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Droplet Impact Sub-cavity Histories and PDPA Spray Experiments for Spray Cooling Modeling

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DROPLET IMPACT SUB-CAVITY HISTORIES AND PDPA SPRAY EXPERIMENTS FOR SPRAY COOLING MODELING

By

NICHOLAS LEE HILLEN

**Thesis submitted to the
Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
Mechanical Engineering**

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**Department of Mechanical and Aerospace Engineering
West Virginia University
2013**

**Keywords: Spray Cooling; Single Drop; PDPA; Spray; Splashing;
Optical Measurements; High-speed Video**

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ABSTRACT

Droplet Impact Sub-cavity Histories and PDPA Spray Experiments for Spray Cooling Modeling **NICHOLAS L. HILLEN**

Spray cooling is a topic of current interest for its ability to uniformly remove high levels of waste heat from densely packed microelectronics. It has demonstrated the ability to achieve very high heat fluxes, up to 500 W/cm^2 with water as the coolant, making it an attractive active thermal management tool.

Full Computational Fluid Dynamic (CFD) simulations of spray cooling are infeasible due to the complexity of the spray (drops fluxes of $10^6 \text{ drops/cm}^2\text{-sec}$) and heater surface physics requiring impractical resources. Thus a Monte-Carlo (MC) spray cooling simulation model based on empirical data is under development to serve as a cost effective design tool. The initial MC model shows promise, but it lacks additional physics necessary to predict accurate heat fluxes based on nozzle conditions and heated surface geometry.

This work reports spray and single drop experiments with the goal of computing the volume beneath a droplet impact cavity (the sub-cavity volume) created by a single impinging droplet on an initial liquid layer. A Phase Doppler Particle Analyzer (PDPA) was utilized to characterize a spray of interest in terms of integrated global Weber, Reynolds, and Froude numbers for varying flow conditions. Results showed that the spray droplet diameters decreased and velocities increased with increasing nozzle gage pressure. A relevant test plan for the single drop experiments has been created from the measured PDPA spray profiles combined with residual spray film thickness measurements from literature resulting in: $140 \leq We \leq 1,000$, $1,200 \leq Re \leq 3,300$, and $0.2 \leq h_0^* \leq 1.0$. Froude numbers were not able to be matched for the current single drop experiments (spray: $32,800 \leq Fr \leq 275,000$).

Liquid film thicknesses under the cavity formed by a single droplet have been measured versus radius and time via a non-contact optical thickness sensor for the selected range of dimensionless numbers (We , Re , and h_0^*). Sub-cavity radius histories have also been analyzed utilizing high-speed imagery techniques to create the cavity thickness traverse profiles. Time dependent sub-cavity volumes have been computed by integrating these sub-cavity liquid film thicknesses versus radius at various times. It is found that higher We and lower h_0^* result in a more radially uniform sub-cavity surface contour versus time, except for thinner liquid film regions which are observed near the outer bottom cavity radius. The sub-cavity volume was found to be nearly constant for a majority of the cavity lifetime and increased with We and h_0^* . These results will be incorporated into the MC model to improve its predictive capability in future work.

In addition, splashed droplet diameters and velocities have been extracted from PDPA data for a spray impinging normal to a smooth surface. It was found that the splashed droplets had sizes which were similar to the impinging spray droplets, and had velocities that never exceeded 3 m/s. The splashed droplet results have a negligible contribution to cavity formations due to their low Weber number. This splashing data has been detailed for future implementation into the MC model in terms of mass conservation in the liquid film.

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APPROVAL OF THE EXAMINING COMMITTEE

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FOR
HALEY
AND
MY FAMILY

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NOMENCLATURE

Latin Symbols

A	=	Area
c_v	=	Coefficient of variation
C_m	=	Mass fraction
C_p	=	Specific heat
d	=	Droplet diameter
D	=	Arithmetic mean droplet diameter
D_{32}	=	Sauter mean droplet diameter
h_{fg}	=	Latent heat
g	=	Gravity
f	=	Frequency
Fr	=	Froude number
h	=	Liquid film thickness
H_{crown}	=	Crown height
K	=	Splashing criteria for a dry surface
m	=	Mass
m_c	=	Liquid mass flow in thin cavity film
N	=	Total number of samples
n_{dec}	=	Decorrelated sample index
Oh	=	Ohnesorge number
P	=	Pressure
Q	=	Volume flow rate
q''	=	Heat flux
R	=	Radial location
Re	=	Reynolds number
RH	=	Relative humidity
std	=	Standard Deviation
T	=	Temperature
t	=	Time
v	=	Droplet velocity
V	=	Arithmetic mean velocity
Vol	=	Sub-cavity volume
We	=	Weber number
xc	=	Center of image from the left hand side
Y	=	Splashing criteria for thin liquid layers
z	=	Standoff distance from the nozzle tip

Acronyms

BV	-	Bottom-view
CFD	-	Computational Fluid Dynamics
CHF	-	Critical Heat Flux
CHR	-	CHRcodile

Greek Symbols

α	=	Half angle of incident beams
Δ	=	Uncertainty
ρ	=	Density
η	=	Index of refraction
μ	=	Dynamic viscosity
λ	=	Incident light wavelength
σ	=	Surface tension
τ	=	Dimensionless time
Φ	=	Volume fraction
Ψ	=	D , D_{32} , V_{axial} , or V_r
ψ	=	d , v_{axial} , or v_r

Superscripts

*	=	Dimensionless parameter
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Subscripts

0	=	Initial value
0.75%	=	Instrumentation uncertainty
$axial$	=	Axial velocity component
B	=	Bottom crown
c	=	Cavity
cw	=	Cavity wave
G	=	Glycerol
cg	=	Cavity growth
$inter$	=	Interaction
lim	=	Limit
max	=	Maximum value
min	=	Minimum value
PV	=	PDPA probe volume
r	=	Radial velocity component
s	=	Spray
sat	=	Saturation
sol	=	Glycerol-water solution
$stat$	=	Statistical data fluctuation
W	=	Water
x	=	x spray traverse profile
y	=	y spray traverse profile

fps	-	Frames per second
LDV	-	Laser Doppler Velocimetry
MC	-	Monte-Carlo
PDA	-	Phase Doppler Anemometry
PDPA	-	Phase Doppler Particle Anemometry/Analyzer/Analysis
PMT	-	Photo Multiplier Tube
PDM	-	Photo Detector Module
PVC	-	Probe Volume Correction
SV	-	Side-view

CHAPTER 1: INTRODUCTION

As technology advances the continuing trend of electronic component size reduction will result in more compact systems and denser geometries, resulting in reduced surface area-to-volume ratios. This is expected to make waste heat removal more challenging requiring active enhanced thermal management systems. Spray cooling is an attractive two phase candidate capable of uniformly removing large amounts of waste heat at relatively low surface temperatures with no temperature overshoot (Kim, 2007). Spray cooling experiments performed by Lin and Ponnappan (2003) demonstrated heat fluxes as high as 500 W/cm^2 before the onset of critical heat flux (CHF) using water as the coolant. They also achieved heat fluxes of 100 W/cm^2 at relatively low surface temperatures of $(T_{wall} - T_{sat}) \approx 12 \text{ K}$ also using water as their coolant. Potential applications include, but are not limited to, small high density electronics in future space-based power systems, lidar instruments, and laser diode arrays (Silk *et al.*, 2008).

There are two main approaches to designing spray cooling systems: either performing experiments on physical systems, or simulations using Computational Fluid Dynamics (CFD). However, issues in the required resources and time are limiting for both methods. Spray cooling experiments are costly and take considerable time to build, with limited flexibility for new iterations for existing setups. The use of CFD to fully simulate spray cooling systems would require impractical resources due to the complexity of the spray. This is true even with advancements in modern computing processes, whereas typical sprays have drop fluxes on the order of a 10^6 drops/(s·cm²) (Kuhlman *et al.*, 2011). An example of the inefficiency of CFD can be found in the direct numerical simulations performed by Sarkar and Selvam (2009) of a single 3-D drop impingement (20 time steps) with $129 \times 129 \times 129$ grid sizes. They were able to reduce the computation time of a single 3-D drop impingement from 60 days to 30 hours using a multigrid

conjugate gradient solver and 32 processors. Thus, a more efficient and feasible solution such as a phenomenological model capable of capturing the basic, relevant physics would be very desirable. Kreitzer (2010) describes one approach to such a model in the form of a Monte-Carlo (MC) simulation spray cooling model. The initial MC model developed by Kreitzer (2010) is still in development with the ultimate goal to accurately predict the heat flux for given nozzle flow conditions, for smooth heater surface geometries, and heater surface temperatures below the Leidenfrost point in reasonable computation times. Figure 1.1 shows an example image of a spray generated by a nozzle impinging normal to a 5.08 cm diameter unheated surface similar to that for which the final MC model will apply.

Figure 1.1: Full cone water spray generated by a Spraying Systems FullJet 1/8-G nozzle on an unheated 5.08 cm diameter surface (Hillen *et al.* 2013).

The Monte-Carlo method can be described as a statistical approach to solve differential equations and is particularly effective simulating fluid flow and heat transfer. In its basic form, random data is generated to fit a range of conditions to solve coupled equations to predict a final solution (Metropolis and Ulam, 1949). The initial MC model developed by Kreitzer (2010) incorporated empirical correlations developed from experiments and CFD simulations. A detailed summary of the initial MC model is given in Chapter 2. Although the MC model shows promise it still lacks the necessary physics to be quantitatively accurate. One important type of missing data is the lifetime and volume of the liquid beneath the cavity generated by an impinging droplet on a

wetted surface. The main focus of the present thesis is on this liquid volume beneath the droplet impact cavity, or “sub-cavity volume” as it will be referred to herein. The importance of the sub-cavity volume will be discussed subsequently.

A brief overview of spray cooling is provided, but it is not the author’s intent to summarize all of the available literature. The basic spray cooling process consists of a liquid coolant, typically dielectric, that is forced through a nozzle orifice generating an atomized spray. The spray delivers many small, cool droplets that directly impinge onto the heated surface, quickly establishing a thin residual liquid film. Additional fresh, cool droplets continuously impinge on the heated liquid film creating a film flow over the heater surface. The interaction of the cool droplets and liquid film on the heated surface results in high heat fluxes. The underlying physics of the heat transfer mechanisms are not fully understood due to their complexity. Therefore, spray cooling remains in the research and development stage. The number of input variables for spray cooling contributes to this complexity; these may be summarized into five main categories: the impinging spray parameters, heater geometry and surface conditions, the working fluid, ambient atmosphere conditions, and gravity (Silk *et al.*, 2008). Extensive literature exists that examines the underlying heat transfer mechanisms, focused on liquid film dynamics on the heated surface. Topics considered include the film’s liquid/vapor interface evaporation; homogenous, secondary, and heterogeneous bubble nucleation; forced convection mixing of the cool droplets and heated film liquid; and vapor bubble departures rewetting the heater surface (Horacek *et al.*, 2004, Kim, 2007, Silk *et al.* 2008, and Sarkar and Selvam, 2009). All of these mechanisms contribute to the heat transfer, but which is the most important is debatable.

One potential contributing spray cooling heat transfer mechanism that is generally neglected in literature is the effect of the aforementioned sub-cavity volume. Kuhlman *et al.* (2007) originally

hypothesized that the sub-cavity volume plays a crucial role in the heat transfer processes such as the onset of boiling and dry out, thus contributing to CHF. The cavity created by an impinging droplet consists of a thin liquid film, comprised of some cool initial drop liquid and some initial heated film liquid. Thus, enhanced local heat fluxes are expected in the cavity region due to the close contact of the cooler droplet liquid with the surface. It is expected that the sub-cavity volume due to higher local heat fluxes, then would be vulnerable to boiling and subsequent dry out before the cavity is refilled by a surface tension wave or covered over by subsequent nearby drop impacts. The combined effect of the localized cavity dry outs would contribute significantly to the onset of CHF.

Evidence of the influence of the sub-cavity volume is supported by observations in the literature. In spray cooling experiments, it has been commonly observed that the highest heat fluxes occur in the spray region with the highest frequency of impinging droplets (Hung *et al.*, 2004, and Shedd and Pautsch, 2005). This shows that the impinging droplets are crucial for spray cooling. However, this correlation cannot be directly linked to the cavities. More direct evidence and the main motivation of the current work can be found in CFD simulations performed by Sarkar and Selvam (2009). Investigating the enhanced local heat flux of the vapor bubble contact line, Sarkar and Selvam (2009) found Nusselt numbers as high as 420 - 490. Their results also show that the cavity formed by a single impinging drop in the vicinity of a nucleated bubble, as depicted in their Figure 3 (c), also has a enhanced localized transient heat flux (maximum Nusselt number of 420). The percent increase of this cavity heat flux is comparable to their calculated average heat flux increase along the contact line of the nucleating bubble on the heater surface. The figure also shows that the cavity cools a significantly larger area than the vapor bubble contact line. Similar trends were observed in experiments by Horack *et al.* (2004) where local heat fluxes as high as nominally 50 W/cm^2 for a FC-72 spray were measured for the contact line with a microheater array using

internal reflection techniques. Additionally, Soriano *et al.* (2010) and Gehring *et al.* (2010) observed that the highest temperature gradients for their experiments and simulations on single drop trains impacting a heated surface consistently occurred at the center of the droplet impact site. This impact site was where they consistently measured the thinnest film thickness. Soriano *et al.* (2010) used thermal imaging to acquire temperature profiles for a surface heated by an Indium Tin Oxide heater for HFE 7100, for the conditions listed in Table 1.1 that was impacted by a train of droplets. Results for both conditions showed that the lowest temperature of nominally 61°C occurred at the impact location. Surface temperature rose to nominally 75°C at the maximum spreading radius, while the impinging droplets had a temperature of 22°C. Single water drop train experiments and simulations performed by Gehring *et al.* (2010) included droplet frequencies of 19.7 kHz to 105 kHz, with droplet sizes ranging between 82.1 μm and 123.5 μm for average overall heat fluxes of 11.8 W/cm^2 to 16.4 W/cm^2 ($T_{\text{surface}} \approx 122^\circ\text{C}$). Simulations at the impact centerline show average local wall temperatures equivalent to the droplet temperature of 17°C. This shows direct evidence that the cool droplet liquid actually penetrates an initial liquid film to contact the heater surface (Gehring *et al.*, 2010).

Table 1.1: Single train droplet frequency, diameter, spreading area, and maximum heat flux for experiments by Soriano *et al.* (2010).

Frequency (kHz)	d (μm)	Spreading Diameter (mm)	Spreading Area (mm^2)	Max Heat Flux (W/cm^2)
2.97	222	1.65	2.14	18.8
12.0	318	2.13	3.56	22.2

The primary purpose of the present work was to utilize unheated single drop experiments to quantify the sub-cavity volume history for a range of droplet impact scenarios relevant to realistic sprays. To accomplish this, a time resolved non-contact chromatic CHRcodile (CHR) thickness measuring sensor was utilized to measure the liquid film thickness beneath the cavity, referred to herein as the sub-cavity film thickness. Similar optical instrumentation has initially been utilized by

Van Hinsberg *et al.* (2010) to profile the time-dependent sub-cavity liquid film thickness at the impact centerline of single impinging droplets. The current work expands upon the experimental methods developed by Van Hinsberg *et al.* (2010) to radially map the sub-cavity film thickness distribution in the cavity versus time. Subsequent sub-cavity volume histories are then computed through integration along the bottom cavity radius for each time step, as first documented by Hillen *et al.* (2012 and 2013). To the author's knowledge no other work has attempted to experimentally measure the sub-cavity film thickness versus both radius and time, or to compute sub-cavity volume histories. Figure 1.2 is an example of an impinging drop on an initial liquid film with its major features defined.

Figure 1.2: Single drop impingement into an unheated initial liquid surface and its components (Hillen *et al.* 2013).

In order to create a relevant test plan for the single drop sub-cavity experiments, a Phase Doppler Particle Analyzer (PDPA) was utilized to profile a full cone water spray of interest. The spray was generated by a Spraying Systems FullJet 1/8-G nozzle (see Figure 1.1) and characterized in terms of overall integrated average values of dimensionless Weber, Reynolds, and Froude numbers. This was the same nozzle considered by Kreitzer (2010), where the spray droplet size and velocity distributions used were recorded at 1.0 cm to 1.5 cm beneath the nozzle tip using FC-72 as the coolant. However, high-speed videos showed the spray not to be fully atomized within this region (Kreitzer, 2010). This fact combined with the different fluid properties justified the new measurements further downstream and using water as the liquid. PDPA was also employed herein to

measure the droplet characteristics of the secondary droplets, referred to herein as splashed droplets, generated by the spray impacting onto a smooth surface as is shown in Figure 1.1. Though not expected to be a major contributor, the splashed droplets have been investigated to observe any contributions to cavity formations on the heater surface. This analysis of the splashed spray droplets was not the primary focus of the presented work, but has been documented in detail for future implementation into the MC model to improve the validity of mass conservation in the model.

Dimensionless numbers have been identified that allow the single droplet experimental parameters to be matched to the corresponding spray results. The most important of these is the Weber number, which is the ratio of inertial force of the impinging droplet to surface tension forces as defined by:

$$We = \frac{\rho v^2 d}{\sigma} \quad 1.1$$

For spray cooling the Weber number has a significant effect on the heat transfer process and it has been found to be directly relatable to the CHF (Silk *et al.*, 2008 and Kim, 2006). The Weber number also is typically used for single droplet correlations due to the dominating effect of surface tension in the impingement process. Other important dimensionless numbers include the Reynolds, Froude, and Ohnesorge numbers. The Reynolds number is the ratio of inertial force of the impinging drop and viscous forces, as defined in Equation 1.2. The Froude number shown in Equation 1.3, is the droplet inertial force to the pressure force of a gravitational surface wave. The Ohnesorge number expressed in Equation 1.4, relates the viscous force to the square root of the inertial and surface tension forces. Note that only three of these four dimensionless parameters are independent.

$$Re = \frac{\rho v d}{\mu} \quad 1.2$$

$$Fr = \frac{v^2}{gd} \quad 1.3$$

$$Oh = \frac{\mu}{\sqrt{\rho\sigma d}} = \frac{\sqrt{We}}{Re} \quad 1.4$$

Dimensionless film thicknesses have been calculated as shown in Equation 1.5. The present work has focused primarily on thin preexisting liquid films, following the terminology of Cossali *et al.* (1997) ($h_0^* < 1.0$), or on thin and intermediate films, using the classification of Vander Wal *et al.* (2006) ($h_0^* \leq 0.1$ and $h_0^* \approx 1$, respectively). These cover the typical ranges of spray drop size and the residual liquid film thicknesses.

$$h^* = \frac{h}{d} \quad 1.5$$

The experiments and results in this thesis are presented in the following order: first the PDPA spray data is analyzed and used to create a detailed single droplet test matrix. Then the bottom inside cavity thickness distribution versus cavity radius and time for the ranges of We , Re , and $h_0^* = h/d$ that are expected in the spray are presented.

