that for the impact heights h_2 and h_3 splash occurred for all sets of impact conditions. In the lower height, the outcomes were very distinct. H_2O did not exhibit splash for $h_1 = 0.175m$ for all sets of impact conditions. Similarly, the 50% JF/50% HVO mixture also did not exhibit splash for the lower impact height. The 100% Jet A-1 and the 75% JF/25% HVO mixture were the two fluids in which the outcomes changed depending on the droplet diameter and on the liquid film relative thickness. For 100% Jet A-1 no splash was spotted for the droplets originated from the three needles with smallest inner diameters, $D_{in} = 0.51mm$, $D_{in} = 0.25mm$ and $D_{in} = 0.10mm$. For the second largest droplet diameter ($D_{in} = 0.84mm$) splash happened for all liquid thicknesses. Lastly, for the largest droplet, splash was just spotted for the thin liquid film. No splash occurred for the shallow liquid film and jetting was formed for the thick liquid film. For the 75% JF/25% HVO mixture no splash was spotted for the droplets originated from the two smallest needle inner diameters $D_{in} = 0.25mm$ and $D_{in} = 0.10mm$. For both $D_{in} = 0.84mm$ and $D_{in} = 0.51mm$ splash was just visible for the shallow liquid film. To end the table analysis, the largest droplet splashes for the thin and shallow liquid films and jetting was spotted for the thick liquid film.

Table 3.6: 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 the similarities between them. Moreover, understand how the outcomes vary with the physical properties, the droplet diameters and the relative thickness of the liquid film.

Due to the wide amount of impact conditions, and to turn the analysis easier, tables will be presented below, where the outcomes will be described (the phenomena spotted, their components along with their number, thicknesses and sizes) for each different set of impact conditions. In addition to the tables, a summary including the relations between the behavior of the different fluids, as well as, the relations with the impact conditions will be evaluated. Table 3.7 shows the description of the outcomes for the lower impact height ($h_1 = 0.175m$).

It is important to address that a qualitative quantification of the sizes of the constituents involved in the impact mechanisms was made and no measurements of them were done, these size references are merely qualitative. These descriptions were made based on the differences between the several cases observed, that is why in some cases the crown was considered high and sometimes low, this is just a relative assumption.

Comparing H_2O with the 50% JF/50% HVO mixture, both did not exhibit splash. For H_2O the crown formed was low in all the cases, while for the 50% JF/50% HVO mixture was also low but only for the three largest droplets, in the remaining cases, it was considered very low. For H_2O no fingers were spotted, while for the 50% JF/50% HVO mixture tiny fingers were observed in the thin liquid films impacts, but only for the three largest droplets. The spread was found to be faster for the 50% mixture, especially for the smallest droplets, the impinging droplet was almost absorbed by the film, which is probably due to its reduced size, which produces a smaller perturbation. The thinner liquid films for H_2O were not correspondent to 10% of the droplet diameter, and that fact should not be forgotten since the occurrence of splash was enhanced by thin liquid films.

It was also verified that the final spread diameter was larger for H_2O. This fact is supported by the assumption that the impact of droplets of fluids with lower viscosity results in larger final spread diameters, which was declared by several authors (e.g. Vander Wal, 2006a).

The 100% Jet Fuel and the 75% JF/25% HVO mixture exhibited both splash and non-splash outcomes. Starting with the similarities, the impact of these two fluids with all the liquid film thicknesses for the two smallest droplets resulted in non-splash, and also for the intermediate needle ($D_{in} = 0.84mm$) for 100% Jet A-1. In all these cases fingers were not formed, except for 100% Jet A-1 in the impact with the thin liquid film for $D_{in} = 0.51mm$. The crown was considered very low for the two smallest droplets of every fluid and only the crowns originated by the impact with $D_{in} = 0.51mm$ were classified as low for all the liquid film thicknesses. The outcomes were very similar to the ones obtained with the 50% JF/50% HVO mixture for the same droplet diameters and liquid film thicknesses. The spread also became less wide while the droplet diameter decreased.

Regarding the special cases, non-splash occurred also for the largest droplet of 100% JF impinging on the shallow film. Its behavior is really similar to the H_20 and the 50%/50% mixture for similar conditions. For the 75%/25% mixture non-splash also occurred for the droplets with $D_{in} = 0.84mm$ and $D_{in} = 0.51mm$ in the impact with the thin and thick films. In both cases fingers were formed but none broke up.

Crown splash was spotted for the impact with the thin liquid film for the two largest droplet diameters. In both cases, the crown was really thin. For $D_{in} = 0.84$ more droplets were ejected than for $D_{in} = 1.50mm$, but their size was similar.

Table 3.7: Description of the outcomes for the lower impact height ($h_1 = 0.175m$).

D_{in} [mm]	δ^*	H_2O	100% JF	75% JF/25% HVO	50% JF/50% HVO
1.50	0.1	No splash, widest spread, no fingers formed, low crown	Crown splash, many fingers formed, few droplets ejected (medium size)	Crown splash, many fingers formed, few droplets ejected (medium size)	No splash, widest spread, tiny fingers formed, low crown
	0.5	No splash, widest spread, no fingers formed, low crown	No splash, widest spread, no fingers formed, low crown	Prompt and crown splash, barely splashes, few droplets ejected (tiny size), no fingers formed, low crown	No splash, widest spread, no fingers formed, low crown
	1	No splash, widest spread, no fingers formed, low crown	Spread follow by Jetting, one large droplet ejected from the jet break up, no fingers formed, widest spread, low crown	Spread follow by Jetting, one large droplet ejected from the jet break up, no fingers formed, widest spread, low crown	No splash, widest spread, no fingers formed, low crown, a jet was almost formed
0.84	0.1	No splash, widest spread, no fingers formed, low crown	Crown splash, several fingers formed, few droplets ejected (medium size)	No splash, several fingers formed that almost broke but none droplet was ejected, low crown	No splash, widest spread, tiny fingers formed, low crown
	0.5	No splash, widest spread, no fingers formed, low crown	Prompt splash, tiny droplets ejected, no fingers formed, low crown	Prompt splash, tiny droplets ejected, no fingers formed, low crown	No splash, widest spread, no fingers formed, low crown
	1	No splash, widest spread, no fingers formed, low crown	Prompt and crown splash, barely splashes, few and tiny droplets ejected, no fingers formed	No splash, less wide spread, no fingers formed, low crown	No splash, widest spread, no fingers formed, low crown
0.51	0.1	No splash, widest spread, no fingers formed, low crown	No splash, some tiny fingers formed, fast spread, almost absorbed, low crown	No splash, some tiny fingers formed, fast spread, almost absorbed, low crown	No splash, a couple tiny fingers formed, fast spread, practically absorbed, low crown
	0.5	No splash, less wide spread, no fingers formed, low crown	No splash, less wide spread, no fingers formed, low crown	Prompt splash, tiny droplets ejected, no fingers formed, low crown	No splash, less wide spread, no fingers formed, low crown
	1	No splash, less wide spread, no fingers formed, low crown	No splash, less wide spread, no fingers formed, low crown	No splash, less wide spread, no fingers formed, low crown	No splash, less wide spread, no fingers formed, low crown
0.25	0.1	No splash, less wide spread, no fingers formed, low crown	No splash, fast spread, almost absorbed, no fingers formed, very low crown	No splash, lesser spread, almost absorbed, no fingers formed, very low crown	No splash, fast spread, almost absorbed, no fingers formed, very low crown
	0.5	No splash, less wide spread, no fingers formed, low crown	No splash, less wide spread, no fingers formed, very low crown	No splash, less wide spread, no fingers formed, very low crown	No splash, less wide spread, no fingers formed, very low crown
	1	No splash, less wide spread, no fingers formed, low crown	No splash, less wide spread, no fingers formed, very low crown	No splash, less wide spread, no fingers formed, very low crown	No splash, less wide spread, no fingers formed, very low crown
0.10	0.1	No splash, less wide spread, no fingers formed, low crown	No splash, fast spread and absorption, no fingers formed, very low crown	No splash, fast spread and absorption, no fingers formed, very low crown	No splash, fast spread and absorption, no fingers formed, very low crown
	0.5	No splash, less wide spread, no fingers formed, low crown	No splash, fast spread and absorption, no fingers formed, very low crown	No splash, fast spread and absorption, no fingers formed, very low crown	No splash, fast spread and absorption, no fingers formed, very low crown
	1	No splash, less wide spread, no fingers formed, low crown	No splash, less wide spread and fast absorption, no fingers formed, very low crown	No splash, less wide spread and fast absorption, no fingers formed, very low crown	No splash, less wide spread and fast absorption, no fingers formed, very low crown

The 75% JF/25% HVO mixture also experienced crown splash in the impact with the thin liquid film for the largest droplet. The outcome was really similar to the 100% JF for identical impact conditions. Prompt splash occurred in the impact upon the shallow film for the 100% JF ($D_{in} = 0.84mm$) and also for the 75%/25% mixture ($D_{in} = 0.84mm$ and $D_{in} = 0.51mm$). In the three cases the secondary droplets were tiny, the crown was considered low, and no fingers were formed.

