BOILING AND SPREADING BEHAVIOR OF IMPINGING NANOFUID

DROPLETS ON A HEATED SURFACE

by

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The effects of nanofluids on water drops impinging onto heated surfaces are studied. This includes analyzing the drop spreading and boiling behavior. In order to view the impingement of the drops, a transparent ITO (Indium Tin Oxide) coated quartz glass is modified into a transparent heater and is used to simulate the heated surface. Two different concentrations of alumina oxide nanoparticles are studied and compared to pure water. The drops are studied under 4 different Weber number conditions and surface temperatures in the range 100°C-200°C and 275°C. The boiling regions observed in this studied ranged from the convective boiling region to the film boiling region. Boiling properties of the drop are visualized with a high speed image acquisition system. The spread behavior of the droplets is studied and compared with analytical theories. Boiling behavior is significantly altered with the addition of nanofluids most significantly in the nucleate boiling region. Nanofluid drops show an increase in bubble production and growth when compared to pure water drops. As a result, the nanofluid drops experience a more intense nucleation boiling than water drops. The Leidenfrost temperature is also
studied for the different nanofluid concentrations. Furthermore results show that nanofluids prevented the formation of dry areas at certain $We$ and $Ts$, but when dry areas are present they last longer. Last, the spreading behavior of nanofluid drops registered higher $\beta$ values especially at the higher $Ts$ when compared to pure water. This is due to their increased amount of nucleation during the boiling of the drop.
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Chapter 1

Introduction

1.1 Motivation

For the past couple of decades, an amazing growth in technology has occurred. Part of this growth has been due to the advances in electronics. While only a couple of decades ago a single computer could fill an entire room, now a days much more powerful computers can fit in one’s hand. This is largely due to the size of chips which have become smaller and more sophisticated. Before electronics were big and bulky, now days they are small and slim. Even though there has been all this progress, a new growing problem has plagued many electronic systems. As electronic devices become smaller and more complex and generate more heat, thermal control becomes increasingly important; when integrated circuits heat-up, computing capacity becomes severely disrupted due to added electronic resistance. Many commercial cooling systems have been created to address the issue but there are either too big and heavy, such as elaborate fan and radiator setups, or simply do not provide the amount of heat transfer necessary to sufficiently cool the component. Spray cooling is an emerging cooling technique that fulfills both of those requirements by using the latent heat of evaporation to absorb large amounts of thermal energy from the surface of a material (Kim (2007)). Nanofluids have also been studied in the past decade as potential cooling fluids. Although these two different techniques have
shown great promise, when combined together, it has produced conflicting result. For this reason, a more in-depth look has to be made into spray cooling with nanofluids on heated surface.

1.2 Review of Spray Cooling Studies
Most heat removal in spray cooling is done through nucleate boiling, which starts in micro-cavities due to surface roughness, and where the liquid reaches temperatures above their saturation value forming steam bubbles. These steam bubbles carry the thermal energy of the heated surface into the surrounding. It is also observed that nucleation rate depends largely in the number of nucleation sites that the surface contains (Çengel (2007)). Traditionally, most spray cooling research has focused on calculating the critical heat flux through temperature measurements. For example, Silk et al (2006) studied the effects that enhanced surfaces and spray angle had on the critical heat flux. Yan et al (2010) used a copper plate to simulate a high-powered electronic and found that impinging spray cooling worked best at high mass flow rate and inlet pressure. Recently, the use of nanofluids to enhance the cooling effects of sprays has been proposed and need to be studied more in depth. To do this, Lee et al (2001) suggest studying single droplets impinging on a hot surface to provide a better understanding of the cooling behavior of sprays.

1.3 Review of Droplet Studies
Even though drop impact has been studied for over 125 years, there are still many aspects that have not been resolved about this complex phenomenon. Worthington (1876), among
the first to study this subject, considered the patterns that water and mercury droplets created when hitting a surface and how the droplet itself behaved during the impact. Since then, many theories have been developed regarding the mechanics of droplet impact and the main parameters of interest will be briefly reviewed next. The first one is the Weber number, $We$, and is considered one of the most important parameters when correlating droplet behavior (Khavkin (2004)) especially in the impact and breakup mechanism of single droplets. At low Weber numbers, drops just experience deposition with recoil. At higher Weber numbers, drops either experience some type of breakup or rebound.

Another parameter of interest is the spreading factor, $\beta$, which considers the spreading behavior of a droplet. For instance, drops tend to spread and recoil in a specific pattern. When considering the spreading factor, two different properties are analyzed. These are the maximum spread of the drop, $\beta_{\text{max}}$, and the spreading behavior as a function of time. The spreading factor strongly depends on the experimental conditions, as discussed by Šikalo et al (2002). They observed that at low Weber numbers, the maximum spread $\beta_{\text{max}}$ was distinctly higher on smoother surfaces and that $\beta_{\text{max}}$ increased with $We$. The viscosity of the fluid was also correlated with $\beta_{\text{max}}$. Mehdizadeh et al (2004) observed an increase in instabilities at the edges of droplets at high-velocity impact. They observed increase in finger-like edge deformation as velocity increased, but rougher surface decrease the rate of these deformations. Chandra and Avedisian (1991) observed the effects that surface temperatures have on the spreading and breakup properties of n-heptane droplets at a fixed $We$. It was found that that spread factor decreases over time at higher temperatures with smaller $\beta_{\text{max}}$ and numerous bubbles were generated inside the drops only when the
surface was below the Leidenfrost temperature, thus showing the boiling behavior of the droplet. Meanwhile, Pasandideh et al (2001) tested and modeled various droplet impact velocities and found only a weak effect on heat transfer from the droplet velocities. These velocities only impacted the spreading behavior of the droplet, thus the area covered by the droplet. When it came to high-velocity impact, Mehdizadeh and Chandra (2006) found that there is an increase in $\beta_{\text{max}}$ as surface temperature increase. They also found that the superheat required for nucleation to occur was dependent on the velocity of the droplet. Bertola (2004) in his study, observed the effects a polymer additive had on droplet when impinging a heated surface. He saw that the additive prevented the droplets from rebounding at most temperature and prevented droplet breakup at higher temperatures and Weber.

1.4 Review of Nanofluid Studies

The study of the heat transfer characteristics of fluids with suspended nanoparticles has been limited to pool boiling experiments. For example, different concentrations of nanoparticles in pool boiling experiments have shown increase in critical heat flux in comparison with pure water (You et al (2003), Bang and Chang (2005)). Also, the critical heat flux reached a plateau after certain concentrations which also depended on the type of nanoparticles (Golubovic et al (2009)). It has also been shown that the size of the particles used can affect the heat transfer properties of the fluid. Anoop et al (2009) found that smaller particles have a higher heat transfer coefficient when compared to bigger particles in the developing region of tube flow. When it came to nucleate boiling, Bang and Chang (2005) reported that particle concentrations performed poorly on a plain
surface and Das et al. (2003) saw that nanoparticles deteriorated the boiling mechanism by changing the surface characteristics as concentration increased. Additionally, You et al. (2003) observed an increase in bubble size coming from the heated surface but a decrease in bubble frequency.