The organization of this thesis presents a background and literature review in Chapter 2. The experimental apparatus and procedures for the spray and single drop experiments are presented in Chapters 3 and 4 respectively. The methodology to compute the single drop sub-cavity volume is documented in Chapter 5. The analyzed spray data used to create the detailed single drop test matrix is detailed in Chapter 6. Additionally, the splashed droplet results from the spray are also included in Chapter 6. Chapter 7 contains the single drop experimental results, including a brief summary of some preliminary experiments. The main content of Chapter 7 includes the bottom inside cavity radius histories, flow visualization, bottom inside cavity thickness distribution versus radius and time, and the computed sub-cavity volume histories for the selected ranges of We , Re , and h_0^* . Conclusions and recommendations are documented in Chapter 8. Appendixes A through Appendix E

contain additional figures and a more detailed explanation of the single drop glycerol-water mixture calculations.

CHAPTER 2: LITERATURE REVIEW

Section 2.1: Introduction

The present literature review provides overviews of three primary topics: an existing Monte-Carlo (MC) model by Kreitzer (2010), single droplet impact dynamics, and single drop cavity dynamics. This is not meant to be a comprehensive review of the MC model, or of the single drop impingement process, but is meant to provide readers with a basic background for a better understanding of the presented work. The main focus of this literature review is on the cavity created by a single droplet impinging onto an initial liquid layer, which is shown for a typical splash condition in Figure 1.2.

A general overview of Kreitzer's (2010) MC model is covered in Section 2.2, which provides a brief explanation of how the current model functions and includes the incorporated time scale arguments. The missing components needed to improve model's validity in order to develop it into a quantitative design tool are also discussed.

Section 2.3 provides a general background to familiarize the reader with the droplet impingement process and its outcomes. The main focus is on single droplets impinging onto a wetted surface, so this is inferred unless otherwise stated. Crown and splashing formation (see Figure 1.2) are discussed including a review of the various influential parameters. Also discussed are the different splash styles and the characteristics of splashed droplets. An overview of the varying droplet impingement outcome criteria and the differences for spray droplet impingements are provided.

Section 2.4 reviews previous studies of the cavity dynamics of single drop impacts. This section contains material directly relevant to the present single droplet experiments encompassing the cavity evolution and various parameters that influence it. Initial sub-cavity film thickness measurements and their trends are discussed in detail in this section.

Section 2.5 reviews the existing work that separately defines the fluid composition of the crown, splashed droplet, and sub-cavity for a single drop impingement on a liquid film.

The origins and justification for the h_0^* utilized in the single drop cavity experiments in Chapter 7 is detailed in Section 2.6. This section summarizes the residual film thicknesses generated by a spray impinging upon a flat surface measured by other works.

Finally, Section 2.7 provides a brief background on how PDPA individually collects droplet diameters and velocities.

Section 2.2: Current Monte-Carlo Spray Cooling Model

The existing MC model uses a random number generator to assign droplet size, velocity, and impact location information based on preexisting characterization of the droplet size distribution, velocity, and flux distribution for a spray of interest. The model incorporates a series of time scales for the spray and individual droplet impacts to approximate the time evolution of the spray impingement process. The time scale concept originated from Kuhlman *et al.* (2007) where the spray process was broken down into individual smaller length and time scales that were computed based on dimensional analysis for each of the relevant processes. Equations 2.1 through 2.7 consist of some of the characteristic time scales computed by Kuhlman *et al.* (2007) for the droplet impingement, droplet cavity formation, cavity fill, and cavity dry out due to boiling. The characteristic interaction time scale between the droplet and heater surface is given by:

$$t_{inter} = d/v \quad 2.1$$

The time scale for the cavity to expand to its maximum radius, or “cavity growth” time scale, is computed by:

$$t_{cg} = 12.5t_{inter} \quad 2.2$$

Equation 2.2 was developed from experimental spray results by Sivakumar and Tropea (2002). Assuming the surface tension forces to be dominant the Weber number, Equation 1.1 can be set to one to solve for the cavity wave propagation by:

$$v_{cw} = \left(\frac{\sigma}{\rho h_0} \right) \quad 2.3$$

The cavity wave travels at a higher velocity than the gravity wave, thus the time scale for surface tension to refill the cavity is estimated as:

$$t_{fill} = R_c / v_{cw} \quad 2.4$$

Therefore the time scale of the total cavity lifetime is the sum of Equations 2.2 and 2.4 given by:

$$t_{total} = t_{cg} + t_{fill} \quad 2.5$$

The time scale for a cavity to be refilled by a neighboring drop impact is computed as

$$t_{cover} = \left(\frac{Vol_{droplet}}{Q} \right) \left(\frac{A_{heater}}{A_c} \right), \quad 2.6$$

where the droplet flux is assumed to be uniform with no overspray, and $Vol_{droplet}/Q$ is the number of spray droplets per second. The ratio A_{heater}/A_c in Equation 2.6 is based on the droplet number flux onto the heater surface area and cavity area.

Again assuming a uniform spray flux with no overspray the time scale for the thin liquid film in a cavity to dry out can be estimated by:

$$t_{dry} = \frac{[m_c C_p (T - T_{sat}) + m_c h_{fg}]}{q'' A_c} \quad 2.7$$

A summary of the time scales used in Kreitzer's (2010) MC model are listed in Table 2.1 encompassing the individual drop impacts, the cavity lifetimes, and heater effects on the cavity.

Table 2.1: Summary of Monte-Carlo simulation time scales for a drop with a $D_{32} = 48 \mu\text{m}$, $V = 12 \text{ m/s}$, FC-72 at a flow rate of 10 GPH, and heater power of 100 W (Kreitzer, 2010).

Time Scale	Time (μs)
Time between droplet impacts	5.05E -03
Time of droplet impacts	0.8
Time for fastest cavity to move 1 pixel	2.2
Time between impacts in a cavity	4.5
Time of cavity formation	32
Time for cavity to reach boiling	75
Time to cause droplet to boil and vaporize	121
Time of crown collapse	160
Time to heat droplet 30 degrees and vaporize	397
Time of surface tension wave to fill in cavity	60
Time of gravity wave to fill in cavity	1224

The model assumes droplets above the deposition/rebound criteria (which will be covered below) that impact the liquid film create instantaneous fully formed axisymmetric cavities. A presumed maximum cavity radius of 2.7 times the droplet diameter is used at a dimensionless time value of $\tau = 5$ computed by:

$$\tau = t(v/d) \quad 2.8$$

These individual cavities are tracked as they move across the heater and throughout their lifetime. A minimum sub-cavity film thickness of 1% of the droplet diameter was assumed based on CFD simulations performed by Cole *et al.* (2005). The cavities retain their full size throughout their lifetimes that are governed by the surface tension refill time scales unless the cavity is covered over by subsequent drop impacts. This timescale was chosen since it was shorter than that for the gravity wave, as listed in Table 2.1. To account for neighboring impacting droplets, if a particular cavity had more than 50% of its area overlapped by a newer cavity, or cavities, then the preexisting cavity was considered to have been filled. This logic was incorporated into the model instead of the using the time scale in Equation 2.6. The cavities themselves were color coded for visualization purposes to represent the state of the sub-cavity film fluid at any time in the process: dark blue for undisturbed liquid film, medium blue for cavities that did not form a thin film at the heater surface, light blue for

cavities that fully penetrated the initial liquid layer that are below the onset of boiling, orange for the onset of boiling in a cavity, and red for when the cavity experienced dry out prior to being re-covered by nearby drop impacts, or filling in due to surface tension (Kreitzer, 2010). This is shown for the initial Monte-Carlo screen shot in Figure 2.1.

Figure 2.1: Simulated heater surface from the MC Spray Cooling model (Kreitzer, 2010).

The model was qualitatively acceptable and demonstrated realistic trends for surface dry out. Results in Kreitzer (2010) showed that the first portions of the heater that experienced dry out occurred on the outer edges of the heater which is consistent behavior with spray experiments in Pautsch and Shedd (2006) where they only observed film boiling at the outer region of the spray. However, even though the model has shown promise, it still needs to incorporate mass conservation of the film flow and fluid ejected by secondary droplets, improved cavity formation time scales, and improved values of the sub-cavity volumes and lifetimes. The present work focuses on experimental determination of the cavity time scales and sub-cavity volumes to be incorporated into the MC model to improve cavity dry out time prediction.

Section 2.3: Single Drop Impingement

Impinging droplets can come in many shapes including spherical, deformed, ellipsoidal, oscillate, and the droplets can have internal circulation (Rein, 1993, and Yarin, 2006). Impingements may be normal to the wall, at oblique angles, or on moving surfaces (Rein, 1993). Impact angles are defined using the commonly accepted definition, shown schematically in Figure 2.2, with the angle measured from the normal to the surface. Both reviews by Rein (1993) and Yarin (2006) explain that the impingement process for any droplet is dependent on the droplet size, impact velocity, impact angle, fluid properties, surface type, surface roughness, and (for a dry surface) surface wettability. There are two main basic droplet impingement processes: impacts on dry surfaces and impacts on wetted surfaces. These different surface conditions result in some similar outcomes, or in radically different outcomes. Rein (1993) mentions that the splashing characteristics of droplet on a dry surface are similar to those on a thin liquid film, while work done by Rioboo *et al.* (2000) show that they have different morphologies, spreading behaviors, and splashed droplet formation.

Figure 2.2: Droplet impact angle.

When a droplet impacts upon a dry surface it can either spread, bounce, splash, cavitate (rare cases), or hover at Leidenfrost temperatures (Rein, 1993, and Yarin, 2006). The determination of splashing for drop impact on a dry surface depends upon the drop diameter to surface roughness ratio, and the kinematic and fluid properties of the drop (Mundo *et al.*, 1995).

Outcomes of a droplet impingement onto a liquid surface include rebound, deposition, partial rebound/deposition, floating, and the generation of a splash (Rein, 1993). Impinging drops of

sufficiently large We and Re generate a propagating corona/crown where splashed droplets can be shed from crown rim breakup (Yarin, 2006).

The single drop experiments in the present work focus on drop impingement into a static thin liquid layer normal to the surface. Thus, dry surface behavior and the effect of the solid surface geometry are unimportant and are not expanded upon further. The spray investigated in the current work consists of droplets impinging normal to the wall or at oblique angles. Additionally, the effects of oscillations of the drops in the single droplet experiments are neglected since Rein (1993) discusses that it is widely believed that any oscillations are dampened upon impact.

Section 2.3.1: Crown Morphology and Formation

A general description of the crown evolution due to an impinging drop on a wetted surface was found in Yarin (2006). During the initial impingement process, inertia and surface tension forces dominate as liquid is displaced from the impact location forming the crown. An undisturbed crown will continuously propagate radially and in height until surface tension and gravity forces cause it to no longer grow, and then collapse. A collapsing crown is followed by a surge of fluid rushing to refill the cavity that, for $h_0^* > 1.0$, can result in the subsequent formation of a central spike of liquid commonly known as the Worthington jet (Yarin, 2006). Splashing originating from the crown is believed to be a result of perturbations in the crown rim that cause cusps to form. Subsequently, jets are formed from the cusps in which splashed droplets pinch off due to capillary instabilities (Yarin, 2006). Cossali *et al.* (2004) observed in their single drop experiments that splashing crowns typically result in at least 10 jets from which splashed droplets may detach. An example of a splashing drop impingement can be seen in Figure 1.2.

Macklin and Metaxes (1976) observed in their experiments that the maximum crown height was 0.5 - 4.0 times the initial droplet diameter. The crown radius size is much larger than the initial

droplet diameter (Mundo *et al.*, 1995) and the generally accepted crown radial growth rate derived from single droplet experiments is dependent on the square root of time (Yarin, 2006). Sivakumar and Tropea (2002) measured crown radii formed by a spray that were nominally 2.5 times the initial droplet diameter. Cossali *et al.* (2004) reported slightly different crown growth rates of $t^{0.43}$ in their experiments. They also found that the Weber number has a strong influence on crown height, but not the crown formation or speed of collapse.

The main contributing parameters to the crown morphology of a drop impingement besides impact velocity are the fluid properties and initial liquid film thickness. Experiments performed by Vander Wal *et al.* (2006) varied the viscosity of working fluid and found that the crown surface became smoother at higher Weber numbers. More influential on the crown shape is the dependence of the crown angle (the angle between the crown side and the free surface) on h_0^* (Fedorchenko and Wang, 2004). For drop impingements on a liquid film thickness of $h_0^* < 0.1$, Chen and Wang (2000) showed that the upper portion of the crown was much larger in diameter than the bottom portion resulting in a “bowl” shape. Fedorchenko and Wang (2004) investigated this effect further and reported that $h_0^* < 0.25$ resulted in acute crown angles while larger h_0^* resulted in crown angles of at least 90° . Variations in surface temperatures below the Leidenfrost temperature are expected to have an indirect effect, in the form of influencing the fluid properties, on the film properties according to Cossali *et al.* (1997). Therefore, single drop experiments may be extrapolated to hot wall conditions.

Even though the present results focus on the sub-cavity film dynamics, the crown morphology and evolution are important to gain a basic understanding of the impingement process. The cavity size and lifetime are directly influenced by the formation and evolution of the crown. Single drop impingements results, discussed in Chapter 7, were observed to follow many of the behavior characteristics described in this section.

Section 2.3.2: Splashing

The splashing phenomenon can be subdivided into four groups: prompt, delayed, film, and Worthington jet splashing (Cossali *et al.*, 1997, Manzello and Yang, 2002, Vander Wal *et al.*, 2006, and Kalantari and Tropea, 2007). The prompt and delayed splash consists of secondary drops that are ejected from the crown during expansion and collapse respectively, as defined by Cossali *et al.* (1997) and Vander Wal *et al.* (2006). Film splashing occurs when liquid ligaments are ejected directly from the film (Manzello and Yang, 2002, and Kalantari and Tropea, 2007). The Worthington jet splashing occurs when secondary drops detach from the central Worthington jet (Cossali *et al.*, 1997, Vander Wal *et al.*, 2006).

There are many contributing variables that influence the splashing criteria. Cossali *et al.* (2004) summarized that the splashing criteria are influenced by the impinging droplet characteristics, surface temperature, surface roughness and wettability (for dry surfaces and extremely thin initial films), and the initial liquid film thickness. Experiments by Shin and McMahon (1990) focusing on Worthington jet formations show that thicker h_0^* actually promote Worthington jet splashing up to a certain point. They found that for thinner target liquid layers the wall greatly influences the outcome of the Worthington jet and could dampen it when the wall was replaced with a sponge. Cossali *et al.* (1997) showed that crown splashing is dependent on viscosity and a thicker h_0^* actually can inhibit crown splashing. Xu *et al.* (2005) reported that variation in the surrounding gas pressure for a single drop impacting onto a smooth dry surface had a pronounced influence on the onset of splashing. Vander Wal *et al.* (2006) concluded that high surface tension and viscous forces inhibit splashing (i.e. large We and Re promote splashing), consistent with Cossali *et al.* (1997).

Several authors have attempted to identify criteria to predict the outcome of an impinging droplet. Initial development of splash criteria incorporating the surface tension and viscosity was

developed by Mundo *et al.* (1995) for droplets impacting onto a solid surface. The following is the most prominent correlation that accounts for the viscous and surface tension effects (Yarin, 2006):

$$K = WeOh^{-0.4} \quad 2.9$$

Splashing typically occurs for the criteria $K > 57.7$ for Equation 2.9. Cossali *et al.* (1997) expanded Equation 2.9 further by incorporating the initial film thickness in the correlation:

$$Y = K/[2100 + 5880(h_0^*)^{1.44}], \quad 2.10$$

where splashing consistently occurred for criteria limits of $Y > 1$. Wang and Chen (2000) reported that the critical splashing Weber number was insensitive to variations of $h_0^* < 0.1$, but was dependent on viscosity and surface roughness. Contrary to this, Riobo *et al.* (2003) did observe a correlation of h_0^* with the splash criteria while varying $0.06 < h_0^* < 0.15$. Table 2.2 is a summary of some of the criteria and critical limits of droplet impingement outcomes reported in the literature for the rebound, deposition, crown formation, and splashing.

Table 2.2: Summary of various deposition/rebound/splash criteria reported in literature.

Author	Wet/Dry	Criteria	Critical Criteria Limit
Ching <i>et al.</i> (1984)	Wet	Rebound/Deposition	$We = 20$
Lee and Hanratty (1988)	Wet	Rebound/Deposition	$We = 20$
Wang and Watkins (1993)	Spray	Rebound	$We < 30$
Rein (1993)	Wet	Rebound/Deposition	$We < 3.0$
Rein (1993)	Wet	Splash	$We = 7.9e^{10} Oh^{2.8} \approx 60$
Mundo <i>et al.</i> (1995)	Dry	Splash	$K = 57.7$
Cossali <i>et al.</i> (1997)	Wet	Deposition/Splash	$Y = 1; 0.1 < h_0^* < 1.0$
Riobo <i>et al.</i> (2003)	Wet	Deposition/Crown	$K = 440; h_0^* < 0.06$
Riobo <i>et al.</i> (2003)	Wet	Crown/Splash	$K = 2100; 0.06 < h_0^* < 0.15$
Vander Wal <i>et al.</i> (2006)	Wet	Deposition/Splash	$We^{0.5} > 20$
Kalantari and Tropea (2006)	Spray	Deposition	$We < 2$
Kalantari and Tropea (2006)	Spray	Partial Deposition	$30 < We < 80$
Kalantari and Tropea (2006)	Spray	Splash	$We > 80$

The criteria limits listed in Table 2.2 are not hard limits, but predict the trends reasonably well. These criteria helped determine in the present work the droplet conditions that would produce a

cavity to examine for the single drop experiments. Also, a basic comprehension of the splashing process has aided with the analysis of the measured splashed spray droplets discussed in Section 6.3.

Section 2.3.3: Splashed Droplet Characteristics

Macklin and Metaxes (1976) observed that the volume of the splashed droplets created from droplets impinging onto shallow h_0^* was two to three times that of the impacting droplet. Mundo *et al.* (1995) utilized Phase Doppler Anemometry (PDA) to characterize the splashed droplets created by a train of single droplets. They measured the splashed droplets to be (0.12 to 0.80) and (0.08 to 0.28) times the respective D and D_{32} . According to Cossali *et al.* (1997), the splashed droplet size and velocity are dependent on viscosity, and later work by Cossali *et al.* (2004) found film thickness did not influence splashed droplet characteristics. Worthington jet splashed droplet sizes have been observed by Fedorchenko and Wang (2004) to be of the same order of magnitude as the initial droplet. Cole *et al.* (2005) developed a Lagrangian spray wall impingement model that was integrated into the Eulerian free surface model (Volume of Fluid). It enabled the modeling of spray impingement and splashing, including fluid film effects on the wall. Their results showed that up to 15 - 18 times the droplet volume was splashed in their single drop simulations. The highest total splashed volumes were for the Worthington jet. Kalantari and Tropea (2006) separated the splashed droplets from impinging spray droplets based on the axial velocity sign convention in their PDA data. They found that the splashed droplets were 0.8 to 1.2 times the size of the spray droplets and their axial velocities never exceeded 3 m/s. They explained that interaction between neighboring impinging droplets could feed excess fluid into the crown, thickening it, which will produce larger splashed droplets. In addition, Kalantari and Tropea (2006) mentioned that ligaments ejected from the film wall which may become spherical over time could also contribute to the larger splashed droplet sizes. Splashed droplet sizes similar to the initial droplet were reported by Okawa *et al.*

(2007) for a train of droplets impacting at oblique angles. They recorded splashed droplet masses of upwards of 100 times that of the initial droplet when increasing the impact angle (defined in Figure 2.2), but recorded splashed droplets 1/10 the size of the initial drop at small impact angles.

In summary, crown splashed droplets for single impinging droplets are numerous and small in size compared to the initial droplet. However, in spray conditions where there are many interacting droplet impacting at varying angles the splashing outcomes becomes dramatically more complicated. The method used by Kalantari and Tropea (2006) to extract the splashed droplet characteristics from the spray did not take into account any of the splashed droplets returning to the impingement surface; an improved technique that does this is covered in Section 3.5.

Section 2.3.4: Spray Impingement Versus Single Droplet Impingement

Behavior of droplet impingements in a spray is much more complex than single droplet conditions. Sivakumar and Tropea (2002) found in their spray experiments the crowns grew at $t^{0.2}$ instead of $t^{0.5}$, as seen for single droplet impacts, while observing irregularities in the crown and splashing formations. They explain the irregularities and slower crown evolution times are due to nonuniformity in the spray residual film, and the interaction between impinging droplets. Results in Kalantari and Tropea (2006) also showed slow crown growth ($-0.2t^{0.3}$) and receding in a spray consistent with Sivakumar and Tropea (2002).

Even though both mentioned authors in this section argue against extrapolating single drop results for a full spray, single drop experiments are vital to understanding the underlying physics occurring in a spray process. The present author was unaware of any literature investigating the effects of real spray condition influences on the sub-cavity film thickness and thus the sub-cavity volumes.

Section 2.4: Cavity Dynamics

Some of the initial detailed studies of the cavity created by an impinging drop were performed by Engel (1965 and 1967). Engel (1965 and 1967) experimentally observed the cavity formation for droplets impinging into a deep pool and reported that the cavities formed hemispherical shapes. Through energy balances, Engel analytically developed a model to predict the cavity depth versus time. She assumed that half of the impact energy of the droplet was transferred into the target liquid, and her predictions were in good agreement with experimental data. Experimental observations for single drops impinging onto varying liquid film thicknesses by Macklin and Hobbs (1969) showed that lowering initial liquid film thickness resulted in a flattening of the hemispherical cavity into a cylindrical shape. Building off of Engel (1967) Macklin and Metaxas (1976) developed an analytical model that predicted the inside cavity radius and crown height for drop impingements on shallow surfaces. They also experimentally observed cylindrical cavity shapes for shallow pool impacts and defined deep pools to be when the wall had no influence on the cavity evolution. The cylindrical shape of the cavity for shallow pools was again observed by Shin and McMahon (1990), and they state that a cavity will have a deep pool behavior for target liquid depths more than twice the hemispherical cavity radius.

Detailed analysis of cavity evolution for $0.5 < h_0^* < 2.0$ were performed by Roisman *et al.* (2008). Roisman *et al.* (2008) reported that the viscous effects on the cavity formation are negligible at high Reynolds and Weber numbers. They experimentally measured the cavity radius, which compared well with their theoretical model, and found that the cavity radius initial growth rate follows the same general $t^{0.5}$ growth rate of the crown. Roisman *et al.* (2008) explained that though inertia governs the drop impingement, surface tension and gravity forces govern the cavity growth at later stages which are responsible for its deviation from $t^{0.5}$. In their experiments they noticed a wave propagating downward from the top of the inside cavity surface that they identify as a capillary

wave. This wave was observed earlier by Fedorchenko and Wang (2004). Roisman *et al.* (2008) further report that the Reynolds number dominates the sub-cavity film flow. Berberovic *et al.* (2009) performed, CFD simulations, analytical analysis, and experiments for three liquids focusing on single drop cavities for $0.5 < h_0^* < 2.0$. They provide a detailed description of the cavity evolution and report that the initial cavity diameter follows the $t^{0.5}$ growth rate while gravity and surface tension forces govern the later times, consistent with Roisman *et al.* (2008). Section 7.5 gives a detailed description of the cavity evolution. Berberovic *et al.* (2009) also explains that the Weber number dominates the maximum cavity expansion and higher We , and h_0^* increases the cavity lifetime until capillary forces cause the cavity to recede. They also observed a cavity capillary wave for nearly all of their cavity formations.

In summary, cavity formation is dramatically different for thin initial liquid films and deep pools as the wall affects cavity morphology and evolution. Many of the observations by Roisman *et al.* (2008) and Berberovic *et al.* (2009) apply to the single drop results that are presented in Chapter 7, though the origin of the cavity wave described in literature as a “capillary wave” will also be discussed in this chapter. Deep pool features are not of interest for the current work as the single droplet experiments have been conducted for thin films, so many of the behaviors recorded in literature for thin film cavities influence the sub-cavity behavior.

Section 2.4.1: Sub-cavity Film Thickness

At various points in the literature, attempts have been made to quantify the sub-cavity film thickness. Rioboo *et al.* (2003) stated that even though they could not measure it, they believed the sub-cavity film thickness to decrease with the initial film thickness. In a computational study by Nikolopoulos *et al.* (2007) the minimum film thickness was found to be 1.98% to 2.06% of the initial droplet diameter for the respective CFD mesh grids of $d/40$ and $d/80$ for $We = 125, 250$, and

598 at $h_0^* = 0.116$. Berberovic *et al.* (2009) concluded, based on their CFD results, that the We and h_0^* did not affect the centerline minimum film thickness.

Van Hinsberg *et al.* (2010) utilized a non-contact chromatic optical sensor to measure the impact centerline sub-cavity film thickness for single droplet impacts for three fluids, varying dimensionless parameters of $0.07 < h_0^* < 2.0$ and $93 < We < 574$. Their results showed that as a droplet impinges onto a liquid layer of finite thickness it quickly creates a virtually constant thin sub-cavity film thickness until the subsequent receding of the cavity. This is called the retraction phase. They also found the centerline sub-cavity film thickness to be dependent upon the initial dimensionless liquid film thickness and the impinging droplet Reynolds number, but this thickness reached a constant value at high droplet Weber and Froude numbers. Additionally, their results show the increased cavity lifetime for increasing We and h_0^* , consistent with Berberovic *et al.* (2009). Hillen *et al.* (2012 and 2013) used a similar optical instrument to measure the sub-cavity film thickness for similar ranges of We and h_0^* , but obtained thickness data traversing radially outward from the drop impact centerline. These data were then used to compute sub-cavity volumes versus time.

The main focus of this thesis is the sub-cavity film thicknesses, used to compute the sub-cavity volumes. Results from Nikolopoulos *et al.* (2007) are felt to be questionable since at a maximum they had only two computational cells in the minimum sub-cavity film thickness region. In addition they observed dry patches in their cavities during simulations which were not observed in the experiments and simulations with higher sub-cavity adaptive mesh grid resolutions of drops under the same impingement conditions in Hillen *et al.* (2012). Initial techniques developed by Van Hinsberg *et al.* (2010) guided the experimental methods presented the subsequent Chapter 4. Chapters 5, 6, and 7 will expand upon the presentations given in Hillen *et al.* (2012 and 2013).

Section 2.5: Composition of Drop and Initial Layer Fluid

Numerous studies have been performed investigating the composition of the droplet and initial target film fluid in the crown. Rein (1993) states that the crown primarily contains the initial liquid layer fluid compared to the drop fluid. This was investigated further through numerical simulations where the drop fluid and initial layer fluid could be distinguished separately by Josserand and Zaleski (2003) and Nikolopoulos *et al.* (2005). They also found that the mass in the crown consists of more initial film fluid than droplet fluid, but did not give quantitative percentages. Kalantari and Tropea (2007) analytically estimated that 48% of the liquid inside the cavity is fed into the crown for $35 < We < 163$ and $280 < Re < 655$ at $h_0^* = 1.0$. Single drop simulations performed by Nikolopoulos *et al.* (2005) showed that the splashed droplets contained 73% to 88% of the mass of the initial target film fluid.

Santini *et al.* (2011) were able to visually show that the droplet liquid and target liquid interface are clearly distinguishable in the cavity for their deep pool single drop experiments by taking advantage of the temperature dependency of the refractive index of the fluids. CFD simulations performed by Dinc and Gray, presented in Hillen *et al.* (2012), were able to expand upon the techniques in Josserand and Zaleski (2003) and Nikolopoulos *et al.* (2005) to quantify the ratio of the initial drop liquid to target film liquid in the drop impact cavity. For the two cases of We and h_0^* studied it was found that the sub-cavity for $We = 633$ and $h_0^* = 0.11$ consisted of almost exclusively of the droplet liquid. The sub-cavity for $We = 141$ and $h_0^* = 0.61$ contained a greater fraction of initial film fluid though it was still predominantly drop fluid.

Though not the focus of the present research, the sub-cavity drop-target film liquid ratio is important to gaining a greater understanding of the spray cooling heat transfer mechanisms and improving the MC model. The amount of cool drop liquid present in the sub-cavity volume will have

a direct influence on the localized transient heat flux to the sub-cavity liquid for drop impingements on a heater, and also influence the time needed to induce cavity film boiling.

Section 2.6: Residual Spray Film Thickness

Table 2.3 summarizes the droplet sizes and residual film thicknesses created by sprays from previous work. The spray film thicknesses in Table 2.3 were measured utilizing various techniques including visual measurements, optical techniques based on total internal reflection, or micro-traversing a needle. The reported spray droplet diameters are arithmetic means unless otherwise noted.

Table 2.3: Summary of measured liquid film thickness created by an impinging spray and spray droplet sizes studied in literature.

Source	D (μm)	We	Re	h_s (μm)	h_s^*
Kalantari and Tropea (2006)	21-47	2-167	10-560	8-107	0.17-5.1
Kalantari and Tropea (2007)	25-30	35-163	280-655	13-80	0.52-3.2
Pautsch <i>et al.</i> (2004)	45-75	147-246	296-493	42-118	0.56-2.6
Pautsch and Shedd (2006)	45-75 [*]	746-1,240	1,330-2,210	18-75	0.24-1.7
Mathews <i>et al.</i> (2003)	110-350 [†]	1,290-1,700	3,120-4,840	20-50	0.06-0.45
Sivakumar and Tropea (2002)	123-310	414-1,096	2,020-5,950	54-193	0.17-1.6
Tilton (1989)	118-136	141-660	1,180-2,370	120-350	0.88-3.0

^{*} Since a spray droplet size was not specified it was assumed Pautsch and Shedd (2006) utilized the same or similar nozzle as in Pautsch *et al.* (2004) since the former was a continuation of the later.

[†] The Sauter mean diameter of the spray droplets was used.

Section 2.7: PDPA Background

PDPA was utilized to characterize the present spray experiments due to various advantages. These include the ability to non-intrusively measure simultaneous individual droplet diameters and velocities with directional sensitivity; a lack of required velocity calibration; high spatial and temporal resolution; and high accuracy (Albrecht, 2003, and TSI Manual, 2005). The system uses two separate techniques, Laser Doppler Velocimetry (LDV) and Phase Doppler Interferometry (PDI) to measure the respective droplet velocities and diameters. LDV is based on a laser that generates a coherent beam in which droplets pass through, reflecting scattered light back to the receiving optics.

Each measuring component consists of two equal intensity beams crossed at a half angle at the focal length of the lens creating the measuring volume at the intersection as shown in Figure 2.3. When droplets pass through the measuring volume light is scattered from the drops, with a light intensity that varies as the drops pass through the fringe patterns that are created. Photomultiplier tubes (PMT) produce an electrical current proportional to the scattered light variation in the fringe pattern to frequencies that can be converted into the particle velocity by Equation 2.11 (TSI Manual, 2005).

$$v = f \frac{\lambda}{2 \sin \alpha} \quad 2.11$$

Figure 2.3: Incident beams crossing creating the measuring volume.

PDI also requires the measuring volume created by the incident laser beams to scatter light off the particles passing through. Glare points in the particle are responsible for the scattered light which affects the amplitude and phase signal of the laser measuring volume. At least two photo detectors positioned off-axis at different elevations are required to interpret the phase shift and amplitude difference of the particle traveling through the measuring volume. Thus, the diameter is inferred by the phase and amplitude differences of the signals from the moving particle (Albrecht, 2003). The diameters are computed from a phase slope given in dimensionless form in Equation 2.12 (TSI Manual, 2005).

$$\frac{\text{Phase}}{360} = \text{"Slope"} \times \frac{\text{Detector Separation}}{\text{Receiver Focal Length}} \times \frac{\text{Particle Diameter}}{\text{Fringe Spacing}} \quad 2.12$$

Section 2.8: Summary

The MC model developed by Kreitzer (2010) shows promise by incorporating various micro timescales for the individual droplet impingements to simulate a spray, but is still lacking many physics that will be required in order to make the model quantitatively accurate. One parameter that could improve the MC model that is the focus of the current work is determination of the amount of sub-cavity liquid volume of the impinging droplets as a function of time. It is hoped that the sub-cavity volumes and respective lifetimes can help predict the onset of boiling in the cavity and thus the CHF.

A broad background of the single drop impingement process and outcomes leads to a better understanding of the cavity dynamics. The drop impingement, crown, and cavity formation process are all interconnected and dependent on each other. Cavity formation and its duration are directly dependent on the impinging droplet dimensionless parameters (We , Re , and Fr). Splashing behavior is relevant for the mass conservation of in the MC model, but in this work it provides comprehension of the measured splashed droplets in Section 6.3.

Previous work focusing on the cavity dynamics has been used in the development of the current experimental method. In addition, this information has provided insight into the single drop sub-cavity film thickness results presented in Chapter 7. The ratio of the drop liquid and initial target film thickness was not studied in depth in the present work, but is expected to be more prominent in future work.

The dimensionless residual spray film thicknesses shown in Table 2.3 have been utilized in the single drop test matrix listed in Section 6.5. These data have provided a realistic range of h_0^* for the single drop cavity experiments that are relevant to spray conditions.

CHAPTER 3: SPRAY EXPERIMENTS APPARATUS AND PROCEDURE

Section 3.1: Introduction

This chapter documents the apparatus and methodology of the spray experiments. The main purpose of the spray experiments was to generate a detailed test matrix for the single drop sub-cavity film thickness experiments for a proper range of relevant spray conditions. Detailed descriptions of the spray apparatus and the PDPA setup used for characterization are given in Sections 3.2 and 3.3 respectively. The methodology and procedures for measuring the spray droplet sizes and velocities via PDPA without an impact surface are detailed in Section 3.4. Initial documentation of the spray apparatus and PDPA spray characterization procedure can be found in Hillen *et al.* (2013).

Additionally, this chapter discusses the methodology and procedures for using PDPA to characterize the splashed droplets generated by the spray impinging onto a surface. As discussed on Chapter 1 these data sets are examined for their contributions to crater formation, but are primarily documented herein for future use. Descriptions of the spray impact surface are provided in Section 3.2.1, while the procedure for collecting and extracting the splashed drop data is presented in Section 3.5. Two main sets of splashed droplet data were collected, the first being in the spray region above the impact surface, and the second being outside of the spray region to the side of the impact surface.

Section 3.2: Spray Apparatus

Figure 3.1 depicts the spray apparatus is depicted schematically. The apparatus consisted of a recirculating loop system driven by a positive displacement pump (Tuthill model number DGS1.3PPPVNN37000). Most of the liquid was recirculated except for the fluid that was splashed when a 5.08 cm diameter impact surface was installed. The working fluid was distilled water, and the spray was contained within an optically transparent 76 x 76 x 23 cm Plexiglas tank open to the atmosphere. Spray flow conditions (nozzle pressure and flow rate) were measured upstream via a

pressure gage and flow meter, and foreign particles were removed from the water by a 0.5 micron filter. The selected spray nozzle was a full cone Spraying Systems 1/8-G FullJet nozzle with 60° cone angle, which produced the spray profile incorporated by Kreitzer (2010) in his original MC model. The nozzle was originally chosen for the MC model since it was determined by Yerkes *et al.* (2006) to give the most uniform spray flux out of several nozzles tested for spray cooling applications.

Figure 3.1: Schematic of spray apparatus (Hillen *et al.*, 2013).

Section 3.2.1: Spray Impact Surface for Splash Droplet Experiments

Splashing droplet sizes and velocities generated by the spray impinging onto a smooth surface were also measured via PDPA for the same nozzle. The spray impact surface was a smooth 5.08 cm diameter and 5.08 cm long cylindrical acrylic pedestal that was mounted beneath the nozzle shown in Figure 3.2. The leveled impact surface was centered with the nozzle orifice exit and positioned at standoff distances from the nozzle exit such that it would be fully covered by the full spray cone with a slight overspray.

Figure 3.2: Spray testing 5.08 cm diameter impact surface apparatus with nozzle.

Section 3.3: PDPA Setup

The PDPA system utilized for spray characterization was a two-component system manufactured by TSI, Inc. This system had a manufacturer reported maximum instrumentation uncertainty of nominally 0.75%. The light source was a water cooled argon-ion laser (maximum 5-W) that was split into four beams by a multicolor beam generator creating the two velocity measuring components. A photo detector module (PDM) contained the PMT and a 175 MHz signal analyzer to interpret droplet size and velocity. The optics consisted of a transmitter and optical receiver that were mounted on a tri-axis traverse with a reported 10 μm resolution as shown in Figure 3.3 a). The receiving optics were positioned 30° off-axis from the transmitter in a backscatter optical configuration (Figure 3.3 b). Light between the optics, beam splitter, and PDM was transmitted via fiber optic cables. Control of the PDPA system and data acquisition was performed with the manufacturer's propriety software FlowSizer v2.0.4.

Figure 3.3: PDPA transmitting and receiving optics and traverse system. a) Optics mounted on the tri-axis traverse. b) Mounted optics configured in back-scatter mode (Menchini, 2013).

A summary of the main system settings used for the PDPA data in Chapter 6 is listed in Table 3.1. The settings were configured for a dense water spray with input from colleagues who had experience in using the apparatus, and from the PDPA manufacturer.

Table 3.1: Summary of PDPA system settings.

Setting	Channel 1	Channel 2
Laser Power (W)	3.34	
Transmitter Focal Length (mm)	1000	
Slit Aperture (μm)	150	
Min and Max Diameter (μm)	2 - 685	
Lower-to-Upper Intensity Ratio	0.1	
Upper Intensity Slope ($\text{mV}/\mu\text{m}^*\mu\text{m}$)	0.015	
Focal Length (mm)	1000	
Measuring Volume Diameter (mm)	0.370	
Measuring Volume Length (mm)	8.77	
Beam Wavelength (nm)	514.5	488.0
Beam Separation (mm)	20	
Laser Beam Diameter (mm)	1.77	
Beam Expander (ratio)	2.11	
Fringe Spacing (μm)	12.1947	11.5666
Beam Waist Diameter (μm)	3.7347	
Bragg Cell Freq. (MHz)	40	
Velocity Limit Min (m/s)	-36.58	-34.70
Velocity Limit Max (m/s)	73.17	69.40
PMT Voltage (V)	350	350
Max Number of Samples	50,000	
Time Out (sec)	30	
Burst Threshold for Both Channels (mV)	30	
SNR Setting	Low	
Band Pass Filter (MHz)	1 - 10 M	
Down Mix Freq (MHz)	36	
Software Coincidence (gate scale) %	250	
Scattering Mode	Internal Reflection	
Scattering Angle Off-axis (deg)	151	
Polarization	Perpendicular	
Refractive Index of Droplet	1.33	

Section 3.3.1: Droplet Size Validation

There are two methods for the system software to check the validity of the droplet size measurements: the intensity validation and the diameter difference validation. The intensity validation follows the principle that the intensity of light reflected by an individual particle should increase as the square of the diameter. Figure 3.4 a) is an example of the intensity validation with its operating settings listed in Table 3.1 configured with input from a representative of the PDPA

manufacturer (Troolin, 2012). The second particle size validation takes advantage of the PDPA system's three photo detectors that recorded simultaneous dual particle sizing measurements. The difference in diameter was computed for the two simultaneous particle diameter measurements and particles with differences greater than 7% were filtered out. An example is shown in Figure 3.4 b). It should be noted that both of these methods also removed the measured velocity component data of the filtered drops.

Figure 3.4: Diameter data validation graphs. a) Intensity validation curve. b) Diameter difference validation (Hillen *et al.* 2013).

Section 3.4: Spray PDPA Characterization Procedure: Without the Spray Impact Surface

PDPA was utilized to characterize the water spray droplet sizes and velocities generated by the nozzle of interest. Table 3.2 lists the physical properties of the distilled water used in the spray at a typical room temperature of 20°C.

Table 3.2: Physical properties of distilled water at $T = 20^{\circ}\text{C}$.

η	1.33
μ (N s/m ³)	1.00×10^{-3}
ρ (kg/m ³)	998
σ (N/m)	7.28×10^{-2}

Data were recorded assuming the spray cone to be axisymmetric with Figure 3.5 defining the global coordinate system and the velocity component convention for the individual impinging

droplets. Defining the nozzle tip as the spray zero location ($x = y = z = 0$ mm), initial sparsely space profiles along the x and y -axis were recorded via PDPA to center the measuring volume.

Figure 3.5: Coordinate system for spray axis and droplet coordinate system (Hillen *et al.*, 2013).

Droplet velocity and size profiles were measured along the x -axis and y -axis at standoff distances from the nozzle tip of $z = 3.18, 3.81$, and 4.45 cm. These distances were determined to be the optimal range needed such that a 5.08 cm diameter surface of interest would obtain full coverage with only a slight overspray, as shown in Figure 1.1. PDPA data were obtained at each nozzle standoff distance at 41 radial locations that were selected to yield equal annular ring area increments along the x -axis and y -axis for the three flow conditions listed in Table 3.3. The reasoning behind the equal area method was to simplify the volume flux calculations. These radial locations spanned the entirety of the spray ($-2.68 \leq R_s \leq 2.68$ cm) for the x -axis profiles, but only two single point measurements were performed beyond the center of the spray in the y -axis before the very high spray density was believed to have affected the measurements. The pressures in Table 3.3 have been recorded just upstream of the nozzle where the manufacturer suggested 4.14 bar as one of the optimum operating conditions for the nozzle and 1.38 bar as on the low end to fully form a spray cone. Reliable constant pressures above 4.14 bar were not attainable, as the pump was unable to maintain steady operating conditions at the higher pressures.

Table 3.3: Spray nozzle settings.

Nozzle Gage Pressure (bar)	Flow Rate (L/hr)
1.38	29.5
2.76	43.5
4.14	54.5

Section 3.5: Splashed Droplets Methodology

PDPA data was also obtained to characterize the splashed droplet sizes and speeds (Figure 3.2). The 5.08 cm diameter impact surface was mounted in the spray apparatus depicted in Figure 3.1 and aligned with the nozzle as described in Section 3.2.1 to generate the splashed spray droplets. The impact surface was positioned at the optimal standoff distance of 3.81 cm from the nozzle exit for full coverage and a slight overspray as in Figure 1.1. The PDPA was operated under the same system settings listed in Table 3.1 to characterize the splashed spray droplets with the measuring volume traversing along only the x -axis in the same location increments and span ($-2.68 \leq R_s \leq 2.68$ cm) as described in Section 3.4. This profile was measured for each nozzle pressure and flow rate condition listed in Table 3.3 at a constant $z = 3.65$ cm, or 1.6 mm above the impact surface. The selection of this standoff distance was based on many contributing factors, but the main consideration was to prevent the spray pedestal from interfering with the x component incident laser beams depicted as a sketch in Figure 3.6. During testing it was observed that at lower flow rates there was a small ring of fluid buildup along the edge of the impact surface that could also interfere with the incident beams. This measuring volume z location also provided ample clearance of the residual spray film thickness, which ranged nominally between 10 to 350 μm as measured in the literature (see Table 2.3). Kalantari and Tropea (2007) suggested in their PDPA experiments that the measuring volume should be positioned at least 1 mm above the impact surface to avoid the maximum crown height and its jet formations, which they computed analytically.

Figure 3.6: Sketch explaining the z positioning of the measuring volume to avoid interference from the impact surface and fluid ring buildup.

The PDPA data acquisition software did not discriminate splashed droplets from impinging spray droplets. As a result, a method had to be developed to extract the splashed droplet sizes and speeds. The developed technique separated the data in greater detail than the method used by Kalantari and Tropea (2006) that was summarized in Section 2.3.3. Figure 3.7 a) depicts the raw PDPA spray droplet population data for one condition and location in the spray with no impact surface in place. Figure 3.7 b) shows the raw PDPA droplet population data under the same spray conditions and measuring location, but with the impact surface in place. Examining Figure 3.7 b) shows a similar spray droplet population, but with the addition of a secondary population formation to its left that was not present in Figure 3.7 a). This additional population was determined to be the splashed droplets since they were significantly slower with a large portion having the opposite axial velocity sign convention relative to the original spray droplets, and since this population only existed for measurements collected with the impact surface in place.

a) **b)**
Figure 3.7: Comparison of raw PDPA spray data of droplet diameter plotted vs. axial velocity. a) $R_s = 0, z = 3.2$ cm for the 2.76 bar spray without the impact surface, b) $R_s = 0, z = 3.2$ cm for the 2.76 bar spray with the impact surface.

The spray and splashed droplet populations shown in Figure 3.8 are categorized into four sub groups: spray, ejected splash, return splash, and absolute splash. The spray droplets always had positive axial velocities that were significantly higher than the corresponding splashed droplets, thus this population always formed to the right of the splashed droplet population in the plots of drop diameter versus axial velocity. The splashed droplets circled in green in Figure 3.8 were divided into the ejected and return splash droplet sub groups based on the axial velocity sign convention. Droplets in the splash region with a negative axial velocity (away from impact surface) were the ejected splash droplets, and droplets in the splash region with a positive axial velocity (returning to the surface due to gravity) were denoted as the return splash droplets. In addition, data have been presented for the splashed particles based on the absolute axial velocity magnitude consisting of the entire splash region termed herein as the absolute splash droplets. Data shows a double peak distribution and the dividing line between the two populations is the minimum between the two peaks. A sensitivity study for the effects of the location of the separation point on the averaged data for the different spray and splash parameters was performed. This study found that any reasonable

location choice within a nominally 3 to 5 m/s range had a negligible effect on the average of droplet data.

Figure 3.8: Separation of the spray and splash regions into the droplet sub-categories.

Section 3.5.1: Vertical Edge Splash Droplet Methodology

The addition of the splashed droplets created larger droplet number fluxes for the PDPA to interpret for the x -axis profiles above the impact surface. This resulted in lower data rates than corresponding measurements without the spray impact surface in place and was most prominent at higher nozzle pressures. Figure 3.9 shows evidence of the data rate decreasing with increasing nozzle pressure for PDPA data collected at $R_s = 0$ cm and 2.1 mm above the impact surface ($z = 3.6$ cm) at equal measuring times. The total droplet diameter counts for increasing the pressure are 27,295, 14,832, and 4,245 for the respective Figures 3.9 a), b), and c). This drop in diameter measurements shows that denser sprays negatively affect the quality of the PDPA data.

Figure 3.9: Spray and splash droplet diameters versus axial velocity at $z = 3.6$ cm at the three nozzle flow conditions. a) 1.38 bar and 29.5 L/hr. b) 2.76 bar and 43.5 L/hr. c) 4.14 bar and 54.5 L/hr.

Also adversely affecting the PDPA splashed data quality was a smaller population on which to base the statistics. This is a result of the splashed droplet data being extracted from a finite amount of overall PDPA data (maximum of 50,000 droplet data per measurement location). Figure 3.10 clearly demonstrates this issue for the sample incoming spray, and splashed droplet diameter histograms at the center of the spray. The absolute splashed droplets histogram in Figure 3.10 c) shows the largest diameter bin counts, of nominally 60 to 70, for histogram depicted in Figure 3.10.

Figure 3.10: Histograms of the separated droplet diameter data for a spray at 4.14 bar impinging on impact surface at $R_s = 0$ cm and $z = 3.65$ cm. a) Spray droplets. b) Ejected splashed droplets. c) Returning splashed droplets. d) Absolute splashed droplets.

The lower data rates combined with less available splash droplet statistics prompted the investigation of the splashed droplets in a region with minimum interference from the impinging spray for comparison purposes. This was accomplished by performing measurements along the z -axis of the ejected splash droplets just beyond the outer edge of the spray, as is highlighted in Figure 3.11. In this region post processing was not necessary to extract the splash data since the droplets were predominantly splash products. Measurements were obtained for vertical profiles on the x z -plane at $y = 0$ spanning between $1.75 \leq z \leq 4.25$ cm at a fixed $R_s = 2.68$ cm for the spray conditions in Table 3.3. This profile allowed measurements just beyond the target pedestal at z coordinates that were located both above and below the plane of the impact surface. The same vertical traverses under the same spray conditions were measured for $R_s = -2.68$ cm to check for symmetry.

Figure 3.11: Spray apparatus impinging onto the impact surface with the laser probe volume traversing along the z -axis to the side. The splashed secondary droplets ejected outside of the spray cone that are being measured are circled in red.

CHAPTER 4: SINGLE DROP EXPERIMENTS APPARATUS AND PROCEDURES

Section 4.1: Introduction

This chapter documents the experimental apparatus and procedures for the single droplet experiments, which were originally reported in Hillen *et al.* (2012), and Hillen *et al.* (2013). The single droplet experiments consisted of measuring the sub-cavity liquid film thicknesses via the CHR sensor along with simultaneous high-speed videos for flow visualization for the appropriate ranges of We , Re , and h_0^* . The methodology for obtaining the transverse profiles and traversing the cavity to record the radial film thickness history profiles are reported herein. The radial profiles of the sub-cavity film thickness were utilized in the sub-cavity volume calculation method, as presented in Chapter 5.

The single drop apparatus is discussed in Section 4.2 including the droplet generator, optical probe housing, and traverse assembly. Descriptions of the noncontact CHR sensor utilized to measure the sub-cavity film thickness, and the high-speed video camera set up used for detailed flow visualization are also given in this section.

Section 4.3 documents the preliminary investigations of the sub-cavity single drop experiments found in Hillen *et al.* (2012). The initial methodology of measuring the crown radius and height versus time is discussed. The original methodology of utilizing the maximum crown radius to determine the radial location to traverse the cavity is also detailed.

For the main single drop experiments, the bottom inside cavity radius, referred herein as the sub-cavity radius, was determined to be the most effective method to determine the radial locations at which to traverse the CHR optical probe. Section 4.4 contains a detailed description of the two high-speed video techniques used to measure the sub-cavity radius versus time. The maximum sub-cavity radius was utilized to generate the traverse limits for the CHR optical probe. Also included in Section 4.4 are the image processing techniques to extract the sub-cavity radius values.

Section 4.5 contains the procedures for producing the desired single drop test conditions and measuring the sub-cavity liquid film thickness histories with the CHR sensor. In addition the methodology for creating the radial cavity traverse profiles for the CHR optical probe is documented. Post processing procedures for correcting the recorded film thicknesses and timing are also reported. A brief summary of the image processing code developed to obtain the single droplet diameter, velocity, and impact location is reported.

Section 4.2: Single Drop Sub-cavity Experiments Apparatus

The apparatus used to measure the sub-cavity film thickness histories for the single drop experiments is depicted schematically in Figure 4.1. Single droplets of the desired size have been produced via a combination of solenoid valve total opening time, pressure head in the generator's liquid reservoir, and the needle orifice opening in which droplets detach due to gravity. The presented single drop experiments incorporated a 12-gauge stainless steel precision tip dispensing needle with a 2.16 mm inside diameter orifice. The droplet generator was attached to a vertical track allowing the droplet velocity prior to impact to be varied by changing the free fall height of the droplet. Generated droplet diameters and velocities had measured standard deviations of nominally 0.015 mm and 0.007 m/s respectively for ten subsequent droplets. The individual droplets impinged onto a static layer of liquid contained within a nominally 15.2 x 15.2 x 5.1 cm optically clear acrylic tank open to the atmosphere. The tank size was deemed adequate to allow surface waves to damp before wall rebound.

Liquid film thickness has been measured with a time resolved non-contact chromatic optical CHRcodile SE sensor using a 3.3 mm full range optical probe. The sensor functions by focusing spectrally broadband light at an interface from which it is reflected back to the sensor. For thickness measurements, the sensor interprets two interfaces at different distances as two sharp peaks in the

wavelengths. The spectral distance combined with the refractive properties of the interfaces result in thickness measurements (Kunkel and Schulze, 2005). The sensor had a sampling rate of 4 kHz and $\pm 0.1 \mu\text{m}$ thickness sensitivity. It was observed that the sensor could reliably read slightly beyond the nominal 3.3 mm range, to between 3.4 - 3.5 mm. The optical probe was housed within an impact stand covered with a 0.152 mm thick, 25 mm diameter borosilicate glass disc that served as the interface between the sensor and the liquid pool as depicted schematically in Figure 4.1 b). Film thickness data acquisition was performed using the manufacturer's CHRView software. The impact stand was fitted in the middle of the acrylic tank resulting in the 10.16 cm diameter surface that functioned as the wall, referred herein as the impact surface. The tank and all of its components were mounted on a single axis micro-traverse allowing sub-cavity thickness profiles to be measured at locations located radially away from the fixed droplet impact centerline. The micro-traverse had a 0.025 mm resolution. The impact surface was leveled via a leveling plate attached to the micro-traverse. Detailed computer aided design (CAD) drawings of some of the major components can be found in Appendix A.

Figure 4.1: Schematics of the single drop experimental apparatus. a) Entire apparatus. b) Cross section of the impact stand and optical probe (Hillen *et al.* 2012).

Droplet impacts were recorded utilizing a gray scale Photron FASTCAM SA5 high-speed video camera equipped with a Nikon ED AF MICRO NIKKOR 2000 mm 1:4 D lens for detailed

analysis. The camera was capable of recording images at a maximum 150,000 frames per second (fps) at 128 x 32 pixel resolution. It had a maximum resolution of 1024 x 1024 pixels up to 7500 fps. For the sub-cavity film thickness experiments the camera's line of sight was aligned parallel to the impact surface in a backlit configuration shown in Figure 4.1 a). The camera was illuminated with a 250-W Lowel Pro halogen lamp positioned at the rear of the tank. A camera frame rate of 12,000 fps, 640 x 640 pixels was required to adequately capture the impact event and to prevent washout from the light source. Using the proprietary Photron FASTCAM Viewer software, a high-speed image of a caliper set to 10 mm was used to calibrate the pixel sizing. Depending on the distance of the camera from the tank, typical backlit configurations resulted in pixel resolutions of 0.0441 mm to 0.0476 mm. A control switch was used to simultaneously trigger the camera during droplet generation and synchronized with the CHR sensor time while it recorded the liquid layer thickness.

Section 4.3: Initial Preliminary Investigation

Initial preliminary development of the current methodology utilizing the apparatus described in Section 4.1 to map the sub-cavity film thickness has been documented in greater detail in Hillen *et al.* (2012). Figure 4.2 is a sketch with definitions of a typical history of the sub-cavity liquid film thickness histories where the cavity lifetime is defined to begin upon droplet impact.

Figure 4.2: Definition of a cavity lifetime for a wetted surface, (Hillen *et al.*, 2012).

Two single drop impingement cases listed in Table 4.1 were studied in the preliminary investigation using distilled water as the working fluid (see Table 3.2 for properties). The low Weber number and medium initial liquid film thickness were chosen for Case A to investigate a low momentum drop impact below the Cossali *et al.* (1997) splashing criteria in Table 2.2. Case B parameters were based on a single drop impingent condition used in simulations by Nikolopoulos *et al.* (2007) for comparison purposes; this case is above the splashing threshold.

Table 4.1: Dimensional and corresponding dimensionless parameters for preliminary single drop cavity investigation (Hillen *et al.*, 2012).

Case	h_0^*	d (mm)	v (m/s)	We	Re	Fr	Y
A	0.614	3.19	1.79	141	5,700	103	0.398
B	0.113	6.39	2.69	633	17,100	115	3.50

The film thickness lifetimes had to be manually determined during post processing with the aid of high-speed flow visualization. Due to a timing error between the CHR sensor and the high-speed camera, the beginning of the sub-cavity liquid film thickness profiles located off the centerline had to be manually corrected by utilizing the bottom crown radius propagation. The measured crown dimensions were also used for comparisons between experiments and corresponding CFD simulations as presented in Hillen *et al.* (2012). In Figure 4.3 the bottom crown radius is defined as the half the distance between the opposite outside edges of the crown and the free surface interface. Crown height was defined as the distance from the crown-free surface interface to the base of the fingering, as also shown in Figure 4.3. Defining the crown height in this manner eliminated any judgment required from trying to measure to a specific point in the fingers, which vary from drop-to-drop.

Figure 4.3: Definition of crown height and bottom radius.

Bottom outside crown diameters and crown heights were extracted from the high-speed videos via a custom automated image processing code. This code was developed in Matlab, for its efficient matrix manipulation routines and to take advantage of the built in Image Processing Toolbox. For the program to efficiently run, the frames of the beginning of the crown formation and its full collapse first had to be inputted. Once the range of frames of interest have been defined, the code extracts an average pixel location of the liquid free surface from an image of the undisturbed free surface. Subsequent video frames are uploaded in sequence and converted into binary (black and white) images to make subsequent image processing simpler. Crowns in subsequent frames were outlined by employing a built in Canny edge detection algorithm. Any holes in the crown outline are connected and the crown and liquid film are filled. Any splashed droplets and noise in the filled image were filtered out. The free surface and corresponding liquid film beneath the crown were then removed with the previously stored undisturbed free surface pixel coordinates. Crown fingers were then removed through the following process. The image was scanned to identify the first and last pixel in each row, removing any rows that contain any black pixels between these pixels. The removal of these rows removes the crown fingers leaving a smooth upper crown surface at the lowest point in the observed cusps. This results in the measuring range from which the crown height

and bottom crown radius are extracted. Figure 4.4 presents the steps used to extract the crown height and bottom crown radius from the high speed video images.

Figure 4.4: A basic overview of the Matlab image processing used to determine the crown height and bottom crown radius. The order of the sequence is left to right from the top (Hillen *et al.*, 2012).

Section 4.4: Single Drop Sub-cavity Radius Video Methodology

The CHR traverse profiles created from the procedure described in Section 4.3 resulted in a low number of sub-cavity film thickness radial profiles, which is explained in more detail in Section 7.2. Thus the sub-cavity radius (see Figure 1.2) was determined to be the most effective method to determine the radial locations at which to traverse the cavity with the CHR optical probe. Therefore, two different high-speed video techniques have been developed to measure the inside sub-cavity radius for a single drop impinging on an initial thin liquid film. These two techniques are herein referred to as the side-view (SV) and bottom-view (BV) methods, based on their respective camera configurations. The camera alignment for the SV method was the same backlit configuration depicted in Figure 4.1 a). Images were acquired at 12,000 fps, 640 x 640 pixels as described in Section 4.2. Because the sub-cavity radius was of primary interest the camera height was adjusted

such that its line of sight was level with the impact surface to provide greater visual clarity of the cavity formation.

The initial investigation into the development of the optimum bottom-view methodology has been reported in Hillen and Kuhlman (2013b). The bottom-view method involved modifications to the single drop apparatus shown in Figure 4.1 a) in order to visualize the impact process from beneath a transparent impact surface. This was accomplished by positioning an acrylic mirror beneath the impact stand. The mirror and high-speed camera were oriented such that the line of sight was perpendicular to the impact surface, as depicted schematically in Figure 4.5. To ensure adequate visualization of this phenomenon, a similar impact stand to the one depicted in Figure 4.1 b) was constructed, but it contained a larger 4.45 cm diameter viewport with a 48 x 60 x 0.15 mm rectangular borosilicate slip glass covering it (this impact stand was exclusive to the BV bottom cavity measurements). Due to less available light, the BV videos were recorded at 1,000 fps with 1,024 x 1,024 pixel resolution. Each pixel had a typical resolution of between 0.0570 mm to 0.0656 mm depending on the camera positioning.

Figure 4.5: Schematic of the configuration utilized to view the impingement process from beneath the free surface (Hillen and Kuhlman, 2013b).

The CHR sensor was utilized to obtain the correct initial film thickness based on the single drop test condition for both sub-cavity radius video techniques. The CHR optical probe was removed prior to testing for the BV technique to create an unobstructed view. The sub-cavity radius was measured versus time, and analyzed using custom image processing codes presented in Section

4.4.1. Figures 4.6 a) and b), respectively, are example images from the SV and BV videos for a drop impingement condition of $We = 140$, $Re = 1,210$, and $h_0^* = 1.0$. Indicated in red in each image is the measured bottom cavity diameter for the time shown.

Figure 4.6: Example images of the measured sub-cavity radius. a) Side-view image of measured sub-cavity radius (red line indicates measured diameter). b) Bottom-view image of measured sub-cavity radius (red circle indicates measured diameter) (Hillen *et al.* 2013).

Section 4.4.1: Sub-cavity Radius Image Processing

Two separate automated Matlab based image processing codes were developed to measure the sub-cavity radius histories for the SV and BV videos. Figure 4.7 depicts a basic overview of the logic used for the side-view code. The first step of the process was to identify the liquid layer region by manually inputting the average pixel location of the impact surface and the bottom of the free surface using a frame consisting of the undisturbed initial film thickness. For simplification of the process, each subsequent frame was converted into a binary image after which pixels not located within the liquid layer region were removed. A Canny edge detection function was again used to outline the remaining cavity, which was subsequently filled and filtered by applying various methods to remove noise. The bottom inside cavity diameter was averaged for the lowest five rows of pixels consisting of the bottom cavity. This reduced noise during the initial cavity depth propagation due to its large curvature, and noise at the bottom cavity and impact surface interface due to minute shadows.

Figure 4.7: A basic overview for the side-view video image processing. From left to right: original image, binary conversion, filled cavity of the Canny edge detection outline, and the final measured bottom cavity diameter.

The code developed for the bottom-view sub-cavity radius measurements follows a similar initial logic used in the SV version. Figure 4.8 is a basic summary of the BV code logic, where the initial step was to convert subsequent frames to binary images. The cavity was then filled for simplification. The positioning of the light source created glare spots in the crown preventing the cavity region from being isolated, as shown in Figure 4.8. To rectify this issue the code searched for the maximum distance between the available inside cavity edges and connected the glare spots based on this distance and the user defined cavity center. Once the cavity region was enclosed the remaining pixels were filtered out leaving the isolated cavity. Cavity diameter and centroid were then measured utilizing the built in Matlab function “`imfindcircles`.”

Figure 4.8: A basic overview for the bottom-view video image processing. From left to right: original image, filled binary conversion with glare spots connected, isolated cavity, and the final measured bottom cavity diameter.

Section 4.5: Single Drop Sub-cavity Methodology

The initial experimental procedures for measuring the single drop sub-cavity film thickness histories were originally described in Hillen *et al.* (2012), with the updated, improved process

documented by Hillen *et al.* (2013). For the results presented in Chapter 7, the initial droplet diameters and velocities were varied nominally between 3 - 3.5 mm, and 1.7 - 4.2 m/s respectively to match a specific We and Re combination in the desired test plan described in Section 6.5. Individual droplet size, impact velocity, and impact location were extracted from the corresponding high-speed video with custom image processing detailed in Section 4.5.1. The measuring point of the CHR optical probe was aligned with the averaged location of droplet impact as measured using high-speed imagery. This measuring point is considered the CHR sensor zero location. Liquid was added to the tank rather than removed to obtain the desired initial film thickness since this resulted in the most significant reduction in the tank wall meniscus. The high-speed video camera was set up in a backlit configuration as depicted in Figure 4.1 with the height of the camera line of sight adjusted so that the free surface would be clearly distinguishable. Each droplet was triggered individually with a programmed 6 second trigger delay between runs that ensured ample time for the free surface to reach steady state after each impact.

The radial measuring points used to traverse the CHR optical sensor was constructed with the maximum sub-cavity radius data obtained from the SV analysis, using the process detailed in Section 4.4. The SV cavity radius data were generally somewhat larger than the respective BV data, thus ensuring full coverage of the bottom cavity history data obtained with the CHR sensor. The utilization of the maximum sub-cavity radius resulted in profiles that contained at least 8 to 14 locations at which film thickness data were recorded. The equal area annular ring method was used to distribute the radial measuring locations, so that a finer radial resolution resulted at the outer edges of the cavity, as shown schematically in Figure 4.9. This focus on the outer radial locations was an attempt to more accurately capture the location where the cavity bottom ended. Small uncontrollable air currents in the lab and the uncertainty in the droplet detachment process from the needle resulted

in a variability in the drop-to-drop impact location. This variability in the droplet impact location determined the minimum meaningful radial step size and thus the number of traverse points for each test scenario. For the range of initial drop conditions presented in Section 7.3 this uncertainty in impact location increased from 4% of the initial droplet diameter at the lowest free fall height to 23% of the initial droplet diameter at the highest droplet free fall height (corresponding to the highest momentum case studied).

Figure 4.9: Schematic representation of the radial cavity traverse locations for the CHR optical probe (Hillen *et al.* 2013).

The optical probe was traversed radially outward from the droplet impact centerline to each of the specified maximum radial locations. This was done by fixing the location of the droplet generator, and traversing the droplet impact tank (see Section 4.2). Individual droplet impact data were recorded for each radial location, maintaining consistent initial droplet impact location and film thickness conditions for the specified case. Droplet impacts which varied more than 1% away from the impact centerline location were excluded from the analysis with aid of the SV videos. This was accomplished using the Photron FASTCAM Viewer software to estimate the average droplet impact pixel location in the videos. The shape of the 1.27 cm diameter view port in the acrylic stand for the CHR probe light to pass through was visible in the backlit videos, as highlighted by the red box in Figure 4.10. Assuming perfect probe alignment, the droplet impact centerline location should be located in the center of this viewport. This location could be determined to within one pixel by subtracting the distances from the left side of the image to the two sides of the viewport and dividing

by two. Adjusting the lateral position of the acrylic tank and the droplet generator until both the average droplet impact location and the viewport were centered in the image ensured that the optical probe measuring point was aligned with droplet impact centerline. Thus, the droplet impact centerline was defined to within one consistent pixel location (nominally 0.0570 mm to 0.0656 mm) for videos for all radial traverse locations for a particular camera alignment.

Figure 4.10: Example determining the CHR optical probe measurement center point in the videos with the probe positioned at $R_c = 0$ mm. The red box highlights the 1.27 cm diameter acrylic hole “viewport” and the red dashed line represents the probe’s center point.

Timing and film thickness corrections for the sub-cavity profiles were performed during post-processing. The cavity lifetime has been defined to start when the droplet first comes into contact with the free surface. This proved trivial for the impact centerline measurements, as the film thickness data abruptly changed when the droplet contacts the free surface creating one interface. Corresponding synchronized high-speed videos of the impinging drop allowed the time corrections for thickness profiles where $R_c > 0$ to be within ± 0.33 msec of the inter-frame time of the video. To properly account for the thickness of the glass interface, the index of refraction of the CHR sensor was set to a value of one so the true liquid film thickness was extracted by the following equation (Hillen *et al.*, 2013):

$$h_{Fluid} = \left(h_{Total} - \frac{h_{Glass}}{\eta_{Glass}} \right) \eta_{Fluid} \quad 4.1$$

Section 4.5.1: Single Droplet Image Processing

Single droplet diameter, velocity, and impact location were measured for each impact in the high-speed videos via an automated Matlab-based image processing code. The user would input a frame number range between when the droplet first fully comes into view and before it passed over the meniscus, or free surface. Subsequent frames were again converted to binary to simplify the code and all pixels were removed other than those consisting of the droplet. The isolated droplet was outlined through the Canny edge detection and the outline subsequently was filled. An ellipse was fitted to the drop since it would oscillate while falling, therefore the extracted droplet diameter was taken as the average of the two ellipse axes. The droplet centroid location from left edge of the image was taken as the center of the ellipse. Velocities were computed from the distance traveled by the droplet centroid for each subsequent frame. The final droplet impact diameter and locations were averaged over the last twenty frames until impact while the impact velocity was averaged for the last ten frames.

Figure 4.11: A basic overview of the single drop image processing. From left to right: original image, binary conversion, isolated filled drop, and the final measured drop diameter.

CHAPTER 5: SINGLE DROP SUB-CAVITY VOLUME CALCULATION METHODOLOGY

Section 5.1: Introduction

The present chapter explains the methodology developed to compute the sub-cavity volumes for the single droplet experiments, as originally documented by Hillen *et al.* (2013). Both the preprocessing of the liquid film thickness histories to apply to the sub-cavity film thickness surface plots and subsequent sub-cavity volume calculations will be discussed in detail. Also, the integration method and iterative process used to determine the final sub-cavity volume histories are documented. The volume calculations for the presented methodology were automated via Matlab. A brief comparison of the sub-cavity volume results computed using the developed numerical method with an estimation utilizing the average minimum sub-cavity film thickness and measured sub-cavity radius history is also included.

Section 5.2: Sub-cavity Integration Method

Time dependent sub-cavity liquid volumes were obtained by numerically integrating the sub-cavity film thickness data at fixed times versus the cavity radius, based on the mapped cavity film thickness histories. Since the sub-cavity volume is the quantity of primary interest, the measured volumes when the droplet is initially forming the cavity, and after the cavity has filled back in, have not been calculated. The film thicknesses of these volumes have been judged to be too thick to have a susceptibility to onset of boiling or dry out similar to the sub-cavity volume. Sub-cavity volumes for specific times were computed utilizing the following integral, which has been evaluated using the trapezoidal rule

$$Vol_i = 2\pi \int_0^{R_{c_i}} (R * h) dR, \quad 5.1$$

where the i subscript indicates the time index for which the volume is computed, and R_{c_i} indicates the maximum sub-cavity radius at the current time.

Section 5.3: Sub-cavity Volume Noise Removal

Limitations of the CHR instrumentation required further post-processing of the sub-cavity thickness histories before the sub-cavity volumes can be computed. Thickness values that were beyond the sensor measuring range, and complex curvature in the free surface would cause data drop out, or noise. Sub-cavity thickness readings are generally very repeatable and reliable; with a majority of issues occurring with the first droplet impact, the collapse of crown walls, and the complex events during and after cavity fill in (e.g., impact of a secondary droplet into the cavity). By referring to the corresponding high-speed videos, any noise within the cavity lifetime was filtered out, and missing data points were then filled in with cubic interpolation. Generally, the greatest amount of noise was observed at the outer most radii (usually the last 1 - 3 histories), where it was more prominent for the thicker initial films. Typically very little filtering was required for the remaining inner radii. Initial film thicknesses of $h_0^* < 0.5$ resulted in the clearest histories since the initial liquid layer thickness was well below the CHR sensor measuring range. This allowed more film thicknesses greater than h_0^* to be captured without data drop out.

Figure 5.1 shows an example of the interpolated and filtered sub-cavity history overlaid with the raw data at the outer most radial location ($R_c = 6.41$ mm) measurement for an initial single drop condition of $We = 621$, $Re = 2,640$, $Fr = 415$, and $h_0^* = 0.5$. Nearly every history for this entire data set did not require any data removal in the minimum sub-cavity film thickness region (0.014 to 0.028 seconds for Figure 5.1). The cavity formation and receding phase shown in Figure 5.1, times of 0.0023 to 0.014 seconds and 0.028 to 0.034 seconds respectively, needed to be manually filtered. Generally, any data forming consistent trend patches such as the data from 0.034 to 0.038 seconds in

Figure 5.1 were retained. Sparsely spaced isolated singular data points usually forming spikes were removed unless they formed part of an obvious greater trend or had clear video evidence of their correctness. For the example shown in Figure 5.1 data were removed between $0.004 \leq t \leq 0.01$ seconds and $0.029 \leq t \leq 0.033$ seconds. The removal of the lower portion of data $h < 1000 \mu\text{m}$ between $0.004 \leq t \leq 0.01$ was justified since the corresponding video showed smooth cavity propagation, so this noise was determined to be a product of the cavity curvature. The data consisting of the upper portion ($h > 1000 \mu\text{m}$) was believed to be a result of the sensor attempting to read the propagating crown that should be beyond its measuring range. This data could not be trusted so it was removed in the example. Similar logic was applied to the removed data between $0.029 \leq t \leq 0.033$ seconds. In addition, no video evidence was observed of a contributing fluid structure for the larger thicknesses for this time frame. Similar noise behavior was consistent across the entire data set, so the same logic was applied to all cases.

Figure 5.1: Filtered and interpolated sub-cavity film thickness history compared with the original ($We = 621$, $Re = 2,640$, $Fr = 415$, $h_0^* = 0.5$, and $R_c = 6.41 \text{ mm}$).

Section 5.4: Sub-cavity Volume Radial Film Thickness Profile Preprocessing

Sub-cavity liquid film thickness values at intermediate radii were linearly interpolated for each time step to increase the resolution of the volume calculations. The filtered and interpolated

cavity film thickness histories were utilized in the radial interpolation. This typically resulted in an additional 95 histories between each measured radial location. An example surface contour plot of the final interpolated sub-cavity film thickness plotted versus time and radius is shown in Figure 5.2.

Section 5.5: Sub-cavity Volume Iterative Technique

The desired sub-cavity liquid volume was computed as the integral of the measured $h(R)$ at each time, as in Equation 5.1. The desired volume consisted of the “floor” of the example surface contour plot shown in Figure 5.2 b), basically in the dark blue region of the plot (roughly $120 < h < 160 \mu\text{m}$). The sub-cavity thickness surface plots such as the sample in Figure 5.2 b) have been constructed from assembling each of the individual film thickness histories at different radii for the same droplet impact conditions.

Two issues arose in determining the sub-cavity volume: first, at what time to begin computing these volumes, and second, the choice of the radial location at which to end the integration at each time. The difficulty was generally due to a film thickness fillet versus time (referred to herein as a time fillet) as the cavity propagates to the impact surface and transitions into a (nearly) uniform film thickness after droplet impact. There is also a spatial fillet of thickness variation as the film transitions into the crown wall at each time, referred to herein as the cavity fillet. Figure 5.2 a) shows an example of the time fillet and in Figure 5.2 b) the cavity fillets are observable at the outer radial locations. Determining how much of the spatial fillets to include in the volume calculation proved challenging as most of the fillet is too thick and has too short of a lifetime to be expected to contribute to the cavity dry out. As of this time, a universal set of conditions to determine this transition have not been developed.

a) b)
Figure 5.2: Interpolated and filtered sub-cavity film thickness vs. time and mapped cavity ($We = 621$, $Re = 2,640$, $Fr = 415$, and $h_0^* = 0.5$). a) Centerline thickness history. b) Sub-cavity thickness surface plot (Hillen *et al.* 2013).

Rather than use an arbitrary set of conditions to define the beginning of the sub-cavity liquid film region and the maximum radial integration limit, the following iterative process was developed. Volumes defined using Equation 5.1 were integrated radially outward using the trapezoidal rule. More specifically, at each time of interest the integration stops at several different radial locations corresponding to a film thickness beyond a selected film thickness constraint limit. The initial film thickness constraint limits were chosen as the average constant minimum film thickness on the drop impact centerline and 2.5 times this value, along with three equally spaced intermediate values. The minimum film thickness constraint value proved inappropriate since this value would fail to capture a significant portion of the sub-cavity volume of interest while twice its value resulted in exaggerated results. The lowest constraint limit was increased until sub-cavity volume curves with minimal noise were produced that had realistic trends consistent with those computed with the upper limit. The upper constraint limit was then decreased until peaks due to steep slopes in the time fillets shown Figure 5.2 a) at the beginning of the upper limit iteration were damped out. The upper constraint was further refined such that the differences in the volume trends began to converge at the upper bounds. The percent variation between sub-cavity volumes for the final film thickness

constraints in Figure 5.3 b) range from 0.61% to 1.26% between $12 \leq t \leq 28$ msec, with an overall average variance of 0.92%. Generally, the final upper and lower constraints were within 1.2 - 1.4 times the averaged minimum film thickness along the droplet impact centerline. This process is summarized visually in Figures 5.4 a) and b), respectively, for the example sub-cavity volumes shown in Figures 5.3 a) and b), using the initial and final film thickness constraint results shown in Figures 5.2 a) and b).

Figure 5.3: Example of the iterative process of the sub-cavity volume trends vs. time ($We = 621$, $Re = 2,640$, $Fr = 415$, and $h_0^* = 0.5$). a) Initial constraints of the averaged and 2.5 times the minimum h . b) Final constraints (approximately 1.2 - 1.4 times the minimum h) (Hillen *et al.* 2013).

Further refinement and confirmation of realistic constraints were obtained by comparing the constraint limits with the corresponding droplet impact centerline history such as in Figure 5.2 a) and surface plots that are cropped using the film thickness constraint limits used to determine the radial limit. Figures 5.4 a) and b) shows cavity surface contour plots cropped and rescaled to the respective initial lower and upper constraint limits. Consistent with the sub-cavity volume trends in Figure 5.3 a), the constraint limits used in Figures 5.4 a) and b) significantly underestimate and overestimate the sub-cavity volume. In Figure 5.4 a) the minimum film thickness constraint limit caused the integration to end at nominally $R_c = 2$ mm neglecting most of the cavity region of interest. Too much

of the time and cavity fillets were included for the initial upper constraint of 2.5 times the minimum film thickness as depicted in Figure 5.4 b). Figures 5.4 c) and d) are the corresponding cropped and rescaled cavity profiles for the final constraint limits, displaying a realistic representation of the sub-cavity liquid film thickness profile versus radius and time. The sub-cavity volumes computed with the middle film thickness constraint obtained at the end of the iterative process have been selected as the best representation for the final sub-cavity volume results presented in Section 7.8.

Figure 5.4: Cropped cavity surface plots ($We = 621$, $Re = 2,640$, $Fr = 415$, and $h_0^* = 0.5$). a) Initial lower limit constraint. b) Initial upper limit constraint. c) Final iterated lower limit constraint. d) Final iterated upper limit constraint (Hillen *et al.* 2013).

Section 5.6: Sub-cavity Volume Accuracy Check

A check of the accuracy of the adopted sub-cavity volume calculation process was obtained through the following procedure. The computed weighted average of the sub-cavity minimum film

thickness, versus time and radius, found as depicted for the example discussed in Figures 5.1 - 5.4, is shown in Figure 5.5.

Figure 5.5: Estimated global minimum sub-cavity film thickness versus time.

The averaged minimum film thickness was multiplied by the cavity total area versus time which was computed using the measured sub-cavity radius versus time. Figure 5.6 shows that volumes computed using the sub-cavity radii from the SV and BV were on the same order of magnitude as the volumes computed by the main process. In fact, sub-cavity volume estimates using the cavity radii obtained by the BV method gave reasonably good agreement with the sub-cavity volumes computed by numerical integration and the main iterative method for this one case that was explained.

Figure 5.6: Sub-cavity volumes computed from the optimized numerical integration method compared with estimates using the averaged h_{min} and R_c (Hillen *et al.*, 2013).

CHAPTER 6: SPRAY RESULTS AND DISCUSSION

Section 6.1: Introduction

Results presented in chapter consist of the characterization of the spray of interest via PDPA, both with and without the impact surface in place. An initial form of these results has been presented in Hillen and Kuhlman (2013a). The spray droplet diameter and velocity results without the impact surface installed have been utilized in creating the single droplet sub-cavity film thickness experimental test matrix.

Spray droplet size and velocity trends and effects of varying the nozzle flow conditions without the impact surface installed are reported in Section 6.2. Also, the effects of varying the standoff measuring distance from the nozzle are examined. The section is concluded with the nozzle of interest characterized in terms of a single set of dimensionless Weber, Reynolds, and Froude numbers at each nozzle pressure.

Data for the characterization of the splashed spray droplets generated by the spray impinging onto the impact surface are documented in Section 6.3. The incoming spray droplet data with the impact surface installed have been compared with the corresponding basic spray results (spray measurements without the impact surface installed). The trends and effects of varying the flow conditions on the splashed droplets are discussed in this section. Splashed droplet data measured traversing vertically to the side of the impact surface are reported for comparison with the splashed data collected for radial traverses above the impact surface. Weber, Reynolds, and Froude numbers were also computed for the integrated global averages of the splashed droplets to investigate if the splashed droplets contribute to cavity formation.

The limitations of PDPA to measure volume fluxes are briefly discussed in Section 0.0. The development of the detailed test matrix for relevant spray conditions is then detailed in Section 6.5.

Section 6.2: Spray Results and Discussion: Without Spray Impact Surface Installed

The data presented in this section focuses on the droplet diameter and velocity distributions measured using PDPA in the spray of interest without the impact surface installed. Figure 6.1 presents typical sample histograms of the spray data for the highest pressure case (4.14 bar gage pressure) listed in Table 3.3 at two measuring locations: at the spray center ($R_s = 0$ cm), and at the spray edge ($R_s = 2.47$ cm) for a standoff distance of $z = 3.81$ cm. Data rates were much larger towards the center of the spray region due to a higher flux of droplets. Also, droplet sizes were noticeably smaller at the centerline than the edge of the spray, and a double peak in the droplet diameters can be noticed in Figure 6.1 a). Further comparison of Figures 6.1 a) and b) shows that the two locations share similar overall droplet velocity magnitudes and trends. However the droplets at $R_s = 0$ cm in Figure 6.1 a) have much larger axial velocities and a nearly negligible average radial velocity component compared to droplets at $R_s = 2.47$ cm in Figure 6.1 b) which have relatively high radial velocities, but smaller axial velocities. This is reasonable since the droplets at the center of the spray should be moving virtually normal to the nozzle. Also, the droplet radial velocity should increase with the impact angle away from the centerline. Additional sample histograms similar to those in Figure 6.1 for $R_s = 0$ cm and $R_s = 2.47$ cm at $z = 3.81$ cm for the two lower pressure cases in Table 3.3 are provided in Appendix B.

Figure 6.1: Spray droplet diameter, speed, axial velocity, and radial velocity for a 4.14 bar and 54.5 L/hr at $z = 3.81$ cm. a) Center of the spray, $R_s = 0$ cm. b) Edge of spray, $R_s = 2.47$ cm.

Section 6.2.1: Spray Trends and Effects of Varying the Nozzle Flow Condition

The effects of varying the spray pressure and flow rate on the arithmetic and Sauter mean diameters at $z = 3.81$ cm are shown in Figure 6.2 a) and b) respectively. It was observed that increases in pressure and flow rate generated smaller droplets, which was consistent with similar results presented by Kalantari and Tropea (2007), and Winkler and Peters (2002). Consistent with Figure 6.1, the arithmetic mean droplet sizes in Figure 6.2 a) decrease near the spray centerline where the spray is the most atomized. Centerline arithmetic mean diameters in Figure 6.2 a) are nominally 47 μm , 54 μm , and 74 μm for the respective 4.14 bar, 2.76 bar, 1.38 bar spray gage pressures. The studied spray produced nearly constant Sauter mean diameters of nominally 110 μm , 130 μm , and 170 μm for the respective 1.38 bar, 2.76 bar, and 4.14 bar spray cases across the span of the spray as shown in Figure 6.2 b). Evidence that the spray cone was not fully formed for the 1.38 bar, 29.5 L/hr spray can be observed in the variations in the arithmetic mean diameters past $R_s = \pm 20$ mm in Figure 6.2 a). Good agreement is observed between the x and y -axis profiles for both the arithmetic and Sauter mean diameters. Uncertainty bars based on 95% confidence interval shown in Figure 6.2 are presented at the spray center ($R_s = 0$ cm), edge ($R_s = 2.68$ cm), and half way in between ($R_s = 1.34$ cm).

a) b)
Figure 6.2: Droplet diameter profiles at a constant $z = 3.81$ cm for the different pressure cases with uncertainty bars. a) Arithmetic mean diameter. b) Sauter mean diameter. $\blacktriangle$ $\triangle$ 1.38 bar, 29.5 L/hr; $\bullet$ $\circ$ 2.76 bar, 43.5 L/hr; $\blacklozenge$ $\diamond$ 4.14 bar, 54.5 L/hr; — x-plane data; ---- y-plane (Hillen *et al.*, 2013).

The global average difference of the D profiles between different pressure settings are decreases of 22.9 μm , 12.4 μm , and 35.3 μm between the respective flow conditions of 1.38 - 2.76 bar, 2.76 - 4.14 bar, and 1.38 - 4.14 bar. The corresponding differences for the D_{32} profiles between different pressure settings are 35.9 μm , 20.4 μm , and 56.4 μm between the flow conditions of 1.38 - 2.76 bar, 2.76-4.14 bar, and 1.38 - 4.14 bar, respectively.

Figure 6.3 shows the effects of the nozzle pressure and flow rate on the average droplet velocity component profiles. It was observed that increasing the nozzle flow rate and pressure resulted in higher droplet speeds and greater droplet incidence angles towards the cone edge. Consistent with Figure 6.1 the average axial velocity increases and the radial velocity decreases to virtually zero at $R_s = 0$ mm when approaching the spray centerline. Maximum axial velocities from Figure 6.3 a) were measured to be nominally 9.8 m/s, 14 m/s, and 18 m/s for the respective flow conditions of 1.38 bar, 2.76 bar, 4.14 bar. The largest radial velocities measured in Figure 6.3 b) are nominally 4.1 m/s, 5.5 m/s, 6.4 m/s for the respective flow conditions of 1.38 bar, 2.76 bar, and 4.14 bar. Measurements showed negligible swirl velocity as was expected for this non-swirl nozzle. The

radial velocity component in Figure 6.3 b) could only be measured along the x -axis of the spray, since the PDPA measured the swirl velocity component for the y -axis traverse. The average axial velocities that have been recorded along the y -axis exhibit some discrepancy with the measurements along x -axis over most of the spray. It is believed that this is due to the PDPA measuring volume length being much longer than its diameter as listed in Table 3.1, resulting in the y -axis profile being less sensitive to the density of the spray. Uncertainty bars shown in Figure 6.3 are presented at the spray center ($R_s = 0$ cm), edge ($R_s = 2.68$ cm), and half way in between ($R_s = 1.34$ cm). The methodology used in determining the uncertainty bars in Figures 6.2 and 6.3 will be explained in Section 6.2.2.

Figure 6.3: Spray flow condition effects on the mean spray velocity components at $z = 3.81$ cm with uncertainty bars. a) Mean axial velocity profile. b) Mean radial velocity profile (Hillen *et al.*, 2013).

The global average difference of the V_{axial} profiles between the different pressure settings are increases of 2.96 m/s, 2.07 m/s, and 5.02 m/s for the respective flow conditions of 1.38 - 2.76 bar, 2.76 - 4.14 bar, and 1.38 - 4.14 bar. The corresponding differences for the V_r profiles between pressure settings are increases of 0.906 m/s, 0.597 m/s, and 1.50 m/s for the respective flow conditions of 1.38 - 2.76 bar, 2.76 - 4.14 bar, and 1.38 - 4.14 bar, respectively.

Appendix B contains the graphs similar to Figures 6.2 and 6.3, but for data collected at standoff distances of $z = 3.18$ and 4.45 cm in addition to the velocity magnitude for all z profile locations. The spray profile graphs shown in Appendix B followed identical trends observed in Figures 6.2 and 6.3 when the spray pressure and flow rate were varied.

Section 6.2.2: Uncertainty Analysis of PDPA Spray Data (No Target Surface)

An uncertainty analysis of the PDPA spray results has been performed for the data presented in Section 6.2.1. There are three main contributing factors to the uncertainty in the PDPA measurements for the D , D_{32} , V_{axial} , and V_r : the 0.75% instrumentation uncertainty reported by the manufacturer, the statistical fluctuation of the data for each measurement location, and the uncertainty between the x and y -traverse profiles due to the spray density effects on the PDPA probe volume (referred to as the PDPA probe volume uncertainty). The uncertainty for V_r consists of only the statistical fluctuation and instrumentation uncertainty since the y -profile is the swirl velocity which is 0 m/s, so there is no way to quantify this effect on V_r .

As mentioned in Section 6.2.1 there is difference in the measurements between the x and y -axis profiles even though it was an axisymmetric spray. This difference between the x and y -axis profiles is the PDPA probe volume uncertainty. This uncertainty is due to data taken for the x -traverse experiencing more interference from the spray density as shown in Figure 6.4. The transmitting and receiving optics were located on the $+y$ portion of the spray.

Figure 6.4: A sketch of the PDPA probe volume at equal R_s locations on the x and y -axis to demonstrate the increased interference of the x -traverse due to the spray density.

The PDPA probe volume uncertainty for each corresponding spatial location is computed by:

$$\Delta(\Psi)_{PV} = |\Psi_x(R_s) - \Psi_y(R_s)| \quad 6.1$$

The symbol $\Psi_{x \text{ or } y}(R_s)$ represents the average value of D , D_{32} , V_{axial} , or V_r at a distance from the spray axis. The subscript x denotes values measured along the x -traverse. Because the x -traverse extended across the spray axis, values were computed according to $\Psi_x(R_s) = \frac{1}{2}[\Psi(x = R_s) + \Psi(x = -R_s)]$. The subscript y denotes values measured along the y -traverse, which did not fully extend across the axis. It should be noted that since the y -traverse measured the swirl velocity a PDPA probe volume uncertainty cannot be computed for the radial velocity component. Table 6.1 contains the global average, maximum, and minimum PDPA probe volume uncertainty between the x and y -axis measurements for the arithmetic and Sauter mean diameters in Figure 6.2. There is very little variation between the two measuring profiles in Table 6.1 further supporting good agreement between the x and y -axis measurements. The larger differences in D for $P = 1.38$ bar is due to the spray cone not being fully formed resulting in data fluctuations towards the spray edges as shown in Figure 6.2 a).

Table 6.1: Average, maximum, and minimum PDPA probe volume uncertainty between the x and y -traverse profiles of the arithmetic and Sauter mean diameter for varying pressures at a constant $z = 3.81$ mm.

P (bar)	$\overline{\Delta(D)_{PV}}$ (μm)	$\Delta(D)_{PV_{max}}$ (μm)	$\Delta(D)_{PV_{min}}$ (μm)	$\overline{\Delta(D_{32})_{PV}}$ (μm)	$\Delta(D_{32})_{PV_{max}}$ (μm)	$\Delta(D_{32})_{PV_{min}}$ (μm)
1.38	2.82	6.42	0.214	7.82	21.0	0.142
2.76	0.767	2.20	0.0483	8.93	18.0	2.12
4.14	0.703	2.22	0.00284	7.56	13.9	1.25

Table 6.2 lists the global average, the maximum, and the minimum PDPA probe volume uncertainty for the axial velocity between the x and y -axis measurements in Figure 6.3. The global average V_{axial} PDPA probe volume uncertainty is lower since the equal area traversing method produces more data points towards the spray's edge where the data is in closer agreement. The maximum V_{axial} uncertainty generally occurs between $0 \leq R_s \leq 1.8$ cm where the measuring volume on the x -traverse has the largest interference from the spray density.

Table 6.2: Average, maximum, and minimum PDPA probe volume uncertainty between the x and y -axis measurements of the mean axial velocity for varying pressures at a constant $z = 3.81$ mm.

P (bar)	$\overline{\Delta(v_{axial})_{PV}}$ (m/s)	$\Delta(v_{axial})_{PV_{max}}$ (m/s)	$\Delta(v_{axial})_{PV_{min}}$ (m/s)
1.38	0.275	0.930	0.00686
2.76	0.442	1.34	0.0863
4.14	0.497	1.29	0.0120

The statistical fluctuation uncertainty is based on the variation of the measured droplet characteristics, the total number of measurement samples, and its corresponding decorrelation sample index at a specified radial location. Equation 6.2 is an attempt to quantify this uncertainty for both the x and y -axis measurements even though the PDPA samples are at random increments and not at equal time samples. The equation is rigorously valid for data taken with a constant time interval between samples for a stationary signal, but for PDPA the sample interval varies.

$$\Delta(\psi(R_s))_{stat} = \frac{std(\psi(R_s))}{\sqrt{\frac{N}{n_{dec}}}} \quad 6.2$$

The $\psi(R_s)$ represents the individual values of d , v_{axial} , and v_r at a distance R_s from the spray axis. Statistical fluctuation uncertainties were computed for the x and y -axis measurements at radial locations of 0, 1.34, and 2.68 cm. These were not calculated for the radial velocity for the y -axis measurements since it is the swirl velocity. The total number of measured samples (N) used in Equation 6.2 is based on either the PDPA system's time out (30 sec), or total sample limit (50,000) listed in Table 3.1. The decorrelation sample index in Equation 6.2 was computed from the indexed total measurement sample to ensure the correct value. Figure 6.5 is example of the axial velocity correlation coefficient versus the sample index for a flow condition of 4.14 bar and 54.5 L/hr at $R_s = 0$ cm and $z = 3.81$ cm, where the decorrelation sample index was taken as the separation between the sequential data sample where the correlation coefficient decays to zero.

Figure 6.5: Example of the correlation coefficient versus the sample index for the axial velocity for a flow condition of 4.14 bar and 54.5 L/hr at $R_s = 0$ cm and $z = 3.81$ cm.

Table 6.3 contains the total measurement sample size and decorrelation sample index values for the measurements located at $R_s = 0, 1.34, 2.68$ cm for the three pressure cases. Typically the total measurement samples are similar between the x and y -traverses except at $R_s = 1.34$ cm where the x -axis measurements have nominally 2,000 - 5,000 more samples. The decorrelation sample index values are all generally small for the droplet characteristics, ranging in value from 3 to 12.

Table 6.3: The total measurement sample and the decorrelation sample index of the droplet diameter, axial velocity, and radial velocity at $z = 3.81$ cm for the x and y -traverses (no $n_{dec}(v_r)$ for the y -traverse).

P (bar)	R_s (cm)	N_x	$n_{dec}(d)_x$	$n_{dec}(v_{axial})_x$	$n_{dec}(v_r)_x$	N_y	$n_{dec}(d)_y$	$n_{dec}(v_{axial})_y$
1.38	0	26,967	8	3	6	27,306	6	3
	1.34	8,590	4	3	4	6,503	4	3
	2.68	643	7	3	3	694	3	3
2.76	0	50,000	4	8	5	50,000	3	8
	1.34	27,406	3	5	5	22,556	4	4
	2.68	3,092	2	3	2	2,893	5	4
4.14	0	50,000	5	7	5	50,000	4	12
	1.34	48,364	3	7	12	44,611	4	5
	2.68	6,923	2	5	5	6,257	4	3

The standard deviation in the measurements of the d , v_{axial} , and v_r used in Equation 6.2 are listed in Table 6.4. The deviation in the data is similar between the corresponding x and y -axis profiles with the largest deviation in the velocities occurring at $R_s = 1.34$ cm. The deviation for the droplet diameters decreased and the deviation of the velocity components increased with increasing the pressure.

Table 6.4: The standard deviation of the droplet diameter, axial velocity, and radial velocity at $z = 3.81$ cm for the x and y -traverses (no $std(v_r)$ for the y -traverse).

P (bar)	R_s (cm)	$std(d)_x$ (um)	$std(v_{axial})_x$ (m/s)	$std(v_r)_x$ (m/s)	$std(d)_y$ (um)	$std(v_{axial})_y$ (m/s)
1.38	0	57.9	1.69	0.629	59.0	1.75
	1.34	56.2	2.80	1.15	56.3	2.61
	2.68	55.4	2.46	1.76	59.6	2.23
2.76	0	42.0	2.30	0.729	41.8	2.31
	1.34	40.2	3.65	1.56	39.2	3.56
	2.68	43.1	3.17	2.29	40.1	2.89
4.14	0	35.7	2.78	0.843	36.4	2.76
	1.34	32.9	4.32	1.86	29.8	4.29
	2.68	34.2	3.55	2.63	34.2	3.45

The final statistical fluctuation uncertainty of the droplet characteristics for the x and y -axis profiles for the varying pressure and radial locations are presented in Table 6.5. These uncertainties

have been computed with the values presented in Tables 6.4 and 6.3 using Equation 6.2. The most notable statistical fluctuation in the data is for the droplet diameter at the edge of the spray at $P = 1.38$ bar for both traverse profiles. This, is again, due to the spray cone not being fully formed and atomized at this flow condition. The uncertainty of the x and y -axis measurements are similar.

Table 6.5: The statistical fluctuation uncertainty of the droplet diameter, axial velocity, and radial velocity at $z = 3.81$ cm for the x and y -traverse profiles (no $\Delta(v_r)_{stat}$ for the y -traverse).

P (bar)	R_s (cm)	$\Delta(d)_{stat_x}$ (μm)	$\Delta(v_{axial})_{stat_x}$ (m/s)	$\Delta(v_r)_{stat_x}$ (m/s)	$\Delta(d)_{stat_y}$ (μm)	$\Delta(v_{axial})_{stat_y}$ (m/s)
1.38	0	0.998	0.0178	0.00939	0.874	0.0183
	1.34	1.21	0.0523	0.0247	1.40	0.0561
	2.68	5.78	0.168	0.120	3.918	0.146
2.76	0	0.376	0.0291	0.00729	0.324	0.0292
	1.34	0.421	0.0493	0.0210	0.522	0.0474
	2.68	1.10	0.0986	0.0583	1.67	0.108
4.14	0	0.357	0.0329	0.00843	0.325	0.0427
	1.34	0.259	0.0519	0.0292	0.282	0.0454
	2.68	0.581	0.0954	0.0706	0.866	0.0755

The total uncertainty for the PDPA spray data for D and V_{axial} in Section 6.2.1 is computed through the following equation:

$$\Delta(\Psi(R_s))_{total} = \sqrt{(2 * \Delta(\psi(R_s)_{stat})^2 + [\frac{1}{2}\Delta(\Psi)_{PV_{max}}]^2 + \Delta(\Psi(R_s))_{0.75\%}^2} \quad 6.3$$

The symbol $\Delta(\Psi(R_s))$ represents an overall uncertainty estimate for D , D_{32} , V_{axial} , or V_r at a distance R_s from the spray axis. The subscripts *stat*, *PV*, and 0.75% represent the respective statistical fluctuation uncertainty, the PDPA probe volume uncertainty, and instrumentation uncertainty. Half of the maximum $\Delta(\Psi)_{PV}$ from Tables 6.1 and 6.2 was determined to give the best representation of the PDPA probe volume uncertainty between the x and y -traverse results. As previously mentioned PDPA probe volume uncertainties were not attainable for the radial velocity, thus it has been excluded in Equation 6.3 for $\Delta(V_r(R_s))_{total}$. The contributions of the statistical fluctuation to the total uncertainty are generally very small. The dominant uncertainty is the maximum PDPA probe volume

uncertainty. Table 6.6 summarizes the total uncertainty computed for D , D_{32} , V_{axial} , and V_r . These are the values used for the uncertainty bars for the corresponding Figure 6.3 and Figure 6.4 presented in Section 6.2.1. Typically the smallest total uncertainties occur at the middle of the spray ($R_s = 0$ cm) and increase towards the edge of the spray ($R_s = 2.68$ cm). This is most prevalent for the D and D_{32} at $R_s = 2.68$ cm for the 1.38 bar spray. The x and y -axis profiles generally have similar uncertainties between them.

Table 6.6: The total uncertainty of the droplet diameter, axial velocity, and radial velocity at $z = 3.81$ cm for the x and y -traverses (no $\Delta(V_r)_{total}$ for the y -traverse).

P (bar)	R_s (cm)	$\Delta(D)_{total_x}$ (μm)	$\Delta(D_{32})_{total_x}$ (μm)	$\Delta(V_{axial})_{total_x}$ (m/s)	$\Delta(V_r)_{total_x}$ (m/s)	$\Delta(D)_{total_y}$ (μm)	$\Delta(D_{32})_{total_y}$ (μm)	$\Delta(V_{axial})_{total_y}$ (m/s)
1.38	0	3.82	10.8	0.472	0.00942	3.67	3.698	0.472
	1.34	4.08	10.8	0.480	0.0304	4.31	4.307	0.482
	2.68	12.0	15.7	0.576	0.124	8.51	8.509	0.551
2.76	0	1.39	9.09	0.681	0.0146	1.34	9.080	0.681
	1.34	1.47	9.09	0.682	0.0480	1.59	9.110	0.681
	2.68	2.53	9.32	0.702	0.124	3.57	9.642	0.706
4.14	0	1.37	7.04	0.662	0.0169	1.33	7.004	0.657
	1.34	1.29	7.02	0.661	0.0645	1.31	7.010	0.658
	2.68	1.69	7.09	0.677	0.149	2.13	7.210	0.667

The Sauter mean diameter results presented in Figure 6.2 b) noticeably varies by radial location resulting in lower quality data compared to the arithmetic mean diameters in Figure 6.2 a). The variation of D_{32} along R_s is due to the larger droplets being weighted more heavily. These larger droplets are more inconsistent in their frequency compared to the smaller droplets. In addition the D_{32} can change by as much as 20 to 25% if a few larger droplets are filtered out by the PDPA software. Table 6.7 lists the spatial standard deviation of D_{32} across $0 \leq R_s \leq 2.68$ cm in Figure 6.2 b). This spatial variation decreases with pressure and is marginally more pronounced in the y -axis profile. This observed spatial variation in the measured Sauter mean diameters has not been separately included in the overall estimated uncertainties using Equation 6.3.

Table 6.7: Spatial standard deviation of D_{32} across $0 \leq R_s \leq 2.68$ cm for varying flow conditions at $z = 3.81$ cm.

P (bar)	$std(D_{32})_x$ (um)	$std(D_{32})_y$ (um)
1.38	6.37	8.56
2.76	5.09	6.84
4.14	5.09	6.41

Section 6.2.3: Effects of Varying the Standoff Distance

As initially reported by Hillen *et al.* (2013) it was found that variation in the data between $z = 3.18, 3.81$, and 4.45 cm was minor. This conclusion is supported by Figure 6.6 which consists of the measured spray droplet arithmetic mean diameters, Sauter mean diameters, and the velocity components for a constant spray condition of 4.14 bar and 54.5 L/hr. The effects varying z for the given range on the diameter size is shown to be negligible in Figures 6.6 a) and b). Very small decreases in the average axial and radial velocity profiles can be observed in Figures 6.6 c) and d) as z is increased. The differences are due to the shorter standoff distances being closer to the nozzle exit where the drops have been exposed to less drag due to air resistance, but, again, the variation is minor. The trends shown in Figure 6.6 were similar for the variation of the standoff distances for the lower spray conditions of 1.38 bar, 29.5 L/hr and 2.76 bar, 43.5 L/hr with the corresponding plots presented in Appendix B including the respective average velocity magnitudes.

Figure 6.6: Variation of the standoff distance of the measuring profile to the nozzle for a spray flow condition of 4.14 bar and 54.5 L/hr. a) Arithmetic mean diameters. b) Sauter mean diameters. c) Average axial velocities. d) Average radial velocities.

Section 6.2.4: Spray Nozzle Droplet Size and Velocity Characterization

Spray droplet and velocity profiles measured using PDPA have been utilized to compute global integrated average values of the dimensionless Weber, Reynolds, and Froude numbers to characterize the sprays at each nozzle pressure. Droplet and velocity data listed in Table 6.8 have been computed via a global average across the span of the spray encompassing every performed spray scenario (such as the example given in Figures 6.2 and 6.3) without the impact surface installed. The global integrated average of the x and y -axis mean arithmetic mean diameter, Sauter mean diameter, and axial velocity profiles have been used to compute the values listed. The global

averages of the spray profiles are consistent with the trends discussed in the previous Sections 6.2.1 and 6.2.2. Note that because the radial traverse locations were selected such that each data point corresponded to an equal (annular) area, this global averaging corresponds exactly to integrating in cylindrical coordinates and dividing by the circular area.

Table 6.8: Global integrated average of spray droplet characteristics across $-2.54 \leq R_s \leq 2.54$ cm.

P (bar)	z (cm)	D (μm)	D_{32} (μm)	V_{axial} (m/s)	V_r (m/s)	V (m/s)
1.38	3.18	90.8	167.7	7.36	3.25	8.18
	3.81	93.9	171.6	7.55	2.78	8.13
	4.45	95.1	175.1	7.51	2.34	7.93
2.76	3.18	70.5	133.9	10.4	4.41	11.5
	3.81	71.0	135.7	10.5	3.68	11.3
	4.45	70.6	135.7	10.2	3.04	10.8
4.14	3.18	59.3	116.2	12.6	5.18	13.8
	3.81	58.7	115.2	12.6	4.28	13.4
	4.45	57.5	114.3	12.4	3.53	13.0

The dimensionless Weber, Reynolds, and Froude numbers characterizing the spray presented in Table 6.9 have been computed with the global arithmetic and Sauter mean diameters listed in Table 6.8. The arithmetic average diameters gave more weight to the smaller droplets that form the majority of the spray population while the Sauter mean diameter weighted more heavily the larger droplets. The global averages of the mean axial velocity profiles were used in computing the dimensionless numbers in Table 6.9 since the majority of the correlations developed for single drops experiments in the literature including those listed in Table 2.2 are based on the axial velocity. The Weber numbers computed based on D are less than or very near to (at the lower spray flow conditions) the typical Weber number criterion found in Table 2.2 for the onset of splashing while the Weber number values computed based on D_{32} are all above this threshold.

Table 6.9: Characterization of the spray in terms of the average We , Re , and Fr for each spray condition. Dimensionless numbers were computed using the axial velocity component.

P (bar)	z (cm)	Calculated with D			Calculated with D_{32}		
		We	Re	Fr	We	Re	Fr
1.38	3.18	68	666	60,800	125	1,230	33,000
	3.81	73	706	61,800	134	1,290	33,800
	4.45	73	711	60,500	135	1,310	32,800
2.76	3.18	105	733	158,000	200	1,390	83,000
	3.81	107	743	158,000	205	1,420	82,900
	4.45	101	720	151,000	195	1,380	78,600
4.14	3.18	128	742	272,000	252	1,460	139,000
	3.81	127	735	275,000	250	1,440	140,000
	4.45	120	707	271,000	239	1,410	136,000

In addition to the dimensionless numbers based on the global diameter and velocity averages, values have also been computed for the 5% population of diameters consisting of the largest and the 5% population consisting of the smallest droplets for each flow condition at the spray center ($R_c = 0$ mm) and edge ($R_c = 2.47$ cm). Table 6.10 contains the droplet arithmetic mean and Sauter mean diameters along with the mean velocity components computed from the 5% of the population consisting of the smallest droplets. These droplets are very small and relatively slow compared to the global averages in Table 6.8.

Table 6.10: Mean drop characteristics calculated from the 5% population consisting of the smallest droplets at $z = 3.81$ cm.

P (bar)	R_s (cm)	D (μm)	D_{32} (μm)	V_{axial} (m/s)	V_r (m/s)	V (m/s)
1.38	0	8.68	10.0	8.68	0.0396	8.73
	2.47	15.3	20.6	5.48	3.35	6.46
2.76	0	8.67	9.64	12.7	0.0877	12.8
	2.47	15.9	21.5	8.36	4.78	9.71
4.14	0	7.79	8.61	15.9	0.117	15.9
	2.47	14.8	19.2	11.0	6.24	12.7

The average droplet arithmetic and Sauter mean diameter in Table 6.10 were used to compute the dimensionless numbers found in Table 6.11 for the 5% population consisting of the smallest droplets. These smallest droplets were generally within the drop rebound/deposition criteria defined

in Table 2.2 and their mass only contributed up to 0.03% of the total spray mass. Thus these droplets were of little interest and were not incorporated into the single drop sub-cavity film thickness matrix to be presented in Section 6.5.

Table 6.11: Dimensionless numbers calculated from the 5% population consisting of the smallest droplets at a constant $z = 3.81$ cm.

P (bar)	R_s (cm)	Calculated with D			Calculated with D_{32}		
		We	Re	Fr	We	Re	Fr
1.38	0	8.96	75.0	885,000	10.3	86.6	767,000
	2.47	6.29	83.5	200,000	8.45	112	149,000
2.76	0	19.2	110	1,910,000	21.4	122	1,710,000
	2.47	15.2	132	448,000	20.7	179	331,000
4.14	0	26.8	123	3,290,000	29.6	136	2,980,000
	2.47	24.5	162	828,000	31.7	210	640,000

Droplet arithmetic and Sauter mean diameters along with the mean velocity components averaged over the 5% of the population consisting of the largest droplets are presented in Table 6.12. These droplets are significantly larger and faster than the global Sauter mean droplet diameters listed in Table 6.8, and thus are expected to be significant contributors to cavity formation in the residual liquid film.

Table 6.12: Mean drop characteristics calculated from the 5% population consisting of the largest droplets at a constant $z = 3.81$ cm.

P (bar)	R_s (cm)	D (μm)	D_{32} (μm)	V_{axial} (m/s)	V_r (m/s)	V (m/s)
1.38	0	204	214	10.4	0.0799	10.4
	24.7	223	234	8.80	5.43	10.4
2.76	0	154	165	15.6	0.0910	15.6
	24.7	184	190	12.3	7.34	14.3
4.14	0	141	154	19.5	0.0934	19.5
	24.7	157	168	14.8	8.93	17.3

Table 6.13 contains the dimensionless averaged We , Re , and Fr numbers computed from the corresponding average data for the 5% population of the largest spray droplets listed in Table 6.12. This range is also considered to be relevant because these droplets make upwards of 39.3% of the

total spray mass. In addition all of these averaged Weber numbers are in the range where cavity formation is expected (see Table 2.2). The highest Weber number computed ($We = 802$) has been used as a guide to set the upper limit of the Weber number for the single droplet test matrix to be discussed in Section 6.5.

Table 6.13: Average dimensionless numbers calculated from the 5% population consisting of the largest droplets at a constant $z = 3.81$ cm.

P (bar)	R_s (mm)	Calculated with D			Calculated with D_{32}		
		We	Re	Fr	We	Re	Fr
1.38	0	302	2,110	54,200	318	2,220	51,500
	24.7	244	2,020	34,400	249	2,050	33,800
2.76	0	512	2,390	160,000	549	2,560	149,000
	24.7	381	2,250	83,600	393	2,320	81,000
4.14	0	734	2,740	275,000	802	2,990	252,000
	24.7	471	2,310	143,000	503	2,470	133,000

Section 6.3: Splash Results and Discussion: Spray Impact Surface Installed

This section focuses only on the splashed droplets generated by the spray impinging onto the installed impact surface. These results are expected to have no influence on the single drop test matrix presented in Section 6.5, but are documented for use in future work.

Section 6.3.1: Comparison of Spray with and without the Impact Surface Installed

A comparison was made in Figure 6.7 between the spray profiles measured at $z = 3.81$ cm presented in Section 6.2 without the impact surface installed and the spray droplet profiles that were extracted from the PDPA data measured at $z = 3.65$ cm with the impact surface installed. Good agreement for a flow condition of 1.38 bar, 29.5 L/hr can be observed in Figures 6.7 a) and b). At the two higher flow conditions of 2.76 bar, 43.5 L/hr and 4.14 bar, 54.5 L/hr the arithmetic mean diameter with the installed impact surface can vary as much as 15 and 21 μm , respectively, compared to the basic spray data. Also, in Figure 6.7 a) the diameter data for installed target spray is nearly constant for the two highest spray flow conditions and nearly identical. The velocity

components of the impact surface spray data in Figures 6.7 c) and d) are in better agreement with the basic spray and follow similar trends, though there is still noticeable variation.

Figure 6.7: Comparison of the spray droplet characteristics with ($z = 3.60$) and without ($z = 3.81$) the impact surface installed for 1.38 bar, 2.76 bar, 4.14 bar. a) Arithmetic mean diameter. b) Sauter mean diameter. c) Mean axial velocity. d) Mean radial velocity. $\blacktriangle$ 1.38 bar, 29.5 L/hr, with impact surface; $\bullet$ 2.76 bar, 43.5 L/hr, with impact surface; $\blacklozenge$ 4.14 bar, 54.5 L/hr, with impact surface; $\triangle$ 1.38 bar, 29.5 L/hr, without impact surface; $\circ$ 2.76 bar, 43.5 L/hr, without impact surface; $\diamond$ 4.14 bar, 54.5 L/hr without impact surface.

It is believed that the variations and disagreements found in Figure 6.7 are due to, at least in part, the denser spray region caused by the splashed droplets when the spray is impinging onto the impact surface. As previously discussed in Section 3.5.1, the quality of PDPA data can be affected by large droplet fluxes, which is why the best agreement is in the sparser spray at the lowest flow settings. An additional contributing factor, also discussed in Section 3.5.1, is the smaller population

on which to base the statistics for the impact surface spray since they are extracted from the overall PDPA data consisting of both the incoming spray droplets and the splashed droplets. Another plausible contributing factor could be the increased droplet-to-droplet interactions between the impinging spray droplets and the ejected splashed droplets. The abnormal spikes in data located between $-25 < R_s < -20$ mm for every plot presented in Figure 6.7 for the 1.38 bar, 29.5 L/hr impact surface spray are believed to be a combination of the aforementioned lower statistics and a not fully formed nozzle spray cone at the lowest pressure (see Section 6.2.1). Appendix C contains the corresponding comparison of the velocity magnitude between the basic spray and impact surface spray.

Section 6.3.2: Separated Splashed Droplet Components: Impact surface Installed

The PDPA data collected for a spray impinging onto the impact surface has been separated into their respective incoming spray and splashed droplet components as described in Section 3.5. Figure 6.8 depicts the arithmetic and Sauter mean diameters of the separated data for a nozzle flow condition of 4.14 bar, 54.5 L/hr in terms of the original spray, ejected splash, returning splash, and absolute splash droplets at $z = 3.65$ cm. Consistent with Kalantari and Tropea (2006) it was found that the splashed droplet sizes were the same order of magnitude as the spray droplets at all radial locations as shown in the respective arithmetic and Sauter mean diameters in Figures 6.8 a) and b). As discussed previously in Section 2.3.3 and observed experimentally, single drop impacts generally produce multiple splash droplets that are considerably smaller than the initial drop. Plausible contributors to the larger splash drop sizes include rebounding drops on the spray film liquid, and Worthington jet droplets, which are on the same size scale as the impinging droplet (see Section 2.3.3). Additional possible contributors include thicker crowns due to neighboring droplet impingement interactions, ejected film ligaments, and the droplet impingement angle (Kalantari and

Tropea, 2006). Another possible explanation includes drop-to-drop interactions where the splash droplets could merge forming larger droplets.

a) b)
Figure 6.8: Droplet sizes of the spray, ejected, return, and absolute splash data with the impact surface installed for a flow condition of 4.14 bar, 54.5 L/hr at a constant $z = 3.65$ cm. a) Arithmetic mean diameter. b) Sauter mean diameter.

Axial and radial mean velocities for the separated spray and splashed droplet components are shown in Figures 6.9 a) and b) respectively. As seen in Figure 6.9 a) the ejected splashed droplet mean axial velocities never exceed 2.5 m/s consistent with Kalantari and Tropea (2006) in which axial velocities were not observed exceeding 3 m/s. The returning splashed droplet mean axial velocity is comparable in magnitude to the ejected, yet it is noticeably slower with a maximum nominal mean axial velocity magnitude of 1.5 m/s. There was not a distinguishing difference in the radial velocity component observed between the different splashing types with measured mean radial velocities increasing nominally from 1.8 to 5 m/s, as shown in Figure 6.9 b). However, because radial splashed droplet velocities are similar in size to axial components, this signifies that the splashed droplets generally have a low trajectory angle with respect to the impact surface. Examining Figures 6.9 a) and b), increases in the ejected droplet axial velocity component correspond to a decreasing radial velocity component towards the spray centerline. This indicates that the splash droplets in this region are ejecting at greater angles from the surface. These results are

also consistent with those found in Kalantari and Tropea (2006). The spray, ejected splash, return splash, and absolute splash droplets for the flow conditions of 1.38 bar, 29.5 L/hr and 2.76 bar, 43.5 L/hr followed identical trends and behaviors to those described for Figures 6.8 and 6.9. The corresponding plots comparing the spray droplets and the various splash droplet categories for these two lower nozzle flow conditions are presented in Appendix C along with the corresponding velocity magnitude plots.

Figure 6.9: Droplet velocities of the spray, ejected, return, and absolute splash data with the impact surface installed for 4.14 bar, 54.5 L/hr at a constant $z = 3.65$ cm. a) Mean axial velocity, b) Mean radial velocity. $\diamond$ Incoming spray droplets, $\triangle$ ejected splashed droplets, $\square$ returning splashed droplets, $\bullet$ absolute splashed droplets.

Table 6.14 presents the global integrated average of the standard deviation for each measuring location of the splashed droplet characteristics. There is a large variance in the droplet diameter data suggesting that the population does contain the expected smaller splash droplets.

Table 6.14: The averaged standard deviation of the splash droplet characteristics averaged across $-2.54 < R_s < 2.54$ cm at $z = 3.65$ cm.

Splash Type	P (bar)	$std(d)$ (μm)	$std(v_{axial})$ (m/s)	$std(v_r)$ (m/s)	$std(v)$ (m/s)
Ejected	1.38	58.1	1.04	1.37	1.42
	2.76	42.1	1.43	1.60	1.76
	4.14	38.8	1.39	1.74	1.85
Return	1.38	58.5	1.00	1.32	1.37
	2.76	42.9	1.38	1.57	1.73
	4.14	38.7	1.34	1.72	1.82
Absolute	1.38	54.4	1.28	1.88	2.02
	2.76	40.9	1.46	1.95	2.11
	4.14	37.1	1.50	1.95	2.09

Section 6.3.3: Effects of Varying the Nozzle Flow Conditions on the Splashed Droplet Components

Since all three splashed droplet types follow similar trends, the absolute splash droplets are utilized in Figure 6.10 to demonstrate the influence of spray flow conditions on the splashed droplet behavior. Figures 6.1 a) and b) show that the spray flow conditions have a negligible effect on the arithmetic and Sauter mean droplet diameters except for the 1.38 bar, 29.5 L/hr case where the Sauter mean droplet diameter is nominally 63 μm larger. The lack of variation in the droplet mean size could be attributed to the lack of adequate quality in the statistical data available for the PDPA spray impact surface data. The flow conditions also have a nearly negligible effect on the mean axial velocity of the splashed droplets with a maximum difference of 0.13 m/s for the example shown in Figure 6.10 c). Of the available data the only definitive splashed droplet trend observed with increasing the spray pressure and flow rate was for the mean radial velocity shown in Figure 6.10 d). Towards the spray edge the mean radial velocity of the splash droplets increases with the nozzle pressure and flow rate. This is reasonable since the spray cone angle increases from 1.38 bar to 4.14 bar resulting in the impinging droplets to have a smaller impact angle, resulting in a lower trajectory for the generated splash droplets. Plots similar to those presented in Figure 6.10 are contained in

Appendix C for the ejected and returning spray splash types in addition to the variation of the flow conditions for velocity magnitude for all three spray splash types.

In all of these plots there was a dramatic fluctuation in the data for the 1.38 bar, 29.5 L/hr spray conditions at radial measurements of $R_s < -20$ mm as shown in Figure 6.10. It is believed that a combination of the spray cone not being fully developed in that region and a reduced quality in the statistical data was the source.

Figure 6.10: Absolute splash droplet characteristics at varying pressures at a constant $z = 36.5$ mm. a) Arithmetic mean droplet diameter. b) Sauter mean droplet diameter. c) Mean axial velocity. d) Mean radial velocity.

Section 6.3.4: Comparison of x -axis Splash Results with Vertical Edge Splash Results

To check the validity of the splashed droplet diameter and velocity profiles measured radially above the impact surface at $z = 3.65$ cm additional measurements were performed for traverses along the z direction on the xz -plane at a radius just beyond the spray edge as described in Section 3.5.1. Because two symmetrical traverses were performed at a constant $R_s = \pm 2.68$ cm, the values shown in Figure 6.11 were computed according to $\Psi(z_i) = 1/2[\Psi_{x=R_s}(z_i) + \Psi_{x=-R_s}(z_i)]$, with appositive radial velocity defined as away from the spray centerline. Figures 6.1 a) and b) show splash droplet sizes of nominally $55 < D < 76$ μm , and $90 < D_{32} < 170$ μm . All the vertical profiles collected at $R_s = 2.68$ cm and $R_s = -2.68$ cm showed excellent symmetry. These data are in good agreement with those presented in Figure 6.8 and Figure 6.10 of nominally $60 < D < 80$ μm , and $100 < D_{32} < 180$ μm , respectively. Data collected above the impact surface level show that the mean diameters decrease with increasing spray pressure and flow rate by as much as 16 μm as shown in Figure 6.11. Additional observations of Figure 6.11 a) show that while approaching the impact surface plane, the arithmetic mean splashed diameters converge to nominally 61 μm at about $z = 3.25$ cm before increasing to nominally 74 μm near the surface. Sauter mean diameters shown in Figure 6.11 b) demonstrate a similar trend as they also nearly converge at $z = 3.65$ cm.

Figure 6.11 c) shows that the splashed droplet axial velocities remain within the range of -1.5 m/s to -1.25 m/s between $1.75 < z < 3.25$ cm for the two extremes of spray pressure and flow rate before rapidly increasing to nominally 3 m/s due to the nozzle overspray of the impact surface. Ligaments from the ejecting residual spray film flow were also suspected to contribute to the spike in data near the impact surface plane. The low splashed droplet trajectory is evident in the mean droplet radial velocities shown in Figure 6.11 d). There is a rapid rise in the mean radial velocities, where the spray flow conditions of 1.38 bar, 2.76 bar, and 4.14 bar reach respective peaks of 3.34, 4.27, and 5.17 m/s at nominally $z = 3.50$ cm. Mean axial velocities between $1.75 < z < 3.25$ cm and

the mean radial velocities near the impact surface plane are consistent with those measured radially 1.6 mm above the impact surface shown in Figures 6.8 and 6.1. As expected, the splashed droplet velocities depicted in Figure 6.11 rapidly approach zero for the measurements beneath the impact surface plane. The corresponding splashed droplet average velocity magnitude data for the flow conditions in Figure 6.11 is located in Appendix C.

Figure 6.11: Vertical PDPA results of the splashed droplets at $R_s = \pm 2.68$ cm. a) Arithmetic mean diameter, b) Sauter mean diameter, c) Mean axial velocity, d) Mean radial velocity.

Section 6.3.5: Splashed Droplets Characterized in Dimensionless Numbers

Global integrated averages of the ejected, return, and absolute spray splashed droplet characteristics measured radially above the impact surface ($z = 3.65$ cm) are listed in Table 6.15 for

varying flow conditions. The global average results confirm the lack of significant correlations between spray flow conditions and the splashed droplet average size and axial velocity. The radial velocity and thus the velocity magnitude listed in Table 6.15 do increase with increasing nozzle pressure and flow rate. Sauter mean diameter decreases with increasing pressure.

Table 6.15: Global integrated averages of the splashed droplet characteristics at $z = 3.65$ cm.

Splash Type	P (bar)	D (μm)	D_{32} (μm)	V_{axial} (m/s)	V_r (m/s)	V (m/s)
Ejected	1.38	75.9	196	0.984	2.42	2.82
	2.76	69.2	135	1.27	3.25	3.73
	4.14	69.6	123	1.25	3.80	4.21
Return	1.38	76.8	196	0.960	2.29	2.68
	2.76	69.9	137	1.22	3.14	3.61
	4.14	70.7	121	1.20	3.67	4.08
Absolute	1.38	76.0	179	1.16	2.66	3.12
	2.76	69.4	130	1.38	3.29	3.82
	4.14	69.9	116	1.47	3.67	4.21

The computed average dimensionless Weber, Reynolds, and Froude numbers for the three splash types presented in Table 6.16 were computed for the corresponding arithmetic and Sauter mean diameters listed Table 6.15. The axial velocities from Table 6.15 were utilized to compute the splash dimensionless numbers consistent with the reasoning used for those presented in Table 6.16. The splashed droplets are not expected to make any significant contribution to cavity formation on the residual spray film. This is because the computed Weber numbers are all well below or near the rebound/deposition criteria presented in Table 2.2 ($We < 3.0$, $We = 20$, and $We < 30$).

Table 6.16: Dimensionless numbers computed from the global average characteristics of the ejected, return, and absolute splashed droplets at $z = 3.65$ cm.

Splash Type	P (bar)	Calculated with D			Calculated with D_{32}		
		We	Re	Fr	We	Re	Fr
Ejected	1.38	1.01	74.4	1,300	2.61	193	503
	2.76	1.52	87.4	2,360	2.96	170	1,210
	4.14	1.49	86.6	2,280	2.63	153	1,290
Return	1.38	0.971	73.5	1,220	2.48	188	479
	2.76	1.43	85.0	1,270	2.79	166	1,110
	4.14	1.40	84.5	2,080	2.40	145	1,210
Absolute	1.38	1.39	87.5	1,800	3.28	206	764
	2.76	1.80	95.1	2,780	3.38	178	1,490
	4.14	2.06	102	3,130	3.41	169	1,890

Section 6.4: Volume Flux

Volume fluxes measured by PDPA were consistently off (low) by nominally a factor of 5. This was low relative to what one would compute by dividing the total spray volume flow rate by the spray cross sectional area. PDPA systems are very effective at collecting statistical information on individual particle size and speed; however, achieving mass conservation in the volume flux is difficult. The difficulty is due to the dependency of flux measurements on the droplet size, number density, and velocity which vary from point to point in a spray. Furthermore the number of particles that can be measured in the measuring volume is limited in dense sprays resulting in unreliable droplet number densities (Bade and Schick, 2009, Schwarzkopf *et al.*, 2006, and Widmann *et al.* 2001).

Improved mass flux measurements require extensive optimization of the PDPA system settings, in which the present author had limited experience and access to the PDPA system. For example, Schwarzkopf *et al.* (2006) suggested using higher PMT voltages to achieve partial intensity saturation to make the system more sensitive to smaller droplets. Even with the correct settings mass conservation is typically no better than to within 30% (Schwarzkopf *et al.*, 2006). Another PDPA manufacturer, Artium, has proprietary auto setup software that can more accurately determine the

volume flux distribution, but the present work did not have access to this capability (Bade, 2009). The data acquisition software used a Probe Volume Correction (PVC) algorithm to attempt to improve the spray flux measurements. PVC scales the measuring volume to the diameter size to weight the smaller droplets more heavily (Widmann *et al.* 2001).

Section 6.5: Development of Test Matrix for Single Drop Sub-cavity Experiments

The single drop sub-cavity test matrix was originally presented in Hillen *et al.* (2013). Formulation of the detailed test matrix has been based on the dimensionless spray droplet parameters listed in Tables 6.9 and 6.1. The initial target droplet Weber and Reynolds number values selected for study in the single drop experiments to cover the relevant range of spray drop conditions are listed in Table 6.17.

Table 6.17: Single drop experiment dimensionless droplet parameters (Hillen *et al.*, 2013).

Case	<i>We</i>	<i>Re</i>	<i>Fr</i>
1	140	1,210	49,800
2	400	2,270	94,000
3	600	2,570	193,000
4	800	2,800	324,000
5	1,000	3,340	313,000

Initial dimensionless film thicknesses were determined by utilizing the range of values of h_0^* for the spray experiments listed in Table 2.3. Taken into consideration was the desired 3 to 3.45 mm range of the single droplet diameter. A minimum attainable initial liquid film thickness of 0.520 mm eliminated some of the smallest ranges of h_0^* . Since the desired drop size is only slightly less than the maximum CHR measuring range, values of $h_0^* > 1$ were excluded. This was actually not a significant problem since one rapidly approaches a deep pool impact behavior as the value of h_0^* increases above 1.0. A thin film would not be formed during the impact on a deep pool. These considerations resulted in selection of values of $h_0^* = 1.0, 0.5$, and 0.2 for each Case listed in Table 6.17.

One limitation of the present work was that matching the single drop Froude numbers with those of the full spray was not possible with the experimental facility at hand. This is because the drops producible for the single drop experiments were on a millimeter scale while the spray droplets were on a scale of 50 to 100 μm , which referring to Equation 1.3, resulted in unattainably high Froude numbers.

Since the spray droplets are much smaller than those producible by the current experimental apparatus, a water-glycerol solution was used as the working fluid for the single drop experiments in order to match the Reynolds numbers from Table 6.17. A 46.2% glycerol in water solution by mass of glycerol allowed the Weber and Reynolds numbers of the single droplets to be matched within 5% of the target values given in Table 6.17. Table 6.18 contains the properties of this glycerol-water solution computed using empirical correlations developed by Cheng (2008) and a detailed collection of databases for glycerol-water solutions (Glycerine Producers' Association, 1963). The correlations in Cheng (2008) produced values consistent with the available databases in Glycerine Producers' Association (1963).

Table 6.18: Computed physical properties of 46.2% by mass glycerol-water solution for $T = 20^\circ\text{C}$.

μ (N*s/m ²)	ρ (kg/m ³)	σ (N/m)
0.00493	1120	0.0699

Solutions were mixed based on the corresponding volume fraction using a series of graduated cylinders. Volumes were attainable to within a 0.2 mL accuracy based on a syringe with uncertainty readings of nominally ± 0.052 mL. To ensure the droplet and target pool had the same concentration, a single batch of the solution was prepared for both the droplet generator and tank initial liquid thicknesses.

Additional detail is provided in Appendix D for the methodology utilized to determine the mass fraction of glycerol needed to provide the correct fluid properties to match the dimensionless

numbers in Table 6.17. Appendix D also contains more detail for obtaining the physical properties of the glycerol-water solution in Table 6.18.

Target single droplet diameters of 3 mm were selected for Cases 1 and 3 in Table 6.17 while a diameter of 3.45 mm was targeted for Cases 2, 4, and 5. The larger diameter was required for Case 2 to obtain a Reynolds number within 5% of the target, but it was also used for Cases 4 and 5 to produce the necessary larger dimensionless numbers at a lower drop height than that required for a 3 mm droplet. The lower drop heights for Cases 4 and 5 made the droplet less susceptible to air currents reducing the variation of the droplet impact location by 50%. Additionally, after examining the sub-cavity film thickness results for at $h_0^* = 1.0$ for Case 2 it was determined that Cases 4 and 5 should be performed at an $h_0^* = 0.9$ instead of $h_0^* = 1.0$. Noise was observed for Case 2 that occurred during the initial droplet impingement and retraction phases due to the thickness being beyond the CHR sensor's measuring range. By lowering h_0^* for Cases 4 and 5, the CHR sensor could measure more data during these time, thus reducing the noise.

CHAPTER 7: SINGLE DROP RESULTS AND DISCUSSION

Section 7.1: Introduction

This chapter focuses on the single drop sub-cavity results for experiments and methodologies described in Chapters 4 and 5. Some of the results contained herein were initially reported by Hillen *et al.* (2012) and Hillen *et al.* (2013). Preliminary sub-cavity experimental results from Hillen *et al.* (2012) are discussed in Section 7.2 for the single drop parameters listed in Table 4.1. This section includes histories of the bottom crown radius, crown height, and centerline film thickness. Also included in this section are sample comparisons between the experimental results and CFD simulations performed by Dinc and Gray in Hillen *et al.* (2012). The remaining portion of this chapter focuses on the single drop sub-cavity results for the target test matrix discussed in Section 6.5 relevant to the spray of interest.

Section 7.3 documents the actual average single droplet parameters measured experimentally for every target test case listed in Table 6.17 at $h_0^* = 0.2, 0.5, \text{ and } 1.0$. These dimensionless numbers apply to the remaining single drop results in Sections 7.4 - 7.8 and should be used for any future comparisons.

Side-view and bottom-view sub-cavity radius versus time results are presented in Section 7.4. The influence of initial droplet parameters (We and h_0^*) on the sub-cavity radius trends are investigated. Also, comparisons between the two methods and the sub-cavity liquid film thickness contour are made.

Flow visualization of the cavity for the different single drop parameters are presented below in Section 7.5. The origin of the “capillary” cavity wave is discussed in detail. Also reported is the splashing behavior of the impinging droplets.

Histories of the centerline sub-cavity liquid film thickness and the liquid film thickness radial distribution are presented in Sections 7.6 and 7.7, respectively. The effects of varying We and h_0^* are

examined for the sub-cavity film thickness histories versus radius. The centerline sub-cavity film thickness was normalized both with the droplet diameter and initial liquid layer thickness.

Sub-cavity volume histories are presented in Section 7.8 and are discussed in detail. The sub-cavity surface plots have been used to compare with the sub-cavity volume histories. The influence of varying the initial droplet test conditions is discussed. The potential contributions of the sub-cavity volume results to the MC model are discussed in detail.

Section 7.2: Preliminary Investigation Results and Discussion

The results in this section are from the preliminary single drop sub-cavity film thickness investigation originally presented in Hillen *et al.* (2012). The sequence of the droplet impingement evolution spanning from the time of impingement to the collapse of crown is shown in Figure 7.1 for Cases A and B. Splashing was not observed for drop impingements for Case A ($We = 141$, $Re = 5,700$, $Fr = 103$, and $h_0^* = 0.614$) consistent with the splash criