A Study on the Violent Interactions of an Immiscible Drop impacting on a Superheated Pool

Thesis by
Mohamad Alchalabi

In Partial Fulfillment of the Requirements
For the Degree of
Masters of Science
King Abdullah University of Science and Technology, Thuwal, Kingdom of Saudi Arabia
5/2014
The thesis of Mohamad Alchalabi is approved by the examination committee.

Committee Chairperson: Dr. Sigurdur Thoroddson
Committee Co-Chair: Dr. Christian Claudel
Committee member: Dr. Erqiang Li
ABSTRACT

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Mohamad Alchalabi

The interactions between two immiscible liquids of different temperatures can be violent to the extent of causing harm to individuals, or damage to equipment, especially when used in the industry. Only a few studies investigated these interactions but they could not produce the violent interactions often reported by the industry, and therefore their results did not help much to develop clear understanding of the dynamics of these interactions. In this work, a high speed imaging system operated at 100,000 frames per second was utilized to record the events and phenomena taking place upon the impact of Perfluorohexane droplet at room temperature onto a hot soybean oil pool at temperatures as high as 300 °C. The impact velocity was varied by varying the height of the droplet before it pinches off under its own weight. The recorded events identified the occurrence of vortex ring vapor explosions, weak and strong nucleate boiling, and film boiling. An impact velocity vs. oil temperature diagram identifying the regions in which each of these phenomena takes place was generated, and the dynamics driving their occurrences were explored. The vortex ring vapor explosions were found to become less violent as the impact velocity was increased, which was attributed to the existence of a smaller amount of liquid Perfluorohexane within the rings at high speed impacts, which does evaporate but does not expand violently. Weak nucleate boiling occurred at very high impact velocities relatively. As the temperature is increased, however, they start
turning into strong nucleate boiling. The strong nucleate boiling usually starts right upon impact, and when the temperature of the oil at one impact velocity is increased, it starts turning into film boiling, in which the liquid Perfluorohexane is covered by a vapor layer of its own vapor.
Acknowledgement

I would like to express my gratitude and appreciation to my advisor and committee chair, Prof. Sigurdur T. Thoroddsen, and to my supervisor and colleague, Dr. Erqiang Li, for their continuous guidance, advice, support, and encouragement throughout the course of this research.

My appreciation also goes to my friends and colleagues in the High Speed Fluids Imaging Laboratory for providing the help and advice whenever I was in need for them.

I would like to extend my heartfelt gratitude and appreciation to my mother and every member of my family for their encouragement, patience, and support.
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CHAPTER 1: Introduction and Thesis Objective

1. Introduction

The interaction of droplets with liquid surfaces has been the interest of many researchers throughout the last century. However, there are still many interaction dynamics that are not fully understood or even known to exist. Fundamental understanding of droplet/surface interaction is important for safety precautions, like operating sprinkler systems, agriculture applications, as in pesticide spraying systems, understanding of oceanic wave formation, atmospheric sciences, and even forensics, such as in blood splatter analyses [1].

For deep liquid pools, a droplet impact generally results in splashing, droplet floating, bouncing, coalescing, and jet ejection from the pool surface [2, 3]. Which phenomena are to take place depends on many properties of the droplet and the liquid pool, such as the temperature, surface tension, density, viscosity, and miscibility of the drop with the pool [3], in addition to droplet kinetic energy, droplet volume, and other properties [4].

The interaction between two liquids of different temperatures is quite common in many applications, such as fire suppression [3], the spraying of molten materials into cold baths [5], accidental release of metallic liquids into hot pools, or drop encapsulation by immersion into reacting liquid baths [6]. Interactions between liquids of different temperatures occur frequently also in research labs, such as when solvents are used for cleaning, perfume manufacturing, chemical syntheses, or even the simple mixing of two,
cold and hot, liquids to start a chemical reaction, and other chemical and technological processes. Explosive boiling, which sometimes happen in industrial operations as a result of such interactions, can initiate shock waves that may damage equipment and even injure personnel in the vicinity of the event [7].

To the author’s knowledge, only a few studies have investigated the influence of the liquid pool temperature on the dynamics of the interaction with droplets at room temperature [3, 8, 9]. Manzello and Yang [3] used a high speed imaging camera at 1000 frames per second (fps) to observe the impact of distilled water droplets on a water pool of a 40 mm depth. The water pool temperature was varied between 20 and 94 ºC and was controlled using a hot plate that heated the pool from the bottom. The purpose of their study was mainly to determine the critical impact Weber number for splashing, which is the Weber number at which the disintegration of a drop occurs (the drop splashes). The Weber number is defined as $We = \frac{\rho D V^2}{\sigma}$, where $\rho$ is the fluid density, $D$ is the droplet diameter, $V$ is its velocity, and $\sigma$ is the surface tension. They concluded that splashing in the case of hot pools may occur at lower impact Weber numbers than in the case of a droplet impact on pools at room temperature. However, it is worth noticing that, as pointed out by the authors, the use of a hot plate at the bottom of the pool to heat and maintain the temperature of the pool imposed a convection flow, which in turn is believed to have affected the penetration depth of the droplet and hence the occurrence of splashing.

Manzello et al [8] studied the impact behavior of distilled water as well as methoxy-nonfluorobutane C₄F₉OCH₃ (HFE-7100) (which has a boiling point of 61 ºC) on a hot pool of peanut oil using a high speed imaging camera at 1000 fps. The peanut oil
temperature was varied up to 220 ºC and the impact Weber number for water and HFE-7100 droplets were fixed at 200, and 188, respectively. They found no violent explosions happening when liquid-liquid contact was made, but after the droplet sinks to the bottom of the container and liquid-solid contact is made, vapor explosions took place, as described by the authors. This was the case with both liquids, water and HFE-7100. They emphasized that for the explosion to happen, the pool temperature must be above the superheat limit of the droplet liquid, which can be estimated by [7]:

\[
T_{sl} = T_{crit} \left[ \left( 0.11 \frac{P}{P_{crit}} \right) + 0.89 \right]
\]

where \(T_{sl}\) is the superheat limit temperature, \(T_{crit}\) is the critical temperature, and \(P_{crit}\) is the critical pressure. Interestingly, for HFE-7100, vapor explosions stopped occurring when the pool temperature was raised above 180 ºC, but no explanation for that was provided by the authors.

Wang et al [9] also used high speed imaging at 1000 fps to study the splashing and jet formation of water droplet impacts on pools of water, alcohol, kerosene, and molten-ghee, as the temperature and Weber number are changed. They concluded that the liquid physical properties such as surface tension, viscosity, and miscibility, have primary influences on the impact dynamics, while the drop Weber number and pool temperature influence the size of the splashed daughter droplets as well as the height of the formed jet. They also reported the non-existence of splashing and jet formation in the cases of water-water and water-ghee impacts. The authors attributed these observations to the differences in the dynamics viscosity and surface tension of water and molten-ghee from
those of alcohol and kerosene. The article, however, did not clarify the range of Weber numbers across which the experiment was carried out. Also, the temperature range adopted (30 – 80 °C) may not be wide enough to make such general conclusions.

2. Thesis Objective

As has been mentioned, the interactions of two liquids of different temperatures have not been studied extensively despite the need to understand their dynamics in many applications. All of the previous studies did not discuss the dynamics of the vapor explosions that happen close to the surface of the hot pools when liquid-liquid contact is initiated [7]. Answers have not yet been provided to questions like: what is the detailed mechanism of explosive boiling or vapor explosions? And when might one expect simple boiling, and under what conditions does such boiling develop into a vapor explosion?

The main objective of this study was to better understand the dynamics of the violent vapor explosions that happen when a room-temperature drop impacts a high temperature liquid pool, using high speed imaging to monitor their evolution under different impact velocities (Weber numbers) and different temperatures. It is known that when contact between a cold liquid and a significantly hotter liquid/surface is near, an insulating vapor layer, from the cold liquid, is created, keeping the two systems from direct contact. This phenomenon is known as the Leidenfrost phenomenon, and also often called film boiling [10]. Unfortunately, none of the previous studies reviewed in the previous section touched on the effect of this phenomenon on the interactions and their evolution. Therefore, this work also aimed at studying the role this phenomenon plays on the interaction, which is why the temperature range studied here was quite wide.
CHAPTER 2: Experimental Apparatus and Methodology

In the series of experiments conducted in this research, FLUTEC PP1 (Perfluorohexane, C₆F₁₄) droplets at room temperature (22 ºC) were dropped from different heights onto a pool of hot soybean oil at much higher temperatures (ranging between 90 to 300 ºC). This chapter discusses the apparatus used, the droplet release, temperature control and measurement devices, as well as image data recording and analysis techniques. The next section starts with an overall description of the setup used, which is shown in figure 1 below.

![Figure 1: Schematic of the setup used in the experiments.](image-url)
1. Apparatus

As shown in the schematic in figure 1, the setup consisted of a Chemyx Fusion 200 Series syringe pump (figure 2) that was set to pump FLUTEC PP1 at 50 µL/min. PP1 has a boiling temperature of 57 ºC, melting point of -90 ºC, density of 1670 kg/m³ at 25 ºC, surface tension equal to 11.91 mN/m at 25 ºC, and viscosity of 1.10 mPa.s also at 25 ºC [11]. Silicone tubing was used to connect the syringe needle to a pulled capillary tube with a diameter of 227.2 µm fixed on a slider (figure 3), and through which the PP1 droplets were released; this tube was not changed throughout this work in order to maintain the drop diameter constant at about 1 mm. The slider was fixed on a railing, and was used to control the height of the tube, and hence the speed of the drop.

Figure 2: Chemyx Fusion 200 Series syringe pump used in the experiment.
Sigma-Aldrich S7381 soybean oil, which was used as the impact pool, has a density of 0.917 g/mL at 25 °C, specific heat capacity of 0.448 cal/g°C, viscosity of 58.5 to 62.2 cP at 20 °C, and a smoke point of 245 °C [12]. The oil was held in either a circular container (Pyrex 100 mL), or a square container (designed and made in a local workshop), both shown in figure 4. A calibration image was taken for the circular container while filled with the oil to ensure no magnification effects are present when it was used. The oil was then heated using a Thermo Scientific Cimarec digital stirring hot plate, or a Thermo Scientific Thermolyne benchtop muffle furnace depending on the targeted temperatures (details on the heating process are in the next section) then moved to the impact stage. The top part of the impact stage was a ceramic hearth plate used to isolate the bottom of the container and prevent high transfer rates which could break the container glass slides.
The temperature of the oil pool was monitored before and after the impact using OMEGA HH802U digital K/J thermocouple, shown in figure 5. The temperatures were measured by inserting the probe in the oil pool and waiting for a few seconds for the reading to stabilize. Once the reading stabilized, the probe was removed, and the impact was initiated.

All the carried out experimental work was video recorded using the Phantom v1610 high speed imaging camera at a frame rate of 100,000 fps, a resolution of 384 x 288 pixels, and with a shutter speed of 1 µs. This short shutter speed was selected as it allows less light to enter for each frame, and thus helps provide crisp images and minimizes any motion blurriness there may be for events that take place very fast.
Moreover, the camera was equipped with a set of three Leica lenses\(^1\) that together were used to provide a magnification of 1.6x. The recording duration of the impacts was long enough to cover the events of interest from the beginning till the end with clear tracking of details, and to allow manual triggering. For each height, one video of freely falling droplet was recorded in order to determine the velocity for all drop impacts at that particular height. One Sumita 350 W metal halide light source (figure 6) was utilized to back light the area of the impact, and a tracing paper diffuser was used to scatter light uniformly within the region of impact.

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\(^{1}\) Details are provided in the “Imaging Equipment and Image Data Processing” section.
2. Heating Process

The soybean oil was first filled in the experimental container to the depth of 30 mm. The soybean oil was heated, separately, prior to performing the experiments, then moved to the impact stage. Although heating the oil continuously while on the stage by, for example, having the hot plate as part of the base and heating the container from its bottom would maintain the temperature of the pool, it was not adopted in this setup to avoid the convection air flow effect caused by the continuous heating of the oil, as was experienced by Manzello and Yang [3] (refer to chapter 1).
When the targeted temperature was 210 °C or lower, the oil was heated on the Thermo Scientific Cimarec stirring hot plate SP131320, shown in figure 7, to temperatures higher than the targeted values by 10 to 20 °C. For example, when a drop impact at pool temperature of 180 °C was desired, the pool was heated to 190 - 200 °C. The oil was overheated since moving it from the heating stage to the impact stage, and positioning it accurately in the drop trajectory, takes some short, yet valuable time that is enough for the temperature to drop significantly.

Figure 7 Thermo Scientific Cimarec stirring hot plate used to heat the soybean oil when targeted temperatures were 210 C or lower.
When temperatures higher than 210 ºC were targeted, the Thermo Scientific Thermolyne benchtop muffle furnace was used, shown in figure 8. Heating the oil on the hot plate to reach temperatures higher than 210 ºC is quite dangerous as the container may not sustain the high temperatures at the bottom (which was often needed to be set higher than the targeted temperature because of the continuous cooling that takes place on the other sides of the container). Unlike the hot plate, the furnace heats its chamber uniformly to the desired temperature and maintains it. Heat resistant lab coats, gloves, and face shields were used during the experiment for safety.

![Figure 8: Thermo Scientific Thermolyne benchtop muffle furnace used to heat the soybean oil when the targeted temperatures were higher than 210 C.](image-url)
Heating the oil repeatedly causes some deterioration and induces some chemical composition changes; this is evident by darkening in the color of the oil [13]. Even though the color is not a reliable indicator of the oil quality in general, it was sufficient in this work to indicate the need to frequently change the oil to avoid any possible errors that may occur as a result of the changes in the oil liquid properties. Therefore, the oil was changed every time its color darkened noticeably.

3. Imaging Equipment and Data Processing Tools

3.1. Imaging Hardware

All drop impacts conducted in this research were recorded using the Phantom v1610 high speed imaging camera, shown in figure 9. This camera is capable of capturing 16 gigapixels per second of data. As a result, at its lowest resolution of 128 x 16, it can operate at a frame rate of 750,000 fps. The higher the frame rate required is, the lower the maximum attainable pixel area size. Table 1 shows the maximum frame rate associated with each pixel resolution [14].

Figure 9: Phantom v1610 high speed imaging camera used throughout this work.
Table 1: Resolutions and the corresponding frame rates of the Phantom v1610 high speed imaging camera [14].

<table>
<thead>
<tr>
<th>Resolution (Horizontal x Vertical)</th>
<th>Maximum Frame Rate (fps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1280 x 800</td>
<td>16,600</td>
</tr>
<tr>
<td>1280 x 720</td>
<td>18,400</td>
</tr>
<tr>
<td>1024 x 800</td>
<td>19,700</td>
</tr>
<tr>
<td>1024 x 512</td>
<td>30,700</td>
</tr>
<tr>
<td>896 x 800</td>
<td>21,800</td>
</tr>
<tr>
<td>768 x 768</td>
<td>25,300</td>
</tr>
<tr>
<td>640 x 480</td>
<td>45,500</td>
</tr>
<tr>
<td>512 x 512</td>
<td>49,100</td>
</tr>
<tr>
<td>512 x 384</td>
<td>64,900</td>
</tr>
<tr>
<td>384 x 384</td>
<td>76,300</td>
</tr>
<tr>
<td>256 x 256</td>
<td>135,300</td>
</tr>
<tr>
<td>128 x 128</td>
<td>312,800</td>
</tr>
<tr>
<td>128 x 64</td>
<td>537,600</td>
</tr>
<tr>
<td>128 x 16</td>
<td>750,000</td>
</tr>
</tbody>
</table>
The pixel size on the sensor of the camera is 28 microns, which provides high light sensitivity, with a bit depth of 12 bits\(^2\), yielding to 4,096 gray levels [14, 15]. The shutter in the camera has exposures that are as fast as 1 µs. Also, the camera has an internal mechanical shutter that can be used to provide the camera with its black reference\(^3\) simply by closing this shutter, and hence sampling a perfectly black image. The camera allows the user to choose the triggering position of the recording. In this work, the triggering position was chosen as “last”; in other words, the camera keeps recording until the triggering button on the Phantom Camera Controller (PCC) software (discussed in a later section) is clicked. Once it is clicked, the recording is stopped and the video can be played and analyzed [14].

The other many features of this camera were not all utilized in this work and therefore are not discussed here. Interested readers may refer to the data sheet of the camera [14].

The camera was equipped with three interchangeable Leica lenses, connected together as one set, shown in figure 10; the first lens, Leica 10447176, has a 1.0x magnification, which was utilized to make the focal length\(^4\) shorter, and to adjust the focus. The second lens, Leica Z16 APO 10447204, lens has an adjustable magnification

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\(^2\) Bit Depth: The number of bits used to indicate the color of a single pixel. The higher the number of bits, the higher the number of levels a color can be. Number of levels = \(2^{\text{bit depth}}\).

\(^3\) Camera Black Reference: a measurement of the fixed and continuous noise the sensor of the camera is subjected to, so that it is subtracted later from all frames captured.

\(^4\) Focal length: is a measure of how strongly light rays are converged or diverged by the optical system. The shorter this distance is, the more the light is bent, and hence the rays are brought to focus in a shorter distance.
of 0.57x to 9.2x range, and an adjustable aperture\textsuperscript{5} that ranges between f-numbers \textsuperscript{6} of 1 and 5. Lastly, the Leica 10447436 zoom lens has a magnification of 1.6x. The total magnification produced by connecting the three lenses together (after, of course, fixing the magnification of the Leica Z16 APO), is found by multiplying the magnifications of each lens. For instance, throughout this work, the Z16 APO lens was fixed at a magnification of 1.0x, and thus the resulting overall magnification was: $1.0 \times 1.0 \times 1.6 = 1.6x$.

\textbf{Figure 10:} The set of three lens elements connected to the Phantom camera.

\textsuperscript{5} Aperture: the opening in the lens through which light travels. If the aperture is narrow, then only the highly collimated rays are admitted, which provides a sharp and focused image. Wide apertures, on the other hand, allow uncollimated rays to pass providing sharpness only around the area on which the lens is focusing.

\textsuperscript{6} f-number: is the ratio of the focal length to the diameter of the lens entrance (also often called entrance pupil).
3.2. Imaging Analysis Tools: Phantom Camera Control and Photron FASTCAM Viewer

3.2.1. Phantom Camera Control (PCC) Software

The PCC software is the interface through which all the functions and settings of the Phantom camera can be controlled, such as the pixel resolution, frame rate, exposure, triggering modes, video cropping, and many other settings.

As an imaging analysis tool, on the other hand, the software was used only to make clear visual observations and conclusions; i.e. to determine whether there were vapor explosions, nucleate boiling, and so on. The software was quite helpful in this regard because of the various features of its image tools. Since the tools are too many to explain in this work, only the used tools are discussed in this section. Interested readers may refer to the Phantom Camera Control Software help file [16].

The image processing techniques available can bring out hidden details in the images or videos. The effectiveness of each technique depends on many factors, such as the illumination of each pixel, the overall brightness, the blurriness in the image or video, and many other factors. The following are the tools which were often used to make the observations and conclusions in this work:

a. Brightness (%)

By sliding a bar that changes the brightness from 0 (default) to the left, the image displayed becomes darker, whereas moving it to the right makes the image lighter. This tool was not utilized that often as the lighting system used
kept the brightness generally in the sufficient level over the whole region of interest.

b. Gain

This tool adjusts the contrast\(^7\) in the image. Just as with the brightness tool, a slider also is used here to change the contrast from the default value of 1.0. Moving the slider to the left reduces the contrast, while moving it to the right increases the contrast.

c. Gamma

A few words on Gamma (or Gamma correction, as it is often called) may be necessary to understand the function of this tool. A Gamma correction is a change imposed on the luminance value of a pixel; all pixels have levels of brightness between 0 (black) and 1 (white). These pixel values are the inputs for the computer monitor or display. However, since our eyes do not perceive light the same way camera sensors do, corrections can be made to images (or pixels’ luminance) before they are displayed to make them easier to perceive by the human eye. Without corrections, pixels that receive twice the number of photons will have twice the amount of illumination; i.e. a linear relation between the amount of light and brightness. Our eyes, however, do not follow this linear relation. Instead, we perceive twice the amount of light as being only a fraction brighter\(^8\) (nonlinear relation) [17 - 18].

---

\(^7\) Contrast: the degree of difference between dark and light regions in an image.

\(^8\) Gamma is defined as: \(V_{\text{out}} = V_{\text{in}}^{\text{Gamma}}\), where \(V\) is the luminance value, and Gamma is the correction (or power) to which luminance is raised.
This tool changes the default value of 2.222 between 0.100 and 10.000. Corrections made with Gamma values greater than one make the shadows in the images look darker, while Gamma values less than one make dark regions lighter. Figure 11 shows an example of an image with its brightness raised to a power of 1 on the left (basically uncorrected), 2.2 in the middle, and 2.5 on the right [18].

![Figure 11: An image with its brightness raised to a Gamma correction value of 1 on the left (uncorrected), 2.2 in the middle, and 2.5 on the right [18].](image)

D. Image Filters

A set of filtering algorithms (masks) are provided in PCC. Only two masks were used often in the analysis of this work:

1- Sharpen: this filter is used to sharpen the edges within the image. Sharpness of edges and boundaries become much clearer when this filter is applied.

2- Edge Hipass 3X3: this filter enhances or isolates 3X3 pixel transition areas, or edges, by enhancing the high-frequency details in the image.
It is important to keep in mind that, as was mentioned at the beginning of this section, these image corrections were only used to determine qualitative features from the videos, not to extract any qualitative measurements.

3.2.2. *Photron FASTCAM Viewer (PFV)*

This software is the interface and analysis tool for Photron high speed cameras. It was used in this work mainly to calculate the droplet diameters and impact velocities. This software was adopted to perform these calculations because it is simpler and more intuitive compared to PCC. For PFV to be able to read the videos recorded by the Phantom camera, the videos had to be saved from the PCC with the .avi extension.

Calculating the diameter using PFV was straightforward. The diameter measurement was made using the videos recorded of freely falling droplet at each height, as can be seen in figure 12⁹, when a rectangular area in the video is selected, the software provides its height and width, (notice on the top left corner). The square encapsulating the drop in the case in the figure has edges of 55 pixel lengths. Therefore, the drop diameter in this case is 55 pixels as well. In order to convert this value into millimeters, it has to be multiplied by the pixel size of the camera’s sensor, which is 28 microns, as was mentioned previously, then divided by the total magnification of the optical system, which was 1.6x, as was calculated earlier. Hence:

\[
\text{Drop Diameter} = \frac{\text{Number of pixels} \times \text{pixel size}}{\text{Magnification}} = \frac{55 \times 10^{-6}}{1.6} = 0.0009625\ m \approx 1.0\ mm
\]

⁹ This image is zoomed in by almost 400%.
This calculation was performed for 112 drops from 112 different videos and the average was calculated and found to be 0.994 mm, with a maximum percentage difference between drops of +4.2%. Therefore, the diameter of all droplets in this work can be assumed to be fixed at 1.0 mm.

The radius of the drop (which is equal to about 0.5 mm) is smaller than the capillary length ($L_c$)\(^{10}\) of Perfluorohexane, which was found to be:

$$L_c = \sqrt{\frac{\sigma}{\rho g}} = \sqrt{\frac{0.01191}{1685 \times 9.81}} = 0.85 \text{ mm}$$

where g is the gravitation force acceleration. Hence, we do not expect the air drag to significantly deform the drop during the free fall.

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\(^{10}\) Capillary length is a characteristic length scale for an interface between two fluids, and where this interface is subjected to a gravitational force a surface tension force.
The speeds of the droplets upon impact were also calculated using the videos recorded of freely falling droplets. The speeds were calculated over a distance of 1.3 mm only (about 75 pixels) that starts at the impact point and end 1.3 mm within the oil pool. Figure 13 clarifies this distance, in which the picture on the left is for the soybean oil pool with the black area at the top being the meniscus, and the picture on the right is for the freely falling droplet paused at 1.3 mm from what would be the impact surface if the oil pool was present.

The number of frames elapsed until the droplet reaches the 75th pixel is divided by the frame rate (which was fixed at 100,000 fps, as have been mentioned previously) to find the time period in seconds. For the example, for the droplet in figure 12, the number of elapsed frames was found to be 50 frames, and thus the impact velocity can be found as follows:

\[
\text{Impact speed} = \left( \frac{75 \times 28 \times 10^{-6}}{1.6} \right) / \left( \frac{50}{100,000} \right) = 2.62 \text{ m/s}
\]

The impact velocities of all videos were calculated using the same method.
Figure 13: An example of the speed measurement method used. On the left, the picture shows the soybean oil pool, and on the right, its corresponding region when the container is removed. The drop is paused at the 75th pixel from the top, which corresponds to a vertical distance of almost 1.3 mm.
CHAPTER 3: Results and Discussion

1. Introduction

The interactions between an impacting PP1 drop and a soybean oil pool under the different oil temperatures and impact velocities resulted in some interesting phenomena. The diagram in figure 14 identifies five main regions; the five regions define the boundaries between the different phenomena. These are evaporation, vortex ring vapor explosion, weak nucleate boiling, strong nucleate boiling, and film boiling regimes. The curves separating the regions are all second order degree polynomial curve fits, applied to the upper and lower data points of each of the phenomena. The curves were extrapolated to fully cover the temperature and impact velocity ranges, or until two curves intercepted.

The evaporation region, occurs at low impact velocities, identifies the temperatures and impact velocity limits within which the drop impact has no effect in general other than evaporating the PP1 drop gradually inside the pool. As per the focus of this work, which is mainly on the violent interactions between PP1 and the soybean oil, this region does not show any such interactions and therefore it will not be discussed further in the sections of this chapter.

Vortex ring vapor explosion refers to the vorticity rings that form, within the defined region, and explode shortly after that. The vortex rings are shaped differently for different velocities and pool temperatures, and how violent the explosions are is also a function of both the temperature and the impact velocity, as can be seen in the diagram.
Figure 14: Diagram showing the evaporation, vorticity vapor explosion, the nucleation, and film boiling regions during the impact of PP1 drop onto soybean oil pool, at various impact velocities and pool temperatures.
Weak and strong nucleate boiling are also present within the regions defined in the diagram. Nucleate boiling can be defined as boiling that takes place when the temperature of the hot liquid/surface is higher than the saturation temperature\textsuperscript{11} of the cold liquid by a certain amount, but also lower than its critical heat flux point\textsuperscript{12}. The main heat transfer mechanism in this case is convection. These two types of boiling are believed to be present as a result of the formation of thin liquid layers of the PP1 on the boundary of the crater of the impacts, as will be explained later.

Lastly, film boiling is when the cold PP1 droplet is covered with a continuous film of PP1 vapor that keeps the liquid PP1 from contacting the hot oil, and hence reduces the heat transfer rate. The point at which film boiling starts is known as the Leidenfrost point since the Leidenfrost effect is the driving force behind this phenomenon. During film boiling, the main heat transfer means becomes radiation instead of convection due to the insulating vapor layer. It must be pointed out that the dashed curve separating the nucleate boiling region from the film boiling region does not necessarily represent the accurate transition points since the transition between the two kinds of boiling is not easy to track.

In the coming sections, the observed phenomena, except for the evaporation region, will be discussed thoroughly.

\textsuperscript{11} Which is the boiling point of the liquid.
\textsuperscript{12} Critical heat flux: is the point at which heat transfer rate drops and at which a vapor blanket or layer starts to form, blocking the heat flow from the hot medium to the cold medium [19].
2. Vortex Ring Vapor Explosion

The diagram in figure 15 is a zoom-in of the vortex ring vapor explosion region that was shown in figure 14. Images of the interface deformation, which we call vortex rings, generated at different impact velocities are shown in figure 16. For a drop impacting at low velocities onto a pool of the same liquid, the section close to the top of the crater curves over (as in the rings pointed at by the arrows in figure 17) to form a vortex ring [20 - 21]. We, therefore, speculate that a vortex ring may be formed in the same way in our configuration. In order to understand the dynamics behind the observed explosions, it is necessary to shed some light on the mechanism behind the formation of the vortex rings in the case of immiscible liquids, such as the case of this study.

The process starts by the rupture of the drop interface upon impact. This rupture causes some of the drop liquid to be drained into the host pool (the soybean oil) and to roll up over the boundary of the evolving crater, and thus vorticity is created [22 – 23].
Figure 15: The region within which vortex ring vapor explosions happen.
Figure 16: Vortex rings formed at impact velocities of: a) 1.35 m/s, b) 1.44 m/s, c) 1.60 m/s. The arrows point at the rings.

Now, it is known that under such liquid-liquid impacts, there will always be some air entrapped between the drop and the receiving liquid pool [24 - 27]. In addition, in this work, there was also some PP1 vapor that is generated starting from the moment the drop approaches the pool because of the big temperature difference. Therefore, the vorticity travelling upward towards the impact interface has a gaseous layer (composed of entrapped air and evaporated PP1), and right above it is a layer of liquid PP1. The gaseous layer stands in the way and prevents any direct contact between the oil and the liquid layer of PP1. Hence, although the liquid layer will still go through some evaporation, the heating will be mainly through radiation.

As the vorticity travels upward along the crater and starts to form the vortex ring close to the interface (as the arrows in figure 17 indicate), some of the oil is also entrained inside the ring [28]. Now, the liquid layer of PP1 is being heated from both of its sides, and despite the insulation provided by the gaseous layer also being on both sides, the total heat flux is in fact doubled in this case, which leads to massive evaporation and hence a vapor explosion, as shown in the time-elapsed images in figure 17.
Figure 17: Time-elapsed images of vortex explosion. Taking the first image as the time reference, the images are 10 µs apart. A close look at the images shows clearly that the explosion starts in the center of ring at the 30th µs. The arrows at the 20th, 60th, 100th, and 140th show how the ring is increasing in size rapidly after the explosion.
This explosion starts at one point or site on the vortex ring and then propagates azimuthally along the entire ring. In figure 17, the explosion starts in the middle of the ring, as can be perceived in the images between 30 and 60 µs. While in figure 18, the explosion clearly starts on the left side of the ring. Most likely, the occurrence of these explosions indicates that both layers of the liquid PP1 and the gases are thinnest there, thus enough heat flux is being transmitted to evaporate the little amount of liquid PP1, and therefore PP1 evaporates and expands very quickly. Another possible reason is that either the liquid PP1 or the gaseous layer is thinnest there, and therefore the heat flux is sufficient to quickly evaporate the contained PP1 liquid. The former is most likely the case since the draining of both layers towards vortex ring is believed to reduce their thicknesses. Furthermore, the vortex may also encapsulate a region of PP1 vapor and prevent it from escaping into the crater.

![Figure 18: Another vortex ring explosion starting on the left part of the ring.](image)

It is worth noting that the diameters of the vortex rings become smaller as the impact velocity is increased, until they cease to form at impact velocities around 2.2 m/s. Figure 19 shows the final forms of the vortex rings that were generated at different impact velocities. The images are taken one frame before the explosions occur. Although
a critical Weber number $We \approx 64$ above which vortex rings cease to exist (for a drop impacting on an identical liquid pool) was reported in a study performed by Hsiao et al. [29] (and thus there exists a critical impact velocity for each liquid), in our study, the vortex ring disappears at Weber numbers larger than approximately $We \approx 212$. Also, to the author’s knowledge, the change in the ring core diameter and shape with the impact velocity has not been explained yet in any study.

![Figure 19: Vortex ring formations at different impact velocities, with pool temperature equal to 160 °C. These images are taken one frame before explosion. The ring disappears completely at the images 'e' and 'f'.](image)

Besides, the strength of the explosions was noticed to become weaker generally as the vortex ring core diameters become smaller. This may be due to the much less amount of liquid PP1 eventually contained in a layer in the ring at these high impact velocities [28], which therefore does not expand as violently when it evaporates.
Finally, as can be seen in the diagram in figure 15, the vortex rings and explosions appear between temperatures of approximately 140 and 190 °C. Why they cease to exist at other temperatures may be due to changes in physical properties of the oil, such as viscosity and density, because of heating, and which in turn affect the dynamics of the interaction. These changes and their effect on the interactions have not been studied well in the literature and deep understanding is yet to be developed.

3. Nucleate Boiling and Film Boiling

Boiling can be defined as the formation of vapor bubbles at the surface separating the cold liquid from the hot liquid/surface. The bubbles are formed at specific nucleation sites. These sites, in the case of solid surfaces, are determined based on the cavities and the roughness of the surface, fluid properties such as its viscosity and surface tension, and interaction conditions [30]. For the nucleation sites in the case of liquid-liquid interactions like here, no conclusive studies have been published yet.

The boiling heat transfer coefficient is a function of the temperature difference between the two interacting mediums. Furthermore, it is a function of the vapor amount, thickness, and rate of vaporization [30]. The dependence of the boiling coefficient on these many parameters makes it difficult to predict its value for a particular interaction and, therefore, the heat flux is also hard to estimate.

The nucleate boiling and film boiling generally observed in the case of solid and liquid interactions at different temperatures were also observed in this study. In our
configuration, the surface tension keeps the liquid surface smooth and the nucleate boiling occurs at isolated points where the two liquids touch across the vapor layer.

### 3.1. Nucleate Boiling

#### 3.1.1. Weak Nucleate Boiling

Weak nucleate boiling occurred during the drop impacts in the region marked in the diagram in figure 14. This nucleate boiling happened at the upper part of the crater created during the impact, as can be seen in figure 20. This nucleation was observed between approximately 140 and 170 °C, and impact velocities that increased with temperature. Since the highest impact velocity attainable with the utilized setup was about 3.5 m/s, it is unknown whether this phenomenon stops at a certain temperature or not.

As was explained in the previous section, the crater is covered by thin layer of liquid PP1, which is also covered by a thin layer of air and PP1 vapor. Also, as is the case with the vortex ring explosion, the two layers are expected to be thinnest in that part of the crater. The fact that this weak nucleation is happening at higher speeds than those at which the vortex ring explosions are happening is probably due to the amount of liquid PP1 at the ring being just so little that even when it vaporizes, it does not expand violently.

If, for a specific impact velocity, the temperature of the oil is increased, the nucleation starts to enter the strong nucleation region (refer to the diagram in figure 14),
which can be interpreted as that the heat flux increases significantly as a result of the higher temperature difference.

Figure 20: Time-elapsed images of weak nucleate boiling happening at the upper part of the crater. The pool temperature in this video was 148 °C.

The change in this phenomenon at higher impact velocities could not be studied due to the limitations imposed by our setup, which limits the maximum impact velocity to about 3.5 m/s.
3.1.2. Strong Nucleate Boiling

As can be seen in the diagram in figure 14, the region defining strong nucleate boiling encloses the region of vorticity ring vapor explosion. This is because strong nucleation takes place right after the beginning of those explosions.

Figure 21 shows a sequence of images of strong nucleate boiling that starts right after impact. The dynamics causing this nucleation are the same as those that caused the weak nucleation. In this case, however, the nucleation is more violent and is happening everywhere on the structure because the temperature difference is higher, leading to higher heat flux that is high enough to evaporate the liquid PP1 layer on all parts of the crater, not only the upper part. Nonetheless, the temperature difference is not large enough to produce Leidenfrost conditions.

It was observed that at different temperatures for the same impact velocity, less nucleation sites are activated for the higher temperature case. This is quite interesting and is in agreement with the observations made in the case of hot-solid-cold-liquid interactions at different temperatures [10, 30, 31]. Before film boiling region is reached, a continuous vapor film layer forms sometimes [31], reducing the heat transfer in general; that is, less nucleation sites are activated. The nucleation becomes less intense as the boiling approaches the film boiling regime (refer to figure 14). As was mentioned at the beginning of this chapter, the dashed curve is not an accurate representation of the points at which the boiling changes from nucleate to film boiling. This transition usually happens within what is known as the transition boiling region which is hard to track and bounding it can be very subjective.
Figure 21: Time-elapsed images of strong nucleate boiling that starts right at the moment the impact. As the images progress in time, it becomes more and more obvious that the nucleation is happening all over the structure.
3.2. Film Boiling

As was explained at the beginning of this chapter, in this phenomenon (also called Leidenfrost regime), the PP1 drop is covered with a continuous vapor layer of its own vapor\(^{13}\). As a result, the vapor layer allows much less heat flux mainly through radiation, and thus the evaporation of the encapsulated PP1 liquid is slowed down. As the thickness of the layer increases with temperature, it is well accepted that, for single component liquids, the heat flux will increase [30].

The layer and the encapsulated liquid PP1 remain quiet and no nucleate bubble formation can be observed on the surface of the layer, as can be seen in the time-elapsed images in figure 22.

It is worth mentioning here that, within the transition region between nucleate and film boiling (i.e. the transition boiling region), the rapid vapor production surrounds the liquid PP1 with a vapor layer that pulsates\(^{14}\), for a very short period of time, before it stabilizes. An example of this pulsation can be observed in the time-elapsed images in figure 23. The images may be confused as weak nucleation because of the disturbance on the boundary of the structure; a close look, however, on the center of the structure, and particularly on the white spot, reveals the absence of any nucleation sites, and clearly shows the pulsation in the vapor layer, indicated by the deformation of the central white spot.

\(^{13}\) This is of course in addition to the entrapped air that is always there; but in this case, its amount is insignificant compared to the PP1 vapor.

\(^{14}\) This may make it seem like weak nucleate boiling, while it actually is not.
It is interesting to note that this layer eventually stabilizes\(^{15}\), unlike in the case of hot-solid-cold-liquid transition boiling, in which this layer occasionally collapses, allowing the liquid to come in direct contact with the solid [10, 30].

Figure 22: Time-elapsed images of film boiling, showing how quiet and stable the vapor layer is. The pool temperature was 261°C and the impact velocity was 2.10 m/s.

\(^{15}\) This was the case in all recorded events in which it occurred.
Figure 23: Pulsation happening at the vapor layer due to boiling being in the transition boiling region, which is between the nucleate boiling and film boiling regions. The pool temperature in the video was 268 °C, and the impact velocity was 1.45 m/s.
CHAPTER 4: Conclusion, Open Questions, and Future Work

In this study, the violent interactions between two immiscible liquids at greatly different temperatures were investigated. This was studied by impacting a cold drop onto a heated liquid pool. The impacts were carried out at various impact velocities. The liquids used were Perfluorohexane, \((C_6F_{14})\), with the brand name FLUTEC PP1, at room temperature of 22 °C, and Sigma-Aldrich S7381 soybean oil at various temperatures. The drop impacts were recorded using the high speed imaging camera Phantom v1610 at 100,000 fps and an optical setup that produces a magnification of 1.6x.

The recorded impacts revealed some interesting phenomena that take place within certain temperatures and impact velocities; vortex rings formed and exploded between temperatures of 140 and 190 °C and impact velocities between about 1.3 and 2.4 m/s (refer to figure 14). These vortex rings form as a result of the vorticity generated by the flow around the outer surface of the growing crater starting at the moment of impact. This vorticity travels towards the impact interface, where it appears to form a vortex ring. We propose that the vortex is composed of a gaseous layer containing some entrapped air and PP1 vapor, followed by a liquid PP1 layer.

The vorticity entrains some of the hot soybean oil, which eventually heats the liquid PP1 layer from two sides. Even though the gaseous layer prevents direct contact between the liquid PP1 and the entrained oil, and hence it reduces heating through convection, the heat flux, absorbed mainly through radiation, is of significant amount to
cause massive evaporation of the PP1 liquid, followed by violent expansion of the vapor. The explosion starts at one point or side of the ring and then propagates azimuthally to blast the rest of the ring.

The vortex rings start to have smaller diameters as the impact velocity is increased. Also, the explosions seem to become less violent as the impact velocity increases until they disappear and strong nucleation starts to happen. The explosions become weaker because less liquid PP1 is contained in the ring at such impact velocities, and hence the evaporated amount of PP1 cannot cause as violent explosions.

Also, between about 140 and 170 °C, as the impact velocity is increased beyond that at which vortex ring explosions occurred, weak nucleation starts to occur at the upper part of the evolving crater. This is also attributed to the liquid PP1 and gaseous layer being thinnest there and hence the heat flux is enough to cause some vaporization. This vaporization happens to only a small amount of liquid and therefore no violent expansion exists. The changes in this phenomenon, if any, at higher impact velocities are not known due to limitations imposed by the used setup.

Strong nucleation also appears at certain impact velocities and temperatures. The nucleation takes place since the temperature difference becomes significant enough to induce a high heat flux that is enough to evaporate the layer of liquid PP1 all over the crater structure, not only the upper part, as was the case in the weak nucleation. This is why the nucleation starts from the moment the impact is initiated, as was shown in figure 21.
In the diagram of figure 14, the strong nucleation regime is to the right of the weak nucleation region; i.e. it occurs at higher temperatures for the same impact velocities. This affirms the explanation provided above.

In the film boiling regime, the liquid drop is enclosed with a continuous layer of its own vapor. Despite the fact that the thickness of the layer increases with temperature, it is well accepted that the heat flux absorption also increases.

Throughout this work, some dynamics were observed for which no legitimate explanations have been provided in the literature or by the author. The change in the vortex ring core diameters, for instance, and their disappearance at certain critical impact velocities are still not fully understood. Understanding the parameters controlling the formation and disappearance of these rings can help in developing some modeling for the occurrence of their explosion.

Also, at low impact velocities, the vortex ring formed in some cases and stopped its rotation after a while, as can be seen in the time-elapsed images in figure 24, where the last image is the last frame right before the ring exploded. This may indicate the existence of a lower critical Weber number (and hence a lower critical impact velocity) below which the vortex ring starts to form but stops perhaps because of insufficient amount of circulation generated by the flow-up along the outer surface of the crater. This mechanism cannot be compared directly with the upper critical Weber number reported by Hsiao [29] since in that study the vortex rings were generated by the impact of a drop onto a pool of the same liquid and direct contact was made between the drop and the pool.
Figure 24: Vortex ring stops rotating after a short amount of time, between the 650th and 750th second, then explodes at the 850th second. The pool temperature was 156 °C and the impact velocity was 1.23 m/s.
Future work should study the interactions with different drop sizes. In addition, higher impact velocities within the region of weak nucleate boiling should be tested in order to determine whether there is any change in the phenomenon, and whether there is some upper limit above which it stops happening.

Lastly, it may also be a good idea to carry out the same experiment within the region of vortex ring explosion, but this time with the addition of fluorescent particles to conduct particle image velocimetry (PIV), which is a quantitative flow visualization technique, and study accurately the velocity field and the formation process of the vortex rings.
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