Although the effects of nanofluids have been studied in pool boiling, when it comes to spray cooling, the influence of nanoparticles has been sparsely considered except for recent studies in drop impact. For instance, Duursma et al. (2009) analyzed the effects that different concentrations of nanoparticles had on water, ethanol, and DMSO (Dimethyl sulfoxide) showing no real increase in critical heat flux when nanoparticles were introduced into the solution. Furthermore, nanoparticles tended to prevent droplet breakup when compared to the pure fluids although it was inconclusive as to whether or not nanoparticles had an effect on $\beta_{\text{max}}$. The effects of nanoparticles have to be studied in much greater depth; especially, the effects that these particles have on nucleate boiling. For this reason, it is proposed to observe the boiling behavior of individual droplets by using a transparent heater.

### 1.5 Thesis Outline

The aim of the present study is to better understand the effect that nanoparticles have on nucleate boiling. It makes use of a transparent heater (Inada (2002) and Lee et al. (2001)) for the first time in these types of studies. It has the advantage of allowing the visualization of the total area that the droplet covers when it spreads during impact while providing a more detailed view of the boiling behavior inside the droplet. The objectives of the study include: (1) visualizing the behavior and characteristics of a droplet
impacting a surface at temperature ranging from 100° C to 275°C; (2) measuring the spreading behavior of the droplet and seeing how different Weber numbers, temperature, and nanofluid concentration effect the spreading behavior; and (3) visualizing the impact that nanofluids have on nucleate boiling.

The layout of the study includes the following: Chapter 2 discusses the theory for droplet spreading and the different boiling regimes. This includes droplet mechanics after impact, and a brief review of the different theories that predict maximum spread of a droplet; Chapter 3 presents the experimental setup including the different components of the measurement system such as the droplet generation system and the image acquisition system; results are covered in Chapter 4 including a discussion of the observed physical attributes of the droplet, boiling behavior characteristics, and droplet spreading; last, Chapter 5 gives a summary of the main results.
Chapter 2
Droplet Mechanics

In this chapter, the droplet mechanics for drop impinging and spreading on a heated surface will be discussed. First, the dynamic mechanics which droplets experience when impacting a surface is presented by considering the initial impact, spreading, and recession of a droplet. Next, current theories that predict the maximum spread of droplets will be discussed. Last, the boiling mechanics of a liquid on a heated surface is shown including the different boiling regimes. These regimes range from natural convection boiling at the lowest temperature to vapor boiling at the highest temperatures.

2.1 Spreading Mechanics
The study of the forces and energy affecting a droplet during impact and spread over a surface can describe the drop mechanics. After the drop is release at some height from the surface, the only type of energy present in the drop is the kinetic energy. Once the drop impacts the surface and starts spreading, kinetic energy is converted into surface energy. While the droplet spreads, viscous forces and surface tension also start working against the drop spread until it reaches a maximum diameter. A common assumption is that the kinetic energy reaches zero at maximum spread. The surface energy that remains begins
transferring back to the drop as kinetic energy and the droplet starts to recede until no more energy is left.

Not all drops behave the same way after impacting a surface. Drops, depending on the impingement conditions, will experience, as discussed by Rioboo et al (2001), among others, one of the following outcomes: deposition, prompt splash, corona splash, receding break-up, partial rebound, or complete rebound. During a deposition, the droplet will spread across the surface until it reaches a maximum diameter and recedes until it reaches a final diameter. At low Weber numbers, this is the most common type of droplet impact and further details about the mechanics involved will be discuss later in the chapter. During a prompt splash, large numbers of very small droplets are produced at the edges of the spreading droplet, but a majority of the droplet still spreads and recedes on the surface. This is usually influenced by an increase in droplet velocities and an increase in surface roughness. If the surface roughness is high enough, the remaining liquid separates from the surface, thus creating a corona splash. Receding break-up occurs during the receding period of the droplet and usually results in the droplet breaking into smaller water droplets. These are usually due to capillary instabilities inside the droplet. When a droplet impacts a hydrophobic surface, it either experiences a partial or complete rebound. Here when a droplet is receding, a certain percentage of the droplet will detach from the surface. This usually occurs at high surface temperature. This indicates that the type of drop impact is affected not only by height, and drop properties, but also substrate properties including temperature.
2.1.1 Maximum Spread Theory

Developing a theory to predict the maximum spread of an impinging droplet has been challenging due to the many different effects that affect this process (Richard et al 2002; Fedorchenko et al 2005; Clanet et al 2004). This includes determining what type of dissipation dominates during the spreading of the drop which can range from viscous dissipation all the way to gravity effects.

One of the theories that predict the maximum spread of an impinging droplet assumes that the viscous force does not play a significant role in the spreading (Richard et al, 2002). They performed experiments with drops impinging in hydrophobic surfaces and assumed that the kinetic energy from the droplet was mostly converted to surface energy with viscous forces being negligible since the droplets experienced rebound. This results in a predicted maximum spread $\beta_{\text{max}}$ for the drops given by

$$\beta_{\text{max}} \sim (We)^{1/2}$$  \hspace{1cm} (2.1)

In the other hand, the work by Fedorchenko et al (2005) suggests that the drop spreading is not only an inertia dominated flow but that viscous friction is important too with kinetic energy being converted to viscous dissipation. This results in a predicted $\beta_{\text{max}}$ for the drops given by

$$\beta_{\text{max}} \approx 1.113 \text{Re}^{1/5}$$  \hspace{1cm} (2.2)

where $\text{Re} = UD/\nu$ is the Reynolds number, D the drop diameter and $\nu$ is the kinematic viscosity. This theory assumes that $\text{Re}>>1$. 
Another theory that predicts the maximum spread and which will be compared with the experimental results from the present work is given by Clanet et al (2004). They compare the drop spread with a small scale gravity puddle where gravity overcomes the surface tension when the drop reaches the maximum spread $\beta_{\text{max}}$. This assumption requires the drop diameter to be greater than the impact capillary length, $a^* = \sqrt{\sigma D_{\infty}/(\rho U^2)}$. This results in a predicted $\beta_{\text{max}}$ for the drops given by

$$\beta_{\text{max}} \sim \left(\frac{8}{9} We\right)^{1/4}$$

(2.3)

A comparison of these three theories given by Eqs. (2.1)-(2.3) with the experimental data from the present work will be performed in Chapter 4. This will help elucidate which forces dominate droplet spreading for the conditions studied.

2.2 Boiling Regimes

The popular description of boiling of a liquid on a heated surface considers that there is the formation of vapor bubbles in the liquid and that the liquid also evaporates. More in depth studies indicate the boiling of liquids is a much more complex process. It has been shown that both the boiling characteristics and heat transfer properties of a liquid are highly dependent on surface temperatures. The liquid boiling behavior can then be divided into different boiling regimes depending on the surface temperature of the heater with each regime having their own boiling characteristics and heat transfer properties. Each boiling regime covers a temperature range which is highly dependent on the liquid that is being boiled, and the properties of the heated surface. These boiling regimes are the following: natural convection boiling regime, nucleate boiling regime, transition
boiling regime, and vapor boiling regime. Each region will be discussed in depth showing their importance in boiling mechanics.

At the lowest boiling temperature the natural convection boiling regime is observed. This regime begins at the saturation temperature, \( T_{\text{sat}} \), of the liquid and extends 5-10° C above the saturation temperature, \( T_{\text{sat}} \). When a liquid is heated above \( T_{\text{sat}} \), it is considered to be superheated and the liquid evaporates at the surface of the liquid. As the temperature of the substrate is increased the nucleation boiling regime is reached. In this regime, bubbles filled with vapor begin to form on the heated surface. They typically form at imperfections found on the surface as shown in Fig. 2.3a. These are known as nucleation sites and can range in size from micrometers to Angstroms. At these sites, the liquid is heated to the point where it evaporates forming bubbles. Figure 2.3b shows a sketch of a time sequence of a bubble forming and growing over time. When they are large enough, they detach from the surface and float away. The production and detachment of these bubbles increases the entrainment of fluid which increases the heat flux in this region.

Increasing the temperature above the onset of the nucleation boiling shows the formation of “isolated bubbles” which we will name as nucleation I boiling regime throughout the rest of this work. At higher temperatures it shows the formation of “jets and columns” of bubbles which we will name as nucleation II boiling regime. The “isolated bubbles” are considered a passive form of boiling as there are only few bubbles taking long periods to form, detach and collapse. The “jets and columns” is a more chaotic form of boiling with
a much higher production of bubbles which merge and form larger ones. This production has been correlated to larger heat fluxes.

Further increasing the temperature of the substrate results in what is known as the transition boiling regime. Here the liquid still experiences high frequency nucleation, but the frequency is so high that vapor films or blankets begin to form between the liquid and the heated surface (Incropera et al 2007). It is worth noting that in this regime the heat flux decreases when compared to the maximum heat flux that can be obtained in the nucleation boiling regime. This is because the heat transfer in the vapor layer has a lower value than in the liquid. For temperatures sufficiently high above the transition boiling regime a vapor film layer completely separates the liquid from the heated surface as seen in Figure 2.4. This is known as the film boiling regime and the lowest temperature at which is first observed is the Leidenfrost temperature. For drops impacting on a surface at this temperature, they will experience rebound multiple times due to the vapor film layer. Also, this film prevents the liquid from contacting the surface so that no nucleation is observed and convection and radiation drive the heat transfer.
Figure 2.1 Nucleate boiling evolution
Figure 2.2. Droplet impact at Leidenfrost Temperature
Chapter 3
Experimental Setup

This chapter describes the experimental setup developed to study droplet impact and spreading on a heated substrate. This includes the construction of a novel apparatus where the droplet impacts on a transparent heater to allow imaging of the drop spreading and boiling directly from underneath the heater. The description of this apparatus and image system shown in Fig. 3.1 will be discussed including: the transparent heating element, droplet generation, camera and laser light illumination system, working fluid, nanoparticle selection, and container unit. Last, the experimental procedure used for this study will be discussed.

3.1 Transparent Heating Element

Most of the studies of droplet impact on a heated surface have been done with copper heater elements due to their heat transfer efficiency and also the ability to build the heaters with this material. In the other hand, the use of an opaque heater, such as copper, requires that the imaging of the drop impinging and spreading over the heater is done by setting up the camera parallel to the heater surface (camera is at 0° from the surface plane) or at an angle (i.e.: typically 30-45° from the surface plane). These configurations allow visualizing the drop spread from the side, which can provide information about the
droplet diameter, but it only provides limited information about the boiling behavior of the droplet.

For the present work, a transparent heater is used where images are obtained from a bottom view camera configuration for a more detailed analysis of the spreading and boiling of a droplet. The design is inspired by the work of Lee et al (2001) and Inada (2002) where they used a transparent heater to study the boiling characteristics of droplets at high temperatures. One of the advantages of using these heaters is that the actual area covered by the drop during spreading can be measured. It also presents a more detailed view of the boiling behavior of the droplet.

When an electric current is applied to an indium tin oxide (ITO) film, it heats up to a certain temperature due to its electrical resistance. Thus, by varying the voltage the temperature can be controlled. The transparent heater is built using a 50 mm X 50 mm commercially available ITO-coated Corning boro-aluminosilicate glass (CB-50IN-50X50/.05, Delta Technologies). The boro-aluminosilicate’s high softening temperature, was a good match for the temperature range in this study. The glass is 2mm thick and has a surface roughness <0.02 μm/5 mm. This smooth surface prevents unnecessary drop breakups due to surface imperfections that might occur during the droplet impact. The ITO film is only coated in one side of the glass and has a thickness of 0.5 mm and a measured electrical resistance of 25Ω.

The current is adjusted with a 50 V/ 5 A DC power supply (Mastech HY 5005-2) and applied through two copper pads that are connected with an electrically conductive silver epoxy (Pure Silver Conductive Epoxy) to the surface of the ITOF film, as shown in Fig.
3.2. The temperature of the heater is monitored using a thermocouple placed directly on the surface of the glass and held in place using a thermocouple adhesive pad (Omega PAD).

3.2 Droplet Generation System

For the experiment, an in-house fabricated droplet generation system delivered small individual droplets with repeatable diameter. A Harvard Apparatus PHD 2000 programmable syringe pump controlled the fluid volume of each droplet. The pump controlled the flow rate and volume delivered by a syringe. This ensured that each droplet had the same size. The working fluid was inside a 1mL syringe (with inner diameter of 4.78 mm) which kept it free from external contamination. The fluid then traveled through a flexible tube connected to a metal tip where the droplet is formed. The larger the inner diameter of the tip was, the larger the droplets that could be formed. For this reason, a 25 gauge stainless steel needle is used as the tip where the droplets would detach. Its small inner diameter provided the desired droplet sizes. Throughout the entire study the drop diameter is maintained constant at 2.98 mm with an estimated 8% variation. This is consistent with published work with estimated 10% variation in drop diameter.

The droplet release system was adjustable horizontally and also vertically with respect to the heater to accommodate different droplet height releases which allowed testing at different Weber numbers. Knowing the vertical distance $\Delta y$ between the heater and the tip of the needle in drop release mechanism, the final velocity $U_y$ of the droplet before hitting the surface can be obtained by
where \( g \) is gravity, and the air resistance is neglected.

### 3.3 Laser Light Illumination

Illumination of the droplet is essential in this study in order to obtain the most detail images of the spreading and boiling characteristics of each droplet. For this reason an adjustable, homogeneous light source is needed for this study. To prevent streaking (multiple images in one frame) of the droplet spreading, the light source is synchronized with the camera. It is also necessary to control the intensity of the illumination source in order to prevent any flooding of light which not only could obscure the details in the images but could also cause permanent damage to the camera.

In most experiments a strobe light source is used (Duursma et al 2009). For the present study, this light source would not have supplied enough illumination for the large series of images taken. A more appropriate device for illumination would be a laser source. With a laser, not only can the laser frequency be controlled, but also the laser beam intensity. As a result, a 527 wavelength NewWave laser (model Pegasus) is used. The Pegasus laser is optically pumped using a flashlamp with an output energy of 10mJ at a repetition rate of 2,000Hz. Since the pulse duration of the laser is only ~150ns, it guarantees sharp images without the blurring observed in longer exposures.

The laser beam is delivered to the measurement area using a mirror, a beam expander and a light diffuser to provide homogeneous illumination for the droplets. The diffuser, shown in Fig. 3.3, is made from Plexiglas and sprayed with five layers of glass frosting (Valspar Frosting) which provided optimal light diffusing ability. Figure 3.4 shows the
laser beam passing through the diffuser which expand the beam and provides a homogenous illumination of the region of interest. Because of the setup of the transparent heater, the illumination source could either come from the top at an angle or from a horizontal direction. After several test, the horizontal illumination arrangement shown in Fig. 3.1, provided the optimal illumination intensity and images captured using this setup showed a homogeneous light distribution.

3.4 Image Acquisition System

The droplet spreading and boiling is imaged using a high speed image acquisition system with a frame rate of 1000 fps. The high speed camera used is a Photron FASTCAM Ultima APX I2 with CMOS sensor and 1000 x 1000 pixel resolution up to 2000 fps. A 180 mm Sigma lens provided a 1:1 magnification ratio at a focal length 0.46m from the heater. Both camera and laser are synchronized, with the laser controlling the frequency rate and the trigger for the camera. The laser frequency was set manually at 1052 Hz (lowest limit when operating manually) which sets the frame rate of the camera at 1052 fps. The imaging software used was the Photron FastCam Viewer 4.0, which utilizes the internal memory of the camera to store up to 2000 images at 1000fps.

3.5 Nanoparticles

For this study, alumina oxide nanoparticles are used. They exhibit larger increases in critical heat flux when compared to other particles. The alumina oxide particles are supplied by Nanophase Technologies (Nano Tek® Alumina Oxide AL-01000-003-025) and have a mean diameter of 60 nm. Nanoparticles have the advantage of staying
suspended in fluids longer when compared to particles in the micron scale (Anoop et al 2009).

### 3.6 Working Fluid

There is a variety of working fluids that have been used for droplet impingement and cooling depending on the objectives of each particular study. Each working fluid in those studies had unique properties (i.e.: surface wettability, viscosity, surface tension, saturation temperature, and density) which can affect the behavior of the droplet. Fluids used in the past include oil, water, ethanol, dielectric fluids, and molten tin. For the present study, de-ionized ultra-filtered water (Fisher Scientific W2-20) is used, since water is the most commonly used liquid in droplet impact experiments. The use of ultra-filtered water prevents any contamination of foreign particles. Any contamination could not only affect the spreading behavior of the droplet but also the boiling behavior. For instance, Cengel (2007) has shown that even small contaminants, such as dirt can increase the frequency of nucleate boiling. The use of de-ionized water helps prevent nanoparticles from clumping together and increasing the size of the particulates. It has been shown that particle size does indeed have an effect on the heating characteristics of the nanofluid (Anoop et al 2009). Last, the initial temperature of the droplet (when is released from the drop generation system) is kept at a constant room temperature of \( T_0 = 24 \pm 1 ^\circ C \).
3.7 Heater Setup

First, the transparent heater is mounted on top of a pyramid-shaped water guard as shown in Fig. 3.1 and it is sealed around with all-purpose epoxy. The water guard is made of acrylonitrile butadiene styrene (ABS P400) which has good thermal insulation properties and high melting point. The guard is mounted inside a Plexiglas box. The inner walls of the box were covered with white reflective material to enhance the illumination of the droplet. The outer walls of the box, except the one facing the laser beam, were covered in black to prevent unwanted laser reflections to the system operator. Figure 3.6 shows how the camera was mounted directly underneath the box and how the entire structure was supported by a rigid metal modular frame by Unistrut. The camera was also mounted on a rail system which controlled the distance between glass heater in the box and the camera for optimal zoom magnification.

3.8 Experimental Procedure

The experimental procedure is designed to observe the droplet behavior when it impinges on a heated surface. It is also designed to study how varying nanofluid concentrations affect the boiling and spreading behavior of a droplet. For this study, the three main variables are the surface temperature $T_s$, the drop release height, and the nanoparticle concentration.

By varying the surface temperature $T_s$ of the transparent heater, the boiling behavior of the impinging droplet at various boiling regions can be studied. Although the work focused mainly on the nucleation regime since it gives the highest critical heat flux, the Leidenfrost point is also considered. The heater temperatures considered range from
100°C to 275°C. These temperatures are monitored with a thermocouple and maintained steady for at least 2-3 minutes before droplet release.

By varying the height at which the droplet is released, the effect of the Weber number on the drop spreading and boiling behavior can also be studied. The three different heights considered are 5, 10 and 30 cm corresponding to $We$ of 32, 96, and 191 respectively. For the Leidenfrost point test, a height of 1 cm is used.

By varying the nanoparticle concentration, its effect on the boiling behavior is also studied. The different nanofluid concentrations used are 1.0 and 2.0 g/L. The concentrations are prepared by taking 40 ml of deionized ultra-filtered water and adding the appropriate weight of nanoparticles to the fluid. Since clumping of particles can affect the heat transfer properties of the droplet, each solution was placed in an ultrasonic bath for at least 24 hrs. A small increase in temperature is observed in the prepared solutions while in the sonic bath so they sit at room temperature until the temperature reaches 24°C before they are used. This allows for accurate comparison with pure water which is also tested at 24°C.

To evaluate the effect of nanofluid concentrations on the boiling and spreading behavior of a droplet, the different concentrations are evaluated at different temperatures $T_s$ and $We$ numbers and then compared to the base case of pure water. All concentrations (1, 2g/L) and pure water are evaluated at all the test conditions summarized in Table 3.1. Three runs are performed at each test condition. Each run consist of 1 second of data corresponding to a time sequence with 1052 images.
The images taken from each run are filtered using image processing software to remove any noise and to sharpen the image. Using the measuring tool from the software, the drop diameter in each image is measured. For all cases the diameter is measured along two perpendicular directions (i.e.: for an ellipse it corresponds to the major and minor axis) and the average obtained. The diameter is used to study the drop spreading behavior as a function of time.

<table>
<thead>
<tr>
<th>Height</th>
<th>$T_s$ 100°</th>
<th>125°</th>
<th>150°</th>
<th>175°</th>
<th>200°</th>
<th>275°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>5 cm</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>15 cm</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>30 cm</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.1. Number of test cases recorded per test condition
Figure 3.1. Sketch of experimental setup
Figure 3.2. Ito-coated quartz glass heater
Figure 3.3 Lab-made laser diffuser
Figure 3.4. Image of laser illuminating test area
Figure 3.6. Camera position underneath the container
Chapter 4

RESULTS

In this chapter, the results from the drop experiments will be discussed. First, a qualitative analysis is shown of the effect of the Weber number on the spreading behavior of drops with different nanofluid concentrations. Next, the role that nanofluids play in the nucleate and transition boiling regime is considered. Also, the behavior of the droplets in the film boiling regime is discussed including the effects of the Weber number. Finally, a quantitative discussion of the spreading of the droplets is given by calculating $\beta_{\text{max}}$ experimentally and comparing the results with various maximum spreading theories from Chapter 2.

4.1 Weber Effects

As discussed previously, when a liquid drop hits the surface of the heated ITO film it spreads over the surface undergoing several stages. A time sequence of a typical drop spreading after impact is in Fig. 4.1. The images in this figure are taking using the setup from Fig. 3.1 where the camera is directly underneath the ITO film heater. This direct bottom view of the drop is ideal for visualizing and measuring the maximum drop spread. In Fig. 4.1, time $t = 0$ms corresponds to the initial impact of the drop on the surface. Next, the drop starts spreading outwardly, showing how the area of the drop in contact with the surface grows. This corresponds to a decrease of the film thickness at the center
of the droplet until the drop has reached a maximum spread at $t = 4.8$ ms. Next, the edge of the droplet starts receding back towards the center of the drop. For instance, at $t = 9.5$ ms the drop edge has receded slightly but more importantly the contact angle has increased significantly due to the kinetic energy of the drop trying to pull the liquid back towards the center. A balance of forces will get the drop edge from receding after which the drop will start spreading outwardly again. The drop keeps expanding and receding until a final diameter was obtained. For the present case, the diameter stayed constant after $t = 20$ ms, only decreasing overtime due to droplet evaporation through convection.

A study of the Weber number effect on the drop film thickness during the spreading is performed by analyzing time sequences of images such as those in Fig. 4.1. The analysis shows that the $We$ plays a crucial role on the film thickness especially at the drop’s center. Droplets that impinged the surface with lower Weber number such as $We = 32$ and $We = 96$ experienced similar spreading and recoiling behaviors. The images show that at the lowest $We$ studied the film thickness is fairly uniform throughout the droplet. With increasing $We$, the spreading is greater and the images show a decrease of the film thickness starting at the center of the drop and propagating outwardly from it. The decrease in film thickness is also enhanced by increasing the substrate temperature. This results in dry areas appearing in the middle of the droplet at $T_s = 175^\circ$C and higher. Furthermore, the nanofluid concentrations used affected the formation of this dry area, as shown in Figure 4.2(a). The figure shows that pure water produced this dried area, but nanofluid concentrations produced no dry area. This suggests that nanoparticles have some type of effect on the internal forces of the droplet that prevent this type of instability from occurring.
As the Weber numbers is increased, such as $We = 191$ shown in Figure 4.2b, the drop spreads over a larger area but a dry area temporarily forms in the midsection with all the liquid concentrated in the ring around the dry area. The creation of the dry area is observed in all of the droplets at this Weber number regardless of the nanoparticle concentration of the fluid. The size of the dry area is enhanced at higher $T_s$. For all the cases studied at this We, the water ring breaks during the evaporation stage.

Not only do the different nanoparticles concentrations affect the formation of dry areas for the lower $We$, but for the higher $We = 191$ it affected the duration they stay dry. For the case with no nanoparticles the dry area lasted for about 6.3 ms, but for all cases with nanoparticles it lasted an average of 14.4 ms (with no significant differences between the three concentrations) before the outer ring with the liquid collapsed during the evaporation stage. These observations suggest again that nanoparticles have some type of effect on the internal forces of a droplet when it is being heated. When observing the high surface temperature $T_s = 200^\circ C$, there are no dry areas. This can be explained by the chaotic state of nucleate boiling found at this high temperature which generates large bubbles quickly inside the drop that cover the dry areas preventing the formation of the dry areas.

Another phenomena caused by variations in $We$ is the formation of capillary waves. These waves appear as rings when the drop spreads over the solid surface as shown in Fig. 4.3. They are created by the counteraction between the inertial spreading of the drop and the surface tension of the drop (Davidson (2000)). The number of rings created and the rate at which they spread are affected by the Weber number. At the lowest $We$ tested ($We = 32$) only one ring is present for all concentrations and for pure water. With the
increase in $We$ ($We = 96, 191$), multiple rings form inside the drop with most of the liquid concentrated in the outer ring as shown in Fig. 4.3b. The higher the $We$ (191), the larger the number of capillary waves, and the more grouped the seemed to be near the edge of the drop and away from the center. This is probably due to the thinner film thickness in the center of the drop at the higher $We$ due to the larger spread of the drop. This behavior was the same for pure water and all concentrations used. In the other hand, for the all $We$ studied as shown in Figure 4.3, the formation and increase in nucleation bubbles with temperatures ($T = 175, 200 ^\circ$C.), did affect the shape of the capillary waves. Instead of the circular capillary waves observed at lower temperatures, they resemble multisided polygons at higher temperatures.

Increasing the temperature also has the effect of deforming the outer boundary of the drop which creates fingers around the edges as shown in Fig. 4.3 for the higher temperature and $We$ used. These deformations of the edges are due to Rayleigh-Taylor instabilities in the droplet as discussed by Kim et al (2000). As the droplet spread outward, these fingers widen and split as discussed by Thoroddsen and Sakakibara (1998). The fingers are also more prevalent at higher $We$ and $T_s$.

4.2 Temperature Effects in the Nucleate Boiling Regime

The surface temperature, $T_s$, plays an important role on the boiling behavior of an impacting droplet. By increasing the temperature of the substrate, different phases of nucleate and transition boiling are observed during the drop spreading. For instance, Fig. 4.4 shows nucleate boiling at different instances after drop impact on a solid surface. Shortly after impact ($t = 1.9$ms) small bubbles are created in nucleation sites. The
formation of bubbles continues at \( t = 4.75 \text{ms} \) while the drop spreads and deform due to Rayleigh-Taylor instabilities. The bubbles grow in size and merge to form much larger bubbles contributing to the drop spreading as shown at \( t = 19 \text{ms} \) and \( t = 39 \text{ms} \). This process enhances the drop evaporation.

For the more chaotic nucleate and transition boiling cases studied, the analysis of time sequence images shows that the droplet decreased in volume in other ways than just evaporation. For instance, Fig. 4.5a shows a large bubble collapsing while it ejects a small secondary droplet, and Fig. 4.5b shows a small liquid jet shooting out which is observed when bubbles burst sideways from the droplet. Also, not all the bubbles are due to nucleate boiling. In a few instances, a small bubble appears inside the drop near the center. This drop is present after impact and it did not show signs of growth or changed in shape during the drop spreading sequence. According to Chandra and Avedisian (1991) this bubble is formed most likely due to air entrapped by the liquid drop when it hits the surface or due to cavitation from the high velocity of the drop hitting the surface.

<table>
<thead>
<tr>
<th>Deionized Water</th>
<th>( We = 32 )</th>
<th>( We = 96 )</th>
<th>( We = 191 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_s = 100 )</td>
<td>Convective</td>
<td>Convective</td>
<td>Convective</td>
</tr>
<tr>
<td>( T_s = 125 )</td>
<td>Convective</td>
<td>Convective</td>
<td>Nucleate I</td>
</tr>
<tr>
<td>( T_s = 150 )</td>
<td>Nucleate I</td>
<td>Nucleate I</td>
<td>Nucleate I</td>
</tr>
<tr>
<td>( T_s = 175 )</td>
<td>Nucleate I</td>
<td>Nucleate I</td>
<td>Nucleate II</td>
</tr>
<tr>
<td>( T_s = 200 )</td>
<td>Nucleate II</td>
<td>Nucleate II</td>
<td>Nucleate II</td>
</tr>
</tbody>
</table>

Table 4.1 Phases of Boiling Observed with Water Droplets
The surface temperature, $T_s$, and $We$ play an important role in the boiling behavior of an impacting droplet as shown in Table 4.1. By increasing the temperature of the substrate, different phases of convective and nucleate boiling are observed during the drop spreading. For instance, at $We = 32$, and $96$ water experienced convective boiling for $T_s = 100$ and $125$, nucleate boiling type I for $150$ and $175$, and nucleate boiling type II for $200$. For the higher $We = 191$ studied, the transitions in boiling regimes occurred at a lower temperature, and convective boiling is found at $100$, nucleate boiling type I for $T_s = 125$ and $175$ and the nucleate boiling type II was observed at the earlier $T_s = 175$ and $200$. These results also show that increasing the $We$ for a fixed substrate temperature could promote changes in the boiling regime that otherwise could only be obtained by increasing $T_s$.

When small nanofluid concentrations are used, the drop boiling characteristics varied when compared to pure water. Figure 4.6 shows a time series of drops spreading and boiling comparing two different nanofluid concentrations and pure water for a fixed $We$ of $96$. The images show that increasing the nanofluid concentration increased the number of nucleation sites causing the droplet to spread more when compared to water. This results in a larger area of the drop in contact with the surface which enhances the heat transfer. It was also noticed that secondary droplets and side jets are more prevalent in these nanofluid droplets when compared to water droplets.

The analysis of drop images show that the transition from nucleate I boiling regime to nucleate II boiling regime occurred at a higher temperature for pure water than for drops with nanofluid concentrations. To study this effect, drop images of pure water and two nanofluid concentrations are compared for various $We$ and $T_s$ in Fig. 4.7. Figure 4.7a
show a base line case \((We = 96, Ts = 150^\circ\text{C})\) where nucleate I boiling regime occurs for pure water and all nanofluid concentrations. In the other hand, significant differences are observed between water and the different nanofluid concentrations for \(Ts\) near the transition temperature between nucleate I and II boiling regimes as shown in Fig. 4.7b,c,d. For example, in Fig. 4.7b \((We = 191, Ts = 150^\circ\text{C})\) and Fig 4.7d \((We = 96, Ts = 175^\circ\text{C})\) the drop with just water is in the nucleate I boiling regime but the cases with nanoparticles already exhibit a violent production of bubbles which is typical in the nucleate II boiling regime. Similarly, in Fig. 4.7c \((We = 32, Ts = 175^\circ\text{C})\) the drops with just water and the smallest concentration 1g/L is in the nucleate I boiling regime but the case with 2g/L is in the nucleate II boiling regime. The images in Fig. 4.7b,c,d show that nanoparticles produced more bubbles during boiling and increased the drop spreading which results in a higher heat transfer rate.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>(We = 32)</th>
<th>(We = 96)</th>
<th>(We = 191)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Ts = 100)</td>
<td>Convective</td>
<td>Convective</td>
<td>Convective</td>
</tr>
<tr>
<td>(Ts = 125)</td>
<td>Convective</td>
<td>Convective</td>
<td>Nucleate I</td>
</tr>
<tr>
<td>(Ts = 150)</td>
<td>Nucleate I</td>
<td>Nucleate I</td>
<td>Nucleate II</td>
</tr>
<tr>
<td>(Ts = 175) (1g/L)</td>
<td>Nucleate I</td>
<td>Nucleate II</td>
<td>Nucleate II</td>
</tr>
<tr>
<td>(Ts = 175) (2g/L)</td>
<td>Nucleate II</td>
<td>Nucleate II</td>
<td>Nucleate II</td>
</tr>
<tr>
<td>(Ts = 200)</td>
<td>Nucleate II</td>
<td>Nucleate II</td>
<td>Nucleate II</td>
</tr>
</tbody>
</table>

Table 4.2 Phases of Boiling Observed with Nanofluid Droplets
The boiling regimes for all the nanofluids tested including those in Fig. 4.7 have been compiled in Table 4.2. When comparing the boiling regimes between pure water (Table 4.1) and nanofluids (Table 4.2) the nanofluid concentrations reach nucleate II boiling regime at a lower temperature than water. This shows that the nanoparticles promote a more intense state of boiling when compared to pure water.

The influence of nanofluids is also observed in the final stages of drop boiling and evaporation. The time-sequences of images in Fig. 4.8 (We=190, Ts=200°C) show in detail the last stages of nucleate boiling for the case of water (Fig. 4.8a) and for the case of a nanofluid with 2g/L concentration (Fig. 4.8b). When comparing both cases at $t = 36\text{ms}$, there is a larger number of bubbles in the case of a nanofluids with the bubbles spreading over a larger area and starting to group in areas within the drop. This grouping of drops is never observed for the pure water. Also, there is a small film of nanoparticles forming in Fig. 4.8b where the original diameter of the spread droplet was. As the boiling continues ($t=205\text{ms}$) most of the liquid has evaporated from the drop, and the boiling is reduced to just a few spots in the case of the nanofluid while no bubbles are observed in the case of the water. These spots with chaotic bubble formation are most likely due to the additional nucleation sites offered by the nanoparticles. These spots are reduced to nanoparticle clumps ($t=940\text{ms}$) leaving a small film of water covering the clumps. An explanation for this clumping behavior cannot be currently found, more experiments have to be done to elucidate these effects. The layer of nanoparticles left behind by a drop can also be of interest in sprays because it could affect the boiling behavior of other drops that could land on the same area.
4.3 Temperature Effects in the Film Boiling Regime

As part of the temperature effect study of droplet boiling, the Leidenfrost phenomenon which occurs at low Weber numbers and high temperatures was also considered. This phenomenon occurs when the temperature of the substrate is high enough that the drop starts evaporating before hitting the surface and forms a thin vapor film between the drop and the substrate. As the drop approaches the substrate, the vapor film keeps the drop from reaching the surface with the drop undergoing some deformation before bouncing off. The drop continues bouncing on the surface until it eventually evaporates. A time sequence of images showing the drop bouncing on the surface at the Leidenfrost temperature is shown in Fig. 4.9. This figure shows how the droplet deforms and slightly spread over the heated surface ($t = 1.9, 3.8\text{ms}$) but no nucleation is observed since the droplet is resting on top of a vapor layer. The droplet recedes ($t = 5.7, 7.6\text{ms}$) and then completely rebounds from the surface ($t = 9.5\text{ms}$). In order to find the Leidenfrost temperature, the drop release height was fixed at $h = 1\text{cm}$ which corresponds to $We = 8$. Measurements were performed at increasing temperatures until the Leidenfrost phenomena was first observed at $T_s = 275^\circ\text{C}$ shown in Fig. 4.9.

Measurements show that for heights above $h = 1\text{cm}$, the Leidenfrost phenomena was not possible with the drop sizes and substrate used. These measurements involved testing at temperatures near $T_s = 275^\circ\text{C}$ but $h > 1\text{cm}$ and analyzing the time sequence images. As the temperature of the substrate kept rising, there were signs that the vapor layer was growing but it was too unstable to produce a total rebound of the droplet. Instead the droplets were experiencing was considered prompt splash shown in Fig. 4.10. In this phenomenon, the droplet reaches the heated surface and upon contacting the surface the
drop disintegrates to an abundant amount of smaller droplets. All these droplets as a whole still boil as if they were in the transitional boiling regime. These results show the dependence of the Leidenfrost temperature on the $We$. Droplets with low $We$ impact the surface at lower velocities, thus giving enough time for a stable vapor layer to be formed. They also indicate that to observe the Leidenfrost temperature the ratio of kinetic energy to surface energy had to be small enough to prevent prompt splash.

4.4 Spread Behavior

One of the most noteworthy behaviors studied in drop mechanics is droplet spread $\beta$. Droplet spread values can be obtained from the time that the droplet touches the surface to the time it stops receding. By comparing these values for the different configurations studied, the effects that nanofluids, surface temperatures and $We$ have on droplet spreading can be elucidated.

4.4.1 Temperature effects at different Weber numbers

First, the effect of the $We$ on the drop spreading is studied for different $T_s$. Figure 4.11 shows the average spreading behavior of water for different $T_s$ at all three heights studied, $h = 5, 15, 30\text{cm}$, which correspond to $We = 32, 96, 191$. For $h = 5\text{cm}$ the droplets experienced spreading until reaching their maximum spread diameter at $t \approx 5\text{ms}$. Then, the droplet receded and spread back out until it reached a point of rest. When comparing the drop receding behavior for different $T_s$, the spread $\beta$ decreased as $T_s$ increased reaching a minimum $\beta$ for $T_s = 175^\circ\text{C}$. This suggests that the droplets become more hydrophobic as $T_s$ increases as noted by Chandra and Avedisian (1991). Only at $T_s = 200^\circ\text{C}$ did the $\beta$
value significantly increased driven by the larger number of nucleation bubbles at this
temperature which prevented the drop from receding as much as in the lower temperature
cases. This is probably due to the surface tension from these bubbles which counteract
the internal forces that causes the droplet to recede.

The effect of $We$ on the drop spreading of water is shown also in Fig. 4.11. As the $We$
increased (i.e.: as the height was increased) the $\beta_{\text{max}}$ also increased. This is expected since
the drops are impacting the surface at higher velocities. A relation between these two
variables, $We$ and $\beta_{\text{max}}$, will be discussed later. At the higher $We$, the drops also tend to
just recede to some constant $\beta$ value (with only some minor oscillations around it) as
compared to the receding and the secondary spread observed at the lowest $We$. Similar to
$h = 5\, \text{cm}$, at $h = 15\, \text{cm}$ the spread $\beta$ decreased as $T_s$ increased reaching a minimum $\beta$ for $T_s$
$= 175^\circ\text{C}$. At $h = 30\, \text{cm}$ the spread $\beta$ decreased as $T_s$ increased reaching a minimum $\beta$ for
$T_s = 150^\circ\text{C}$ and then started increasing again for $T_s = 175^\circ\text{C}$ and $200^\circ\text{C}$. This increased
may be explained by the study of time sequence images that showed that these last two
temperatures had the largest amount of nucleation bubbles. This prevented the drop from
receding as much as in the lower temperature cases and provided larger $\beta$ when the drop
receded between $t = 10\text{-}20\,\text{ms}$.

The effect of $We$ on the drop spreading for different nanofluid concentrations is shown in
Figs. 4.12,4.13. For instance, Fig. 4.12 shows the average spreading behavior of water
with $1\, \text{g/L}$ nanofluid concentration for different $T_s$ at $We = 32, 96, 191$. At all the $We$
tested, the spreading is affected by the substrate temperature specially during the receding
of the lamella. This behavior is similar to the water drop (Fig. 4.11), although more
pronounced for the nanofluid concentration. Here the spread $\beta$ decreased as $T_s$ increased
reaching a minimum $\beta$ for $T_s = 150^\circ C$ and slightly increasing for $T_s = 175^\circ C$. This small shift in minimum $\beta$ from $T_s = 175^\circ C$ to $T_s = 150^\circ C$ between water and the nanofluid with 1g/L concentration, is most likely due to the excess nucleation sites at these temperatures created by the nanoparticles and observed between Table I and II. In comparison, there is a very large increase in $\beta$ for $T_s = 200^\circ C$ due to the large increase in nucleation sites which produces more and larger bubbles and kept the lamella from receding. It should be noted that at $We = 191$ with $T_s = 175^\circ C$, the drop experienced breakup after spreading and values were only taken until the time of breakup.

The effect of $We$ on the drop spreading for the highest nanofluid concentration tested of 2g/L is shown in Fig. 4.13. The behavior is very similar to the case of 1g/L with only a few differences. For instance, the minimum $\beta$ also occurs at $T_s = 150^\circ C$, but at $T_s = 175^\circ C$ there is a significant increase in value especially when compared to the 1g/L. This can be explained by the earlier transition to nucleate II boiling regime observed for this higher concentration with the additional nucleation sites expected at 2g/L compared to 1g/L which would produce more bubbles and prevent the drop from receding as far. The other significant difference is observed at $T_s = 200^\circ C$. At this temperature, the drops seemed to experience almost no recession at all due to the fact the nucleation inside these drops was so great. This increase in nucleation is once again due to the increase in nucleation sites from the particles. Droplet breakup was once again seen when $h=30cm$ and $T_s = 175^\circ C$.

### 4.4.2 Concentration comparisons

The effects of the nanofluid concentration on the drop spreading are shown in Figs. 4.14-4.18. For instance, Fig. 4.14 show these effects for a fixed $T_s = 105^\circ C$ at three different
The results show that the different concentrations do not affect the spread at the lowest height \( h = 5 \). In the other hand, at \( h = 15 \text{cm} \) the \( \beta \) value for water is clearly lower during the receding of the drop when compared to the 1 and 2 g/L concentrations. This difference suggest that the influence of the nanofluid involves the drop converting kinetic energy to surface energy faster than for the water case. A proposed hypothesis is that this is due to the local accumulation of nanoparticles in the outer edge of the drop which changes the local properties of the receding front. This is observed in the time sequence images, such us in Fig. 4.8, where a thin film of nanoparticles deposited at the outer edge of the drop during maximum spread. At \( h = 30 \text{cm} \) the differences in \( \beta \) value between water and the 2 g/L concentrations is even more pronounced than at \( h = 15 \text{cm} \). Considering that the thickness of the lamella decreases with increase in \( We \), the hypothesis is that the accumulation of nanoparticles at the lamella has a stronger effect at preventing the drop from receding with thinner lamellas.

The effect of the nanofluid concentration on the drop spreading at \( T_s = 125^\circ \text{C} \) shown in Fig. 4.15 is very similar to that discussed for \( T_s = 125^\circ \text{C} \) in Fig. 4.14. First, the differences in concentration did not affect the spreading at the lowest \( We = 32 \) tested. Next, the increase in \( We \) \((We = 96)\) showed that the \( \beta \) value during drop receding increased with the increasing nanofluid concentration. Last, this increased in \( \beta \) was more pronounced as the \( We \) was further increased \((We = 191)\).

The discussed effects of nanofluid concentrations on the drop spreading become more important at the highest temperatures tested \( T_s = 150^\circ \text{C}, 175^\circ \text{C} \) and \( 200^\circ \text{C} \). This is shown in Figs. 4.16-4.18. We attribute this larger increase in \( \beta \), especially at the largest \( T_s \) due to the earlier transition to nucleate I and II boiling regimes occurring at \( T_s \) from \( 150^\circ \text{C} \) to
200°C depending on the concentration and nucleation regime as discussed in Table I and II. This hypothesis suggests that the effect of nanofluid concentration on the drop spreading is larger during the nucleate boiling regimes especially during nucleate boiling II regime. This is apparent when comparing the results for nucleate I boiling regime at $T_s = 50^\circ C$ (Fig. 4.16) with those for nucleate II boiling regime at $T_s = 175^\circ C$ (Fig. 4.17) or at $T_s = 200^\circ C$ (Fig. 4.18). For instance, during nucleate II boiling regime at $T_s = 200^\circ C$ with the higher nanofluid concentration of 2g/L the drop reaches the maximum diameter and does not recede. Thus the $\beta$ value remains almost constant for all three $We$ at this concentration while it decreases significantly for pure water. For instance, $\beta_{\text{max}}$ is 2.5 for 2g/L concentration and water ($We = 32$) and it stays constant after that for the nanofluid but recedes to a minimum of 1.6 for water after receding. Similarly, $\beta_{\text{max}}$ is 3.5 for 2g/L concentration and water ($We = 191$) and it stays constant after that for the nanofluid but recedes to a minimum of 2.5 for water. These differences in spreading at the nucleation boiling regime due to nanofluid concentration are noticed even at the lowest $We = 32$ tested as shown in Fig. 4.16-4.18, which was not the case at this low $We$ for the convective boiling regime as shown in Fig. 4.14, 4.15.

The nanofluid concentrations did not affect the drop spreading at the Leidenfrost temperature ($T_s = 275^\circ C$) for $We = 5$ as shown in Fig. 4.19. The drop reached a maximum spreading $\beta_{\text{max}} = 1.25$ at 3-4 ms from the time if first started deforming over the thin vapor film between the drop and the substrate. After $t = 3-4\text{ms}$ the drop begins rebounding and it is completely separated from the substrate at $t = 7-8\text{ms}$. Considering that it takes about the same time to reach maximum spread (3-4ms) as it is to rebound completely (an additional 3-4ms) it suggest that very little energy is lost during the entire
process. The process of spreading and rebounding repeats itself until the droplet evaporates which can last more than 10 seconds. This type of film boiling regime is clearly a not very efficient heat transfer regime as the thin vapor film has a much lower heat transfer coefficient than that of water.

The nanofluid concentrations did not affect the maximum drop spreading as shown in Fig. 4.19. In this figure, the average experimental $\beta_{\text{max}}$ value is shown for all concentrations and compared with those from the theories presented in Chapter 2. The measurements show that as $We$ increases the $\beta_{\text{max}}$ values also increase. When comparing all the concentrations, no statistical difference is observed between them and pure water. When comparing the experimental measurements with the theories described in Chapter 2, these are best fitted using the relation by Clanet et al (2004) which suggest that the drop spreading is dominated by capillary forces. When comparing $\beta_{\text{max}}$ to the other theories, there was no correlation.
Figure 4.1. Typical drop spreading sequence. Conditions were 1 g/L, We=32 and $T_s=150^\circ$C
Figure 4.2. Formation of dry areas inside impact drop at $T_s=175^\circ$C. It appears at low concentrations only for $We=96$ in (a) and at all concentrations for higher $We$ such as $We=191$ in (b).
Figure 4.3. Evolution of capillary waves at different $T_s$ showing the effect of We ($t=4.8\text{ ms}$)
Figure 4.4. Evolution of nucleate boiling over time (2 g/L, $T_s=200^\circ$C, $We=96$)
Figure 4.5. Example of boiling instabilities: (a) droplet ejection at $t=199\text{ms}$ and (b) side jetting due to bubble collapse at $t=132\text{ms}$ (Water, $We=96$, $T_s=200^\circ\text{C}$)
Figure 4.6. Difference of nucleate boiling behavior for different concentrations at $T_s=200^\circ$C when $We=96$
Figure 4.7. Effects of nanofluids during boiling showing (a) We=96, T_s=150°C, (b) We=191, T_s=150°C, (c) We=96, T_s=175°C, and (d) We=32, T_s=175°C, all at t=269 ms.
Figure 4.8. Stages of nucleate boiling over time for (a) water, and (b) 2g/L nanofluid concentration (We=190, T_s=200°C, and time from impact for left to right images of 36 ms, 205 ms, and 940 ms).
Figure 4.9. Typical sequence of drop spreading at Leidentfrost Temperature (Water, $\text{We}=8$, $T_s=275^\circ\text{C}$)
Fig. 4.10 Prompt splash due to vapor layer instability (Water, We=32, $T_s= 275°C$)
Figure 4.11. Spreading behavior of water at different height and different $T_s$
Figure 4.12. Spreading behavior of 1 g/L at different height and different $T_s$.
Figure 4.13. Spreading behavior of 2g/L at different height and different $T_s$. 
Figure 4.14. Spreading behavior of solutions at different heights with $T_s=100^\circ$C
Figure 4.15. Spreading behavior of solutions at different heights with $T_s=125^\circ$C
Figure 4.16. Spreading behavior of solutions at different heights with $T_s=150^\circ$C
Figure 4.17. Spreading behavior of solutions at different heights with $T_s=175^\circ$C
Figure 4.18. Spreading behavior of solutions at different heights with $T_s=200^\circ C$
Figure 4.19. Spreading behavior of solutions at Leidenfrost temperature
Figure 4.20. Max Spread, Experimental vs. Theoretical
A novel apparatus setup was built to study the effect of nanofluid concentration in drop impact and boiling. This included the use of a transparent heater to observe the boiling and spreading behavior of an impinging drop on a heated surface. Two nanofluid concentrations were compared with pure water at six different $T_s$ for three different $We$. The main conclusions include:

1) The highest nanofluid concentration used (2g/L) exhibited the most intense amount of nucleation boiling when compared to the other concentration and to water.

2) The two nanofluids concentration caused nucleation boiling to occur at a lower $T_s$ when compared to pure water specially at the higher $We$ studied.

3) When it came to spreading, as $T_s$ rose the differences in $\beta$ values between water and the different concentrations increased specially after reaching the maximum spreading. This was even more evident with higher $We$.

4) Spreading was also measure at the Leidenfrost temperature but there was no difference in spreading between water and the two concentrations studied. It was
also observed that rebound during Leidenfrost temperatures depended highly on the We of the drop.

5) The experimental results obtained for the maximum droplet spreading $\beta_{\text{max}}$ at various $T_s$ and $We$ were compared with three different maximum spread theories. The theory by Clanet et al (2004) provided the best fit for the results.

5.1 Concluding Remarks

Nanofluids can play an important role when it comes to spray cooling. Results have shown that even small nanofluid concentrations can play a significant role in the boiling and spreading mechanics of an impinging drop. When it came to boiling, as the nanofluid concentration was increased, an increase in bubble size and frequency during nucleation boiling was observed. This could be due to the increase in nucleation sites that could be generated by the nanoparticles in contact with the surface. Nanofluids also affected the spreading of a drop. This is most evident at higher $T_s$, where higher $\beta$ values were observe during the spreading sequence for higher concentrations. This is explained by the enhanced nucleate boiling due to the nanofluids, which generated sufficient bubbles which partially prevented the receding of the drop after reaching maximum spread.
REFERENCES