There were two cases where prompt and crown splash were spotted together, $D_{in} = 0.84mm$ in the impact with the thick film for the 100% JF and $D_{in} = 1.50mm$ in the impact with the shallow film for the 75%/25% mixture. In both cases, the droplet barely splashes, just few tiny droplets were ejected. No fingers were formed, and the crown was also considered low.

Lastly, jetting was observable in the impact of the largest droplet with the thick film for both fluids. This phenomenon was explained in detail in section 3.2. A jet was formed and a droplet was ejected without the occurrence of a prompt or crown splash. As explained before, this phenomenon will not be treated as splash or non-splash due to the disagreement in the scientific community in catalogue jetting.

Table 3.8 shows the description of the outcomes for the second impact height ($h_2 = 0.5m$). Splash occurred for all cases. For all the fluids, the impact with the thin liquid films created crown splash. For the three fuels the crown formed was always very thin and average (it was considered as "average" a crown which height was between low and high).

In this condition, the H_2O also exhibited an average crown, but the thickness of the crown increases while the droplet diameter decreases, being thin for the two largest droplets, thick for the smallest one and medium for the other two. This trend shows that with these impact conditions for H_2O the crown thickness increases while the droplet diameter decreases. This may suggest that the crown thickness might be related to the droplet size. For these impact conditions the crown is almost completely disintegrated into secondary atomization.

Considering all the outcomes obtained for H_2O, crown splash always occurred, and jetting was observable only for a set of impact conditions ($D_{in} = 1.50mm,\ \delta^* = 1$). Considering all the outcomes obtained for 100% JF, crown splash always occurred and jetting was observable only for three sets of impact conditions, all of them corresponding to the impact upon the thicker liquid film ($D_{in} = 1.50mm$, $D_{in} = 0.84mm$ and $D_{in} = 0.51mm$).

The 75%/25% mixture was also identical to the H_2O and 100% Jet A-1, crown splash occurred for all the impact conditions, but there was even more events of jetting spotted (8 occurrences), all of them in the impact with shallow and thick liquid films. This mixture also had an event of a prompt splash.

Table 3.8: Description of the outcomes for the second impact height ($h_2 = 0.5m$).

D_{in} [mm]	δ^*	H_2O	100% JF	75% JF/25% HVO	50% JF/50% HVO
1.50	0.1	Crown splash, many splashed products (very tiny to tiny), thin and average crown, some fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), thin and average crown completely disintegrated into secondary atomization, no fingers	Crown splash, many splashed products (very tiny to small), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up
	0.5	Crown splash, many splashed products (tiny), medium to thick and average crown, fingers started forming but none evolved or broke up	Crown splash, many splashed products (very tiny to tiny), medium and high crown, some fingers formed and broke up	Crown splash, barely noticeable, many splashed products (very tiny), medium and average crown, some fingers formed which did not break up	Prompt and crown splash and jetting, some splashed products (very tiny to small), thick and average crown, a couple fingers formed but none broke up, a jet was formed and 2 large droplets were ejected
	1	Crown splash and jetting, many splashed products (tiny), thick and average crown, almost started fingers formation but none evolved, a jet was formed and 2 large droplets were ejected	Crown splash and jetting, many splashed products (very tiny), thick and low to average crown, almost started fingers formation but none evolved, a jet was formed and 3-4 large droplets were ejected	Crown splash and jetting, many splashed products (very tiny and small), thick and average crown, some fingers formed and broke up, a jet was formed and several large droplets were ejected	Crown splash and jetting, some splashed products (tiny to small), thick and average crown, no fingers formed, a jet was formed and 3-4 large droplets were ejected
0.84	0.1	Crown splash, many splashed products (very tiny to tiny), thin to medium and average crown, some fingers formed and broke up	Crown splash, many splashed products (very tiny), very thin and average crown completely disintegrated into secondary atomization, small fingers formed which broke up	Crown splash, many splashed products (very tiny to small), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up	Crown splash, many splashed products (very tiny to small), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up
	0.5	Crown splash, many splashed products (very tiny to tiny), thick and average crown, fingers formed but none broke up	Crown splash, many splashed products (very tiny and small), medium and average crown, some fingers formed and a few broke up	Crown splash and jetting, some splashed products (tiny), thick and high crown, no fingers formed, a jet was formed and 4-5 large droplets were ejected	Prompt and crown splash and jetting, many splashed products (very tiny to tiny), thick and average crown, no fingers formed, a jet was formed and 2-3 large droplets were ejected
	1	Crown splash, many splashed products (very tiny), thick and low crown, some fingers formed but none broke up, jet was formed but none droplet was ejected	Crown splash and jetting, many splashed products (very tiny), thick and low to average crown, almost started fingers formation but none evolved, a jet was formed and 2-3 large droplets were ejected	Crown splash and jetting, some splashed products (very tiny to tiny), thick and average crown, no fingers formed, a jet was formed and 3-4 large droplets were ejected	Prompt and crown splash, and jetting, some splashed products (very tiny to tiny), thick and low crown, no fingers formed, a jet was formed and 2 large droplets were ejected
0.51	0.1	Crown splash, many splashed products (very tiny to small), medium and average crown, some fingers formed and broke up	Crown splash, many splashed products (very tiny to small), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up	Crown splash, many splashed products (very tiny to small), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up	Crown splash, many splashed products (very tiny to small), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up

Table 3.8: Description of the outcomes for the second impact height ($h_2 = 0.5m$). (continued)

D_{in} [mm]	δ^*	H_2O	100% JF	75% JF/25% HVO	50% JF/50% HVO
0.51	0.5	Crown splash, some splashed products (very tiny to tiny), thick and average crown, some fingers formed but none broke up	Crown splash, many splashed products (very tiny and tiny), medium and average crown, some fingers formed but none broke up	Crown splash and jetting, few splashed products (very tiny to tiny), thick and average crown, fingers formed but none evolved, a jet was formed and 1 large droplet was ejected	Prompt, crown splash and jetting, some splashed products (very tiny), thick and average crown, fingers formed but none evolved, a jet was formed and 1 large droplet ejected
	1	Crown splash, some splashed products (very tiny), thick and low crown, fingers formed but none evolved, jet was formed but none droplet was ejected	Crown splash and jetting, many splashed products (very tiny), thick and low crown, fingers almost formed but none evolved, a small jet was formed and 1 large droplet ejected	Prompt and crown splash and jetting, some splashed products (very tiny to tiny), thick and low crown, no fingers formed, a jet was formed and 2-3 large droplets were ejected	Prompt splash and jetting, many splashed products (very tiny), thick and low crown, no fingers formed, a jet was formed and 2-3 large droplets were ejected
0.25	0.1	Crown splash, few splashed products (very tiny), medium and average crown, some fingers formed but none broke up	Crown splash, many splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny to small), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up
	0.5	Crown splash, few splashed products (very tiny), thick and low crown, fingers formed but none evolved	Crown splash, barely splashes, few splashed products (very tiny), thick and low crown, fingers formed but none evolved	Crown splash and jetting, some splashed products (very tiny), thick and low crown, no fingers formed, a jet was formed and 2 large droplets were ejected	Prompt splash and jetting, some splashed products (very tiny), thick and average crown, fingers formed but none evolved, a jet was formed and 1 large droplet ejected
	1	Crown splash, some splashed products (very tiny), thick and very low crown, fingers formed but none evolved, jet was formed but none droplet was ejected	Crown splash, barely splashes, few splashed products (very tiny), thick and low crown, no fingers formed, a small thick jet was formed but none droplet was ejected	Crown splash and jetting, some splashed products (very tiny to tiny), thick and very low crown, no fingers formed, a jet was formed and 1 large droplet was ejected	Prompt splash and jetting, some splashed products (very tiny), thick and low crown, no fingers formed, a jet was formed and 1 large droplet was ejected
0.10	0.1	Crown splash, few splashed products (very tiny), thick and average crown, fingers forming but none evolved	Crown splash, many splashed products (very tiny), very thin and average crown completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up	Crown splash, some splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, tiny fingers formed and broke up
	0.5	Crown splash, barely splashes, few splashed products (very tiny), thick and low crown, no fingers formed	Crown splash, barely splashes, few splashed products (very tiny), thick and low crown, fingers formed but none evolved	Crown splash and jetting, some splashed products (very tiny), thick and low crown, no fingers formed, a jet was formed and 1 large droplet was ejected	Crown splash, few splashed products (very tiny), thick and low crown, no fingers formed
	1	Crown splash, few splashed products (very tiny), thick and very low crown, no fingers formed	Crown splash, barely splashes, few splashed products (very tiny), thick and very low crown, no fingers formed, a small jet was formed	Crown splash, few splashed products (very tiny), thick and very low crown, no fingers formed, a small jet was formed	Crown splash, few splashed products (very tiny), thick and very low crown, no fingers formed, a small jet was formed

Thus, it was noticed that these three fluids (H_2O, 100% JF and the 75%/25% mixture) had identical behavior and the occurrence of jetting can be enhanced while the viscosity increases, since H_2O (lower viscosity) had only one event, 100% JF had three and the 75%/25% mixture had 8 (higher viscosity of these three fluids).

Regarding this assumption, it will be expected that the 50%/50% mixture exhibited even more episodes of jetting. Well, this was not the case, only 6 occurrences were observable. However, for this fuel, prompt splash happened several times, which also suggests that prompt splash can be enhanced by high viscosities. Point out that this mixture was the only one that did not exhibit crown splash for all the impact conditions.

Considering all the outcomes for the second height the ejected droplets were mostly considered tiny and/or very tiny. Furthermore, for all these impact conditions, splash always occurred. This confirms that all Weber's numbers obtained for this height were equal or superior to the critical Weber number necessary to produce splash.

Table 3.9 shows the description of the outcomes for the highest impact height ($h_1 = 1.0m$). Splash also occurred for all cases, identical to h_2. Similarly to the second impact height, crown splash occurred for all the fluids in the impact with the thin liquid films for all droplet sizes. However, it was sometimes combined with prompt splash for the 75%/25% mixture ($D_{in} = 0.84mm$ and $D_{in} = 0.51mm$) and for the 50%/50% mixture ($D_{in} = 1.50mm$ and $D_{in} = 0.84mm$).

An increase in the crown thickness was noticeable while the droplet diameter decreased, identical to the observable for the second height. For the three fuels, the crown formed was always very thin but its height changed between high and average with the decrease of the droplet diameter. The change in the height it was also applied to H_2O.

Considering all the outcomes obtained for H_2O, crown splash always occurred and jetting was observable three times, always in the impact with the thicker film ($D_{in} = 1.50mm,\ D_{in} = 0.84mm$ and $D_{in} = 0.51mm$). Regarding the 100% JF, crown splash always occurred and jetting was observable for some sets of impact conditions, all of them corresponding to the impact upon the shallow or thick liquid film.

The 75%/25% mixture was also identical to the outcomes of H_2O and 100% Jet A-1, crown splash occurred for all the impact conditions, but there were again some events of jetting spotted (6 cases) including all set of conditions for the impact with the thick liquid films. This mixture also had two events of prompt splash in the impact with thin liquid films ($D_{in} = 0.84mm$ and $D_{in} = 0.51mm$). As mention in section 3.2, an unexpected phenomenon happened for the 75%/25% mixture. In the impact of the largest droplet with the shallow film crown splash happened, a high crown was formed and later closed forming a dome or a bubble. This phenomenon was illustrated and explained in detail in section 3.2.

Once more this three fluids (H_2O, 100% JF and the 75%/25% mixture) had an identical behavior concerning the occurrence of a crown splash, and again the occurrence of jetting may depend on the viscosity of the fluids.

For this height crown splash was always spotted for all the outcomes of the 50%/50% mixture. Thus, all the fluids exhibited crown splash for sets of impact conditions. This may suggest that with a Weber number much higher than the critical, can enhance the formation of secondary atomization from the crown.

However, for the 50%/50% mixture, similarly to the second height, prompt splash happened even more times, which supports the assumption that prompt splash can be enhanced by high viscosities and also by high Weber numbers. Point out that prompt splash was spotted for the three largest droplets for all the relative thicknesses, except the thin film for the droplet with $D_{in} = 0.51mm$.

Considering all the outcomes for the third height, there was a wide range of ejected droplets sizes, varying from very tiny to medium (to consider a droplet as large, its size must be similar to the original droplet). Once more, for all these impact conditions, splash always occurred. This confirms that all Weber's numbers obtained for this height were equal or superior to the critical Weber number necessary to produce splash since that was already been confirmed for h_2. Therefore, in this impact height, the impact energy was way higher than the necessary to occur splash. It was probably due to this surplus of energy that more and larger splashed products were created.

In summary, for h_1 both H_2O and the 50% JF/50% HVO mixture did not exhibit splash, consequently, the lower impact height did not provide enough impact energy to occur splash, which suggests that the splashing limit required critical Weber numbers higher than 188 for H_2O and higher than 321 for the 50%/50% mixture. The 100% Jet A-1 and the 75% JF/25% HVO mixture exhibited both splash and non-splash outcomes for h_1. Consequently, the Weber numbers provided by these impact conditions stayed between the splash and non-splash regime, under and above the critical Weber necessary to the splash formation.

Considering all the outcomes obtained for h_2 and h_3 splashing always occurred. This confirms that all Weber's numbers obtained for h_2 were equal or superior to the critical Weber number necessary to produce splash.

On the other hand, for the third height, all Weber's numbers obtained were superior to the critical Weber number necessary to produce splash, since that was already been confirmed for h_2. Therefore, in this impact height, the impact energy was much higher than the necessary to occur splash. It was probably due to this surplus of energy that more and larger splashed products were created.

Table 3.9: Description of the outcomes for the higher impact height ($h_3 = 1.0m$).

D_{in} [mm]	δ^*	H_2O	100% JF	75% JF/25% HVO	50% JF/50% HVO
1.50	0.1	Crown splash, many splashed products (very tiny to medium), very thin and high crown almost completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up	Prompt and crown splash, many splashed products (very tiny to small), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up
	0.5	Crown splash, many splashed products (very tiny to small), thin and high crown, some fingers formed and broke up, a thick jet formed	Crown splash and jetting, many splashed products (very tiny to medium), thin and high crown, fingers formed and broke up, some rotation imposed to the crown and jet which ejected 2 large droplets	Crown splash and bubbling, many splashed products (very tiny to small), thin and high crown, fingers formed and broke up, the crown closes forming a dome or a bubble with a vortex inside, later broke up	Prompt and crown splash, many splashed products (very tiny to medium), medium and high crown, fingers formed and broke up, a thick small jet formed
	1	Crown splash and jetting, many splashed products (very tiny to tiny), thick and high crown, fingers formed but none evolved, a jet was formed and 2 very large droplets were ejected	Crown splash and jetting, many splashed products (very tiny to small), medium and high crown, fingers formed and broke up, a thin high jet was formed and many medium droplets were ejected, the crown almost close forming a dome	Crown splash and jetting, many splashed products (very tiny to small), thin and high crown, fingers formed and broke up, a rotating jet was formed and 2-3 large droplets were ejected, the crown almost close forming a dome	Prompt and crown splash and jetting, many splashed products (very tiny to small), thick and high crown, fingers formed and broke up, a thin high jet formed and several medium droplets ejected
0.84	0.1	Crown splash, many splashed products (very tiny to medium), very thin and high crown almost disintegrated into secondary atomization, many fingers formed and broke up, a tiny jet formed	Crown splash, many splashed products (very tiny to tiny), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up	Prompt and crown splash, many splashed products (very tiny to tiny), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up	Prompt and crown splash, many splashed products (very tiny to small), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up
	0.5	Crown splash, many splashed products (very tiny to small), medium and high crown, fingers formed and broke up, a thick tiny jet formed	Crown splash, many splashed products (very tiny to medium), thin and high crown, fingers formed and broke up, a thick and small jet formed	Crown splash, many splashed products (very tiny to small), thin and high crown, fingers formed and broke up, a thick small jet formed	Prompt and crown splash and jetting, many splashed products (very tiny to medium), thin and high crown, fingers formed and broke up, a thick small jet formed and 1 large droplet ejected
	1	Crown splash and jetting, many splashed products (very tiny to tiny), thick and average crown, fingers formed and broke up, a thick jet was formed and 1-2 very large droplets were ejected	Crown splash and jetting, many splashed products (very tiny to tiny), medium and high crown, fingers formed and broke up, jet formed and 1-2 large droplets ejected	Crown splash and jetting, many splashed products (very tiny to small), thick and high crown, fingers formed and broke up, a thin high jet formed and several large droplets ejected	Prompt and crown splash and jetting, many splashed products (very tiny to tiny), thick and high crown, fingers formed and broke up, a thin high jet formed and several medium droplets ejected
0.51	0.1	Crown splash, many splashed products (very tiny to small), very thin and high crown almost disintegrated into secondary atomization, many fingers formed and broke up, a tiny jet formed	Crown splash, many splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, many fingers formed and broke up	Prompt and crown splash, many splashed products (very tiny to tiny), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up

Table 3.9: Description of the outcomes for the higher impact height ($h_3 = 1.0m$). (continued)

D_{in} [mm]	δ^*	H_2O	100% JF	75% JF/25% HVO	50% JF/50% HVO
0.51	0.5	Crown splash, many splashed products (very tiny to medium), medium and high crown, fingers formed and broke up, a very thick small jet formed	Crown splash, many splashed products (very tiny to small), thin and high crown, fingers formed and broke up, a thick small jet formed	Prompt and crown splash and jetting, many splashed products (very tiny to small), thin and high crown, fingers formed and broke up, a jet formed and 1-2 large droplets ejected	Prompt and crown splash and jetting, many splashed products (very tiny to medium), medium and high crown, fingers formed and broke up, a jet formed and 1-2 large droplets ejected
	1	Crown splash and jetting, many splashed products (very tiny to tiny), thick and average crown, fingers formed and broke up, a jet was formed and 1 very large droplet ejected	Crown splash and jetting, many splashed products (very tiny to tiny), thick and average crown, fingers formed and broke up, a high jet was formed and 2-3 large droplets ejected	Crown splash and jetting, many splashed products (very tiny to tiny), thick and average crown, fingers formed and broke up, a high jet was formed and 2-3 large droplets ejected	Prompt and crown splash and jetting, many splashed products (very tiny), thick and high crown, some fingers formed but none broke up, a high jet formed and 2-3 large droplets ejected
0.25	0.1	Crown splash, many splashed products (very tiny to small), thin and high crown almost disintegrated into secondary atomization, many fingers formed and broke up, a thick tiny jet formed	Crown splash, many splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and high crown completely disintegrated into secondary atomization, many fingers formed and broke up
	0.5	Crown splash, many splashed products (very tiny and small), thick and high crown, fingers formed and broke up, a very thick tiny jet formed	Crown splash and jetting, many splashed products (very tiny to small), thin and high crown, fingers formed and broke up, a jet formed and 2 medium droplets ejected	Crown splash, many splashed products (very tiny to small), thin and high crown, fingers formed and broke up, a small jet formed	Crown splash and jetting, few splashed products (small), medium and high crown, fingers formed and broke up, a thick small jet formed and 1-2 large droplets ejected
	1	Crown splash, many splashed products (very tiny to tiny), thick and average crown, fingers formed and broke up, a thick small jet was formed	Crown splash and jetting, many splashed products (very tiny to tiny), thick and average crown, fingers formed and broke up, a jet formed and 1 large droplet ejected	Crown splash and jetting, few splashed products (very tiny), thick and average crown, fingers formed none evolved, a jet formed and 3 medium to large droplets ejected	Crown splash and jetting, many splashed products (very tiny), thick and average crown, fingers formed but none evolved, a jet formed and 2-3 large droplets ejected
0.10	0.1	Crown splash, many splashed products (very tiny to small), medium and average crown, many fingers formed and broke up	Crown splash, some splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny), very thin and average crown completely disintegrated into secondary atomization, many fingers formed and broke up	Crown splash, many splashed products (very tiny to tiny), very thin and average crown completely disintegrated into secondary atomization, many fingers formed and broke up
	0.5	Crown splash, some splashed products (very tiny to small), thick and average crown, many fingers formed and broke up	Crown splash, few splashed products (very tiny), thin and average crown, fingers formed but none broke up, a small jet formed	Crown splash and jetting, few splashed products (very tiny), thick and low crown, no fingers formed, a jet formed, 1 large droplet ejected	Crown splash, some splashed products (very tiny to small), tick and average crown, fingers formed and broke up
	1	Crown splash, some splashed products (very tiny), thick and low crown, fingers formed and broke up, a thick small jet formed	Crown splash and jetting, barely splashes, few splashed products (very tiny), thick and low crown, no fingers formed, a small jet formed and 1 large droplet ejected	Crown splash and jetting, few splashed products (very tiny), thick and low crown, no fingers formed, a small jet formed and 2 medium droplets ejected	Crown splash and jetting, some splashed products (very tiny), thick and average crown, no fingers formed, a thick small jet formed and 1 large droplet ejected

It was also noticed that the size and number of the splashed products changed depending on the relative thickness of the liquid film and also on the impact energy. For the second height, the ejected droplets were mostly considered tiny and/or very tiny. However, considering all the outcomes for the third height, there was a wide range of ejected droplet sizes, varying from very tiny to medium.

The occurrence of prompt splash for H_2O was never spotted, this is probably due to the influence of surface tension since H_2O has the higher surface tension of all the fluids studied.

Other authors reported that higher surface tension results in a thicker outer rim, and in this case, It was often times observed that the crown seemed thicker for the outcomes with water since H_2O possesses the highest surface tension (three times superior to the fuels), then probably the same trend was followed.

Another trend was observable for H_2O, since the crown thickness increases while the droplet diameter decreases. This may suggest that the crown thickness might be related to the droplet size. Coghe et al. (1999) reported that the crown thickness is independent of the film thickness and impact velocity, no considerations were made about the droplet diameter.

It was also reported in the literature that higher surface tension reduces the crown height, that was also spotted in these experiments since the height of the crown for H_2O was often considered smaller than the crowns obtained for the fuels, which have lower surface tension. Since all fuels have similar surface tension values, these two trends were not significant between them.

Jetting often occurred for the impact upon the thicker liquid films, which suggests that this phenomenon was enhanced by the increase of the liquid film thickness. However, it was spotted more often for the two mixtures, which suggests that it can be also enhanced by the increase of the viscosity.

It was also verified that the final spread diameter was larger for H_2O compared to the three fuels, which supports the assumption that the impact of droplets with lower viscosity results in larger final spread diameters, which was declared by several authors (e.g. Vander Wal, 2006a). The spread was found to become less wide while the droplet diameter decreases.

Both for h_2 and h_3 crown splash occurred for all the fluids in the impact upon the thin liquid films for all droplet sizes. In the higher impact height, the crown splash was sometimes combined with a prompt splash for the two mixtures.

For the 50%/50% mixture, prompt splash happened several times, which also suggests that prompt splash can be enhanced by high viscosities.

An unexpected phenomenon happened for the 75%/25% mixture for the higher impact height, in the impact of the largest droplet upon the shallow liquid film. Crown splash happened, a high crown was formed and later closed forming a dome or a bubble, this phenomenon was called bubbling.

All the fluids exhibited crown splash for the third height. This may suggest that with a Weber number much higher than the critical the formation of secondary atomization from the crown can be enhanced.

However, for the 50%/50% mixture, similarly to the second height, prompt splash happened even more times, which supports the assumption that prompt splash can be enhanced by high viscosities and also high Weber's numbers.

3.4 Splashing/Deposition Threshold

In this section, the data of these experiments will be compared with several empirical correlations presented in the literature for the splashing limit. The criteria used were developed by Bai and Gosman (1995), Cossali et al. (1997), Senda et al. (1997), Vander Wal et al. (2006a) and Huang and Zhang (2008). All these authors developed empirical correlations to determine the deposition/splashing boundary in the impact with liquid films and their correlations were commonly used and evaluated by several other authors (Lindgren and Denbratt, 2000; Silva, 2007; Huang and Zhang, 2008; Moita, 2009; Rodrigues et al., 2012; Rodrigues, 2016).

Since their limits were based in their experimental data with different fluids, droplet diameters, impact velocities and relative thicknesses of the liquid film, the goal of this section is to evaluate if their empirical correlations fit properly the experimental data obtained in this study and if not, to try to understand which are the differences.

3.4.1 Bai and Gosman (1995)

Bai and Gosman (1995) derived three transition criteria. First, they developed a criterium for the transition between spread and splash for dry walls using the data of Stow and Hadfield (1981). Then they developed an empirical correlation for the transition between rebound and spread, but in this case for wetted walls. Lastly, they develop a threshold between spread and splash for wetted walls trough the equation created for the dry walls assuming that a wetted wall behaves as a very rough dry surface. This assumption was made based on some studies where the authors considered the droplet dynamic behavior between rough surfaces and liquid films similar. The equation 1.13 shows the deposition/splashing boundary for wetted walls and the other two empirical correlations were presented in the subsection 1.2.5.

$$We_c = 1320 \cdot La^{-0.18} \quad (1.13)$$

Figure 3.7 shows the comparison between the experimental data obtained in these studies with the Bai and Gosman's correlation.

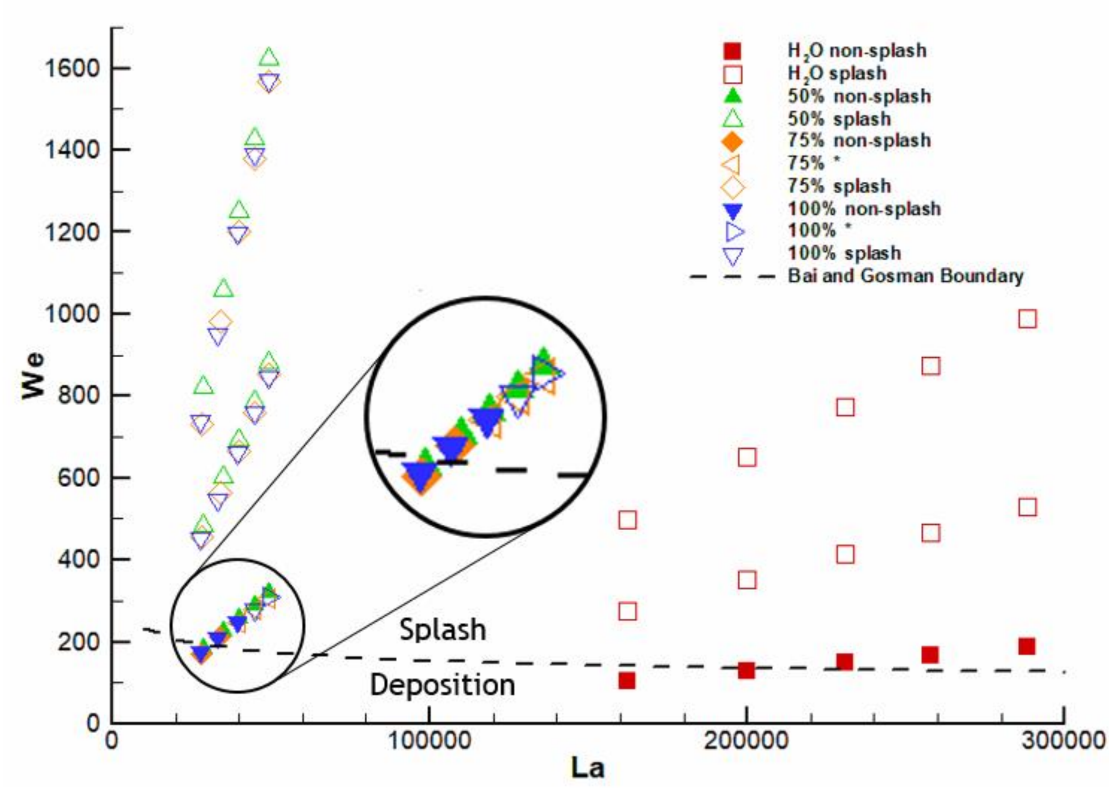


Figure 3.7: Graphic comparing the study results with Bai and Gosman splashing threshold.

As can be seen by the graphic, this threshold does not fit these experiments. All the cases where the outcomes exhibited splash are plotted in the splash area of the graphic. However, the scenario for the non-splash outcomes is different. For H_2O only the two smallest droplets are in the deposition regime, but the other three are very close to the line. For the fuels, only the smallest droplet of each one is in the deposition regime. A zoom in of the fuels outcomes for the lower height was made to better understand their positions. As can be seen, the three mixtures were almost coincident. Looking at the symbols positions for these three fluids almost seems that there is no variation between them. Taking into account that, this correlation was based on the similarity between rough and wetted surfaces, and also based on experiments made with water. It was possible to conclude that this limit is suitable to the water outcomes.

3.4.2 Cossali et al. (1997)

Cossali et al. (1997) also proposed a splashing threshold for droplets impinging upon wetted solid surfaces, created using their experimental results. In their experiments, they varied the droplet diameter between $2.00mm$ and $5.50mm$, the impact height between $0.05m$ and $2.00m$ and the maximum terminal velocity was $6.5m/s$. To achieve a wide range of Ohnesorge numbers, pure water and four mixtures of water-glycerine were used. Their empirical correlation is described by the equation 1.14. In the description, they said that this deposition/splashing threshold is appropriate for $0.1 < \delta < 1$ and $Oh > 7 \cdot 10^{-3}$ and also for $Oh = 2.2 \cdot 10^{-3}$ for pure water but only for $\delta < 0.2$.

$$K_L = (Oh^{-0.4} \cdot We)_L = 2100 + 5880 \cdot \delta^{*1.44} \quad (1.14)$$

In this way, the only fluid expected to fit this correlation is the 50%/50% mixture. Figure 3.8 shows 4 graphics comparing their empirical correlation with the data of this study, one for each fluid. It was decided to separate the different fluids since including all the results in the same graphic made it difficult to understand.

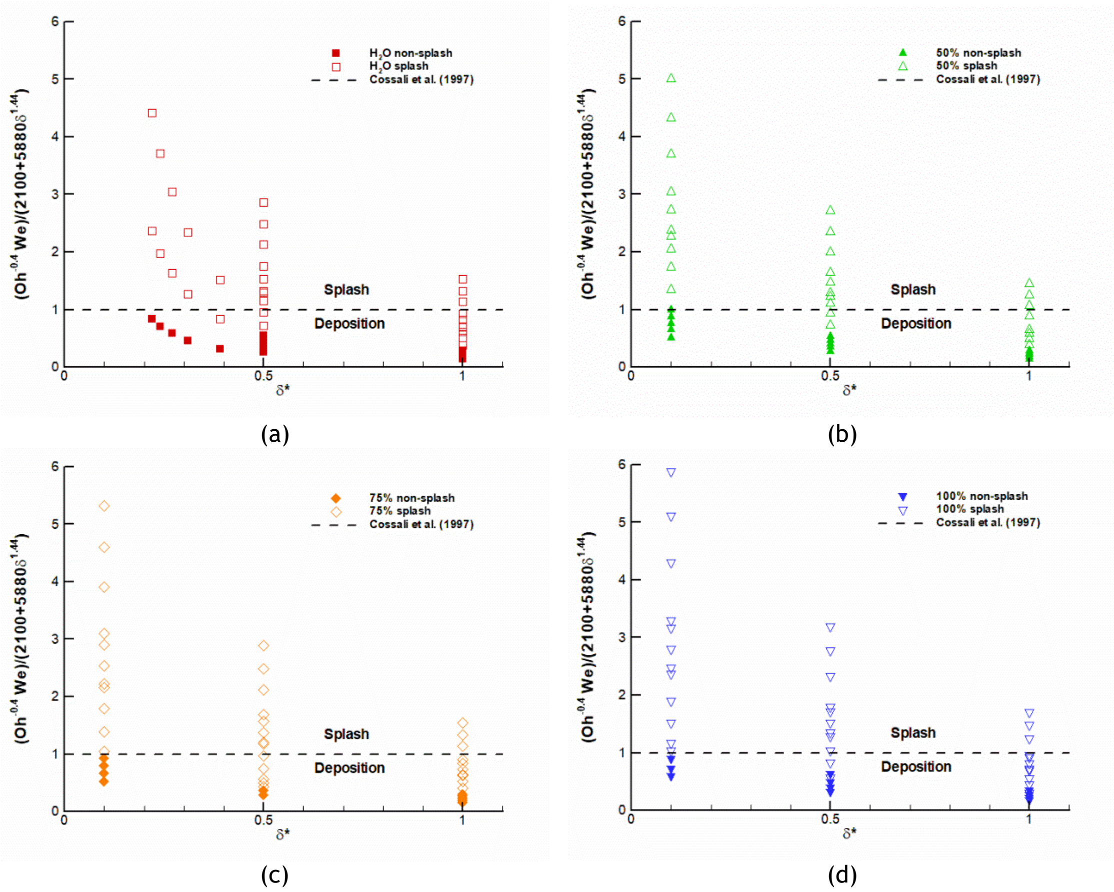


Figure 3.8: Graphics comparing the study results with Cossali et al. splashing threshold for each fluid: a) H_2O; b) 50%/50% mixture; b) 75%/25% mixture; d) 100% Jet A-1.

The horizontal line in the graphics defined as $(Oh^{-0.4} \cdot We)_L/(2100 + 5880 \cdot \delta^{*1.44}) = 1$ separates the deposition and splash regions. As can be seen, the correlation fits better the results for the impact with the thin films. The threshold was expected to fit better the data of the 50%/50% mixture, since this fluid fit the conditions where the boundary should provide good accuracy. Still, it was observed that for the thinner films this limit is very precise. For all fluids, this criterion fitted perfectly the outcomes for the thin films and looking at the graphic present by the authors in the article it is noticeable that the majority of the data used to build the empirical correlation corresponds to thin to shallow films, so it was expected a better correlation for these cases. Both for shallow and thick films some outcomes where splash was spotted are plotted in the deposition regime. It is important to mention that for water, the real relative thicknesses for the thinner films were considered (table 3.4).

3.4.3 Senda et al. (1997)

According to Lindgren and Denbratt (2000) the impingement was divided into two cases by Senda et al. (1997). In the first case they studied the droplet-droplet interaction and in the second case a criterion for the deposition/splash transition was developed. For the second case they considered high Weber numbers ($We > 300$). The proposed boundary is showed in the equation 1.15 and it is also presented in Senda et al. (1999).

$$We = (2164 + 7560 \cdot \delta^{*1.78})La^{-0.2} \qquad (1.15)$$

Figure 3.9 shows 4 graphics comparing their empirical correlation with the data of this study, one for each fluid. It was decided to separate the different fluids since including all the results in the same graphic made it difficult to understand.

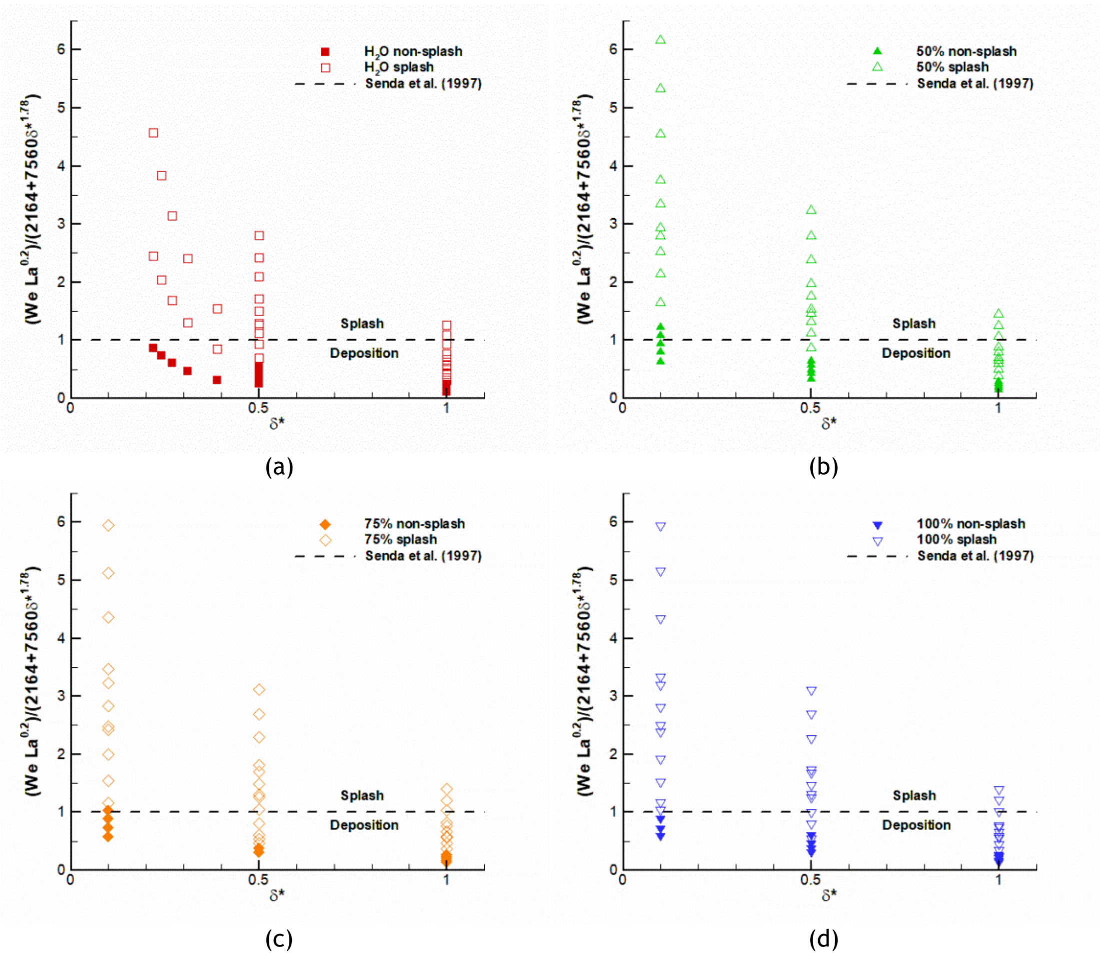


Figure 3.9: Graphics comparing the study results with Senda et al. splashing threshold for each fluid: a) H_2O; b) 50%/50% mixture; b) 75%/25% mixture; d) 100% Jet A-1.

All the data in this study were compared with the Senda et al. criterion but only the impacts from the second and third impact height were considered since the limit was developed for

We>300. The largest droplet in the impact from the lower height of each fuel also exhibited Weber numbers greater than 300.

The horizontal line in the graphics defined as $(We \cdot La^{0.2})/(2164 + 7560 \cdot \delta^{*1.78}) = 1$ separates the deposition and splash regions. As can be seen, the correlation fits properly the results for water, 100% Jet Fuel and the 75%/25% mixtures in the impact with the thinner films. For the shallow and thick films the boundary does not adjust to the data of this study. Regarding to the fact that this correlation should be used only for We>300 was not verified, since the outcomes of non-splash for the impact with the thin films correspond to We<300 and the adjustment to the boundary was good.

For shallow films, some outcomes where splash was spotted are plotted in the deposition regime and for thick films only two or three outcomes are plotted in the correct area in the graphic. It is important to mention that for water, the real relative thicknesses for the thinner films were considered (table 3.4). The results suggest that this criterion should have better precision for fluids with lower viscosity and for the impact with thin films.

3.4.4 Vander Wal et al. (2006a)

Vander Wal et al. (2006a) also determined an empirical correlation for the splash/non-splash boundary both for dry surfaces and thin liquid films. The liquid thickness used was $0.2mm$ and the droplet diameter was $2.0mm$. They used different fluids to vary their outcomes. Based on the obtained results they tested some combinations with Ohnesorge, Reynolds, Weber, and Laplace numbers, but only the power-law correlation between Oh and Re give a clear boundary between the two regimes. These correlation is presented in equation 1.16.

$$Oh \cdot Re^{1.17} = 63 \qquad (1.16)$$

The figure 3.10 compares the results obtained in this study with the Vander Wal et al. empirical correlation. Although their empirical correlation was developed for thin films, it was decided to compare all the results with the splashing threshold. Therefore, the symbols in the graphic represent the outcomes obtained for the three liquid film thicknesses. For the same droplet diameter, the outcomes were often equal for the different thicknesses, except some cases for the two mixtures in h_1, marked with an asterisk.

In the graphic, the dashed line corresponds to the Vander Wal et al. splashing threshold. As can be seen, the results fitted very well their splash/non-splash boundary. All the cases where splash has been spotted are located above their splashing limit, both for the thin films and for the other thicknesses. For H_2O all the non-splash outcomes are under the line, but the highest needle is almost on the line. For the 50%/50% mixture one case of non-splash is over the line, but it is very close. For the 100% JF and the 75%/25% mixture all the non-splash outcomes are located in the non-splash area. However, these two fluids had different outcomes depending on the liquid film thickness. For the 100% Jet A-1 the thin liquid film exhibited splash which agrees with the splashing boundary. For the 75%/25% mixture only the largest droplet splashes upon the thin liquid film and this result also agrees with the Vander Wal et al. splashing threshold. The other two droplet sizes where splash happened upon the shallow film for this mixture were near and over the line.

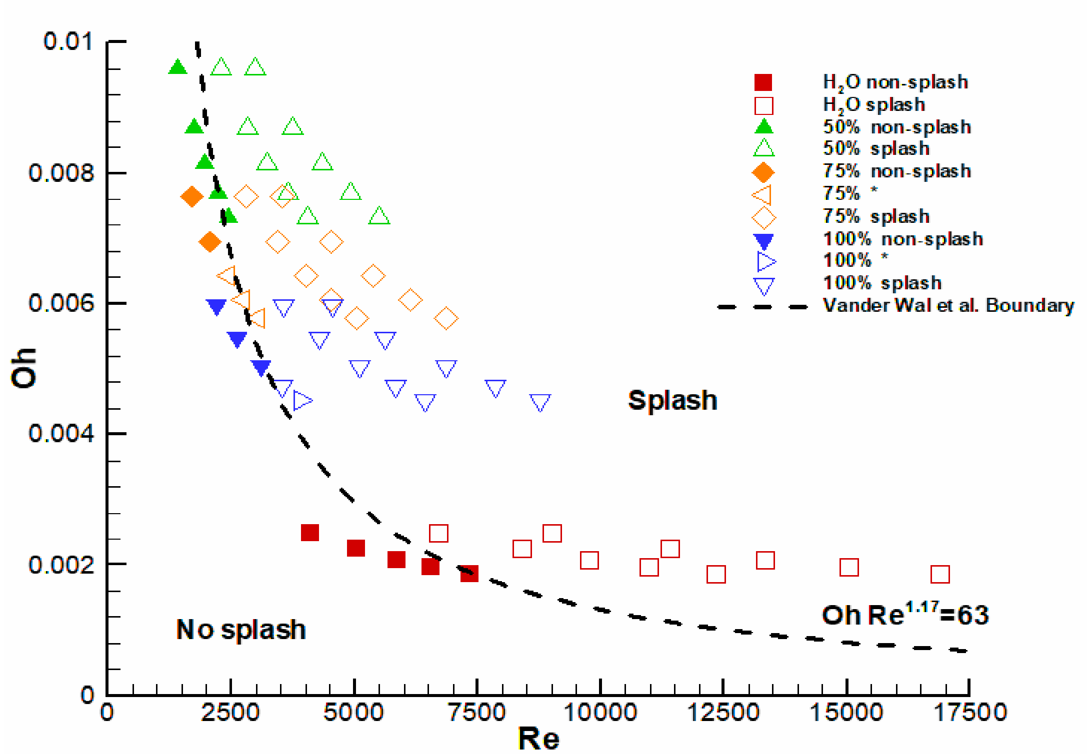


Figure 3.10: Graphic comparing the study results with Vander Wal et al. splashing threshold.

This shows that Vander Wal et al. empirical correlation perfectly fits the results for the thin liquid films, but also provides a good adjustment for the other thicknesses.

3.4.5 Huang and Zhang (2008)

Huang and Zhang (2008) realized several essays of a droplet impinging upon liquid films. They compared their results with transition criteria available in the literature, and since these correlations did not fit properly with their data, they also proposed their own correlation to predict the deposition-splashing transition. They used different needles which provided a range of droplet diameters between $1.8mm$ and $4mm$ (similar to this study). However, they used relative thicknesses of the liquid films varying between 0.3 and 1.3 (between shallow and thick), and in this study thin liquid films were also used. Thin films are known to enhance splashing, so it will be expected that this correlation does not fit properly with the results obtained for thin liquid films. Their empirical correlation is presented in the equation 1.17:

$$(We \cdot Re)^{0.25} = 25 + 7 \cdot \delta^{*1.44} \qquad (1.17)$$

The figure 3.11 shows 4 graphics comparing their empirical correlation with the data of this study, one for each fluid. It was decided to separate the different fluids since including all the results in the same graphic made it difficult to understand.

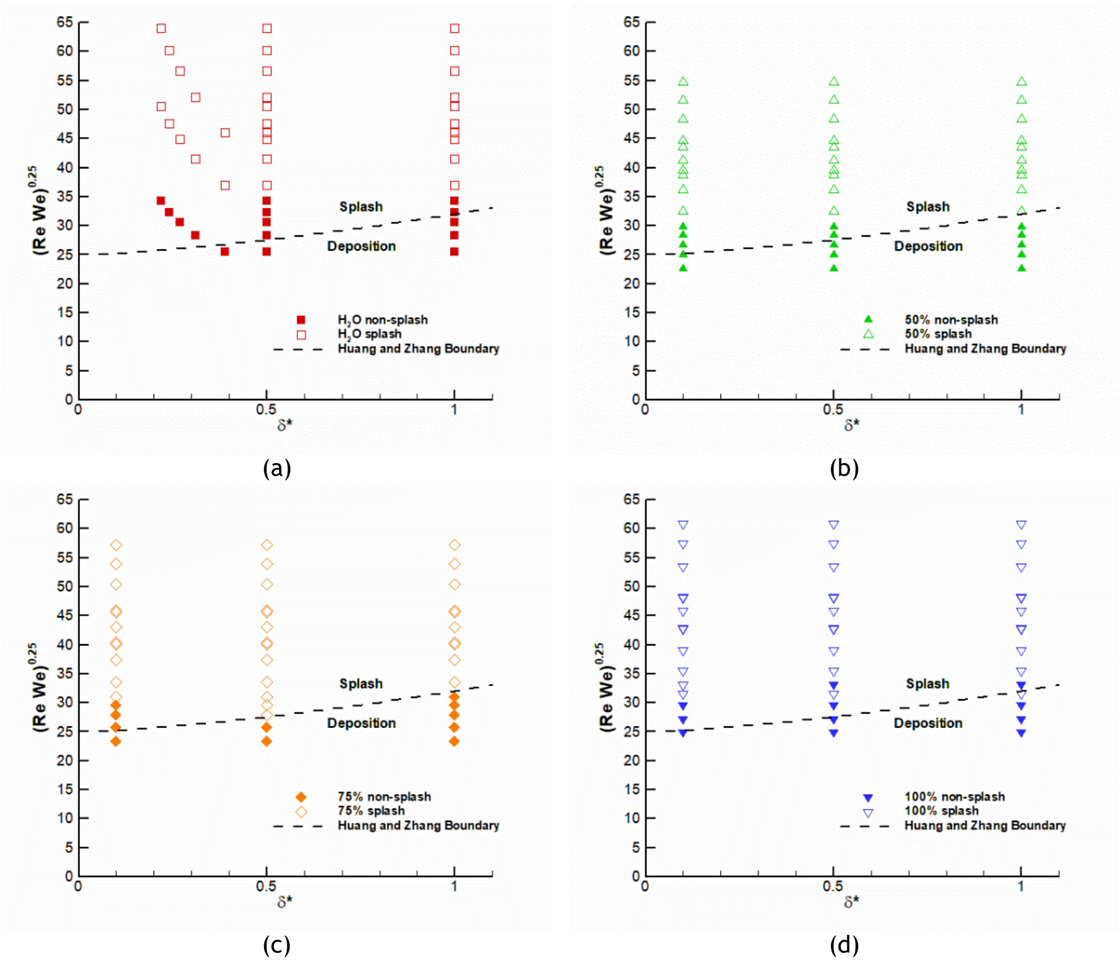


Figure 3.11: Graphics comparing the study results with Huang and Zhang splashing threshold for each fluid: a) H_2O; b) 50%/50% mixture; b) 75%/25% mixture; d) 100% Jet A-1.

As predicted, in the impact upon thin liquid films the correlation does not agree with the results of this study. The correlation fits better the results for the impact with the thick films. The results were expected to fit better the data, since the authors utilized water and oil in their experiments, and the properties of the oil are quite similar to the properties of the 100% JF and the mixtures. It is important to mention that for water, the real relative thicknesses for the thinner films were considered (table 3.4). The combination $(We \cdot Re)^{0.25}$ obtained in these experiments for the non-splash outcomes were higher than what it was predicted by the Huang and Zhang correlation, at least for $\delta^* = 0.1$ and $\delta^* = 0.5$.

3.4.6 Summary

Considering the five splashing thresholds used, it was found that Vander Wal et al. (2006a) presented the boundary that better fits these experiments. Vander Wal et al. empirical correlation perfectly fits the results for the thin liquid films, but also provides a good adjustment for the other thicknesses. However, the outcomes change according to the relative thickness of the liquid film and these cases are not considered in this limit, and should be.

For all fluids, Cossali et al. (1997) criterion fitted perfectly the outcomes for the thin films, and both for shallow and thick thicknesses some outcomes where splash was spotted are plotted in the deposition regime.

In the impact upon thin liquid films, the Huang and Zhang (2008) correlation does not agree with the results of this study. The correlation fits better the results for the impact with the thick films. The results were expected to fit better the data since the authors utilized fluids with physical properties quite similar to the 100% JF and the mixtures.

The Senda et al. (1997) fits properly the results for water, 100% Jet Fuel and the 75%/25% mixture in the impact with the thinner films. For the shallow and thick films the boundary does not approach to the outcomes obtained. The results suggest that this criterion should have better precision for fluids with lower viscosity and for the impact with thin liquid films. The Cossali et al. provides a better relation with the data for the impact upon thin liquid films than Senda et al.

Regarding Bai and Gosman (1995), their threshold only fit the H_2O outcomes. For the fuels, all the cases where the outcomes exhibited splash are plotted in the splash region. However, the scenario for the non-splash outcomes is different. Considering the fact that this correlation was based on the similarity between rough and wetted surfaces, and also based on experiments made with water, it was possible to conclude that this limit is only suitable to the water outcomes.

Chapter 4

Conclusions and Future Work

The last chapter of this dissertation will be divided into two sections. In the first section all the conclusions obtained through this experimental study will be presented and in the second one, a number of guidelines for future works will be proposed, as well as, some suggestions to improve the quality of the study.

4.1 Conclusions

The goal of this experimental study was to determine and evaluate the outcomes of a single droplet impinging upon a liquid film. Moreover, analyze the influence of the parameters involved in the dynamic behavior of the droplet, such as the physical properties of the fluid, the droplet diameter, the impact velocity and the relative thickness of the liquid film (0.1, 0.5 and 1). After that, compare the results with available splashing thresholds. To achieve this goal, four fluids were used: H_2O, 100% Jet A-1, 75% JF/25% HVO mixture and 50% JF/50% HVO mixture. Using these substances provided a range of different viscosities. The surface tension between the three fuels is quite similar as well as the density, but there is a discrepancy when compared with H_2O.

An experimental facility was built to allow the visualization and documentation of the phenomena. To vary the impact velocity three heights were used to release the droplets. In addition, to turn the impact conditions wider, five different inner needle diameters and three relative thicknesses were used. The droplet impact was then studied, catalogued and several conclusions were made.

Starting with the measurements of the droplet diameter, the largest diameters were registered for H_2O. This fact is due to its higher surface tension and density relative to the fuels. The differences between the Jet A-1 and the two mixtures are quite reduced, but it is noticeable that the mixture with 50% Jet A-1 has the largest diameters, then the mixture with 75% Jet A-1 and lastly the 100% Jet A-1 with the smallest values. This trend in the fuels droplet diameters is assumed to depend mainly on the density since their surface tension is quite similar.

The measured droplet size was compared with the theoretical one and it was verified that the real diameter was higher than the theoretical and that equation just provided a good accuracy for the largest needle inner diameter.

Moving on to the impact velocity measurements, varying the impact height provided a range of impact velocities between $1.78 m/s$ and $4.21 m/s$. Similar to the droplet diameter, the highest impact velocities occurred for H_2O. As could be expected, the impact velocities grow while the droplet diameter increases. Between the 100% JF and the two mixtures the differences were quite reduced. As expected the density is an important physical property governing the impact velocity, but the surface tension and the viscosity also play their role.

A wide range of impact conditions was provided. It was verified that the highest Reynolds numbers occurred for H_2O, which is understandable since H_2O exhibits the highest values of the parameters which govern it except for the dynamic viscosity (which is inversely proportional). As could be expected both Reynolds and Weber's numbers increase with the impact height, since both depend on it. Ohnesorge number decreases while the droplet diameter increases and Laplace, Reynolds and Weber's numbers increase while the droplet diameter increases.

The tiny differences in the droplet diameters and impact velocities become widely significant in the value of the dimensionless numbers. That shows that although these two parameters were very close, the impact conditions were large, and a wide variety of outcomes occurred. Six different phenomena were spotted: spreading, fingering, prompt splash, crown splash, jetting and bubbling.

For h_1 both H_2O and the 50%/50% mixture did not exhibit splash, consequently, the lower impact height did not provide enough impact energy for it to occur, which suggests that it was required Weber numbers higher than 188 for H_2O and than 321 for the mixture. The 100% JF and the 75%/25% mixture exhibited both splash and non-splash outcomes for h_1 depending on the droplet diameter and on the relative thickness of the liquid film. Consequently, the Weber numbers provided by these impact conditions stayed between the splash and non-splash regime, under and above the critical Weber necessary to the splash formation.

Considering all the outcomes obtained for h_2 and h_3 splashing always occurred. This confirms that all the Weber numbers obtained for h_2 were equal or superior to the critical, necessary to produce splash. On the other hand, for the third height, all the Weber numbers obtained were superior to the critical. Therefore, the impact energy was much higher than the necessary to occur splash. It was probably due to this surplus of energy that more and larger splashed products were created. It was also noticed that the size and number of the splashed products changed with the relative thickness of the liquid film and also with the impact energy.

H_2O possesses the highest surface tension and might be due to its influence that prompt splash was never spotted for H_2O. It was also observed that the crown seemed thicker for the water outcomes and some authors reported that higher surface tension results in a thicker outer rim. It was also reported in the literature that higher surface tension reduces the crown height, that was also spotted in these experiments since the height of the crown for H_2O was often considered smaller than the crowns obtained for the fuels. Since all fuels have similar surface tension values, these trends were not significant between them.

Another trend was observable for H_2O, since the crown thickness increases while the droplet diameter decreases. This may suggest that the crown thickness might be related to the droplet size. Coghe et al. (1999) reported that the crown thickness is independent of the film thickness and impact velocity, but no considerations were made about the droplet diameter. It was also verified that the final spread diameter was larger for H_2O compared to the three fuels, which supports the assumption that the impact of droplets with lower viscosity results in larger final spread diameters, which was declared by several authors.

The spread was found to become less wide while the droplet diameter decreased. Jetting often occurred for the impact upon the thicker liquid films, which suggests that this phenomenon was enhanced by the increase of the liquid film thickness. However, it was spotted more often for the two mixtures, which suggests that it can also be enhanced by the increase of the viscosity.

Both for h_2 and h_3 crown splash occurred for all the fluids in the impact upon the thin liquid films for all droplet sizes. In the higher impact height, the crown splash was sometimes combined with a prompt splash for the two mixtures. For the 50%/50% mixture, prompt splash happened several times. In the third height, prompt splash happened even more times, which supports the assumption that prompt splash can be enhanced by high viscosities and also high Weber numbers. All the fluids exhibited crown splash for third height. This may suggest that with a Weber number much higher than the critical, the formation of secondary atomization from the crown can be enhanced.

An unexpected phenomenon happened for the 75%/25% mixture. In the impact of the largest droplet upon the shallow film, bubbling occurred.

Globally, the behavior of 100% JF and the 75%/25% mixture was very similar, the major differences were spotted for the 50%/50% mixture. However, the differences between the fuels were quite small probably due to the similarities in their density and surface tension, which turns the viscosity the most influence parameter.

Considering the splashing thresholds, it was found that Vander Wal et al. (2006a) presented the boundary that better fits these experiments results. However, the outcomes changed according to the relative thickness of the liquid film and these cases are not considered in this limit.

Cossali et al. (1999) criterion fitted perfectly the outcomes for the thin films. On the other hand, the Huang and Zhang (2008) correlation fitted better the results for the impact with the thicker films. The Senda et al. (1997) fitted properly the results for water, 100% Jet Fuel and the 75%/25% mixture in the impact with the thinner films. The results suggest that this criterion should have better precision for fluids with lower viscosity and for the impact with thin liquid films. However, the Cossali et al. provides a better relation with the data for the impact upon thin liquid films than Senda et al. Regarding Bai and Gosman (1995), their threshold is only suitable to the water outcomes.

4.2 Future Work

Through the development of this work, several guidelines and recommendations can be suggested. First, it is suggested to investigate the differences between the measured and the theoretical droplet diameter and try to understand the origin of this errors, in order to allow the researchers to have a clearer idea of the droplet size range that they can expect only through the fluid physical properties and especially for the smallest needle inner diameters. It is also important to make the same study for the theoretical impact velocity.

It is recommended to be really carefull with the tip of the needles in order to avoid the liquid accumulation, but it is also interesting to evaluate the influence of this liquid accumulation in the droplet size and in the outcomes. Concerning the thinner films, new methods should be found and applied to produce them with increased precision.

Thinking about these experiments, the study could become richer using other surface materials, perhaps using a rough surface underneath the liquid film and study its influence. The splashing threshold for these mixtures should be found, varying the impact height in order to find the impact energy where non-splash still occur and the following impact energy where splash happen. Using that data and also some available data presented in the literature an empirical correlation could be developed, accounting the influence of the fluid physical properties and the relative thickness of the liquid films.

Lastly, to improve the visualization of the droplet impact, a camera should be put underneath the container to record the phenomena from the bottom, allowing the crown diameter measurement, for example.

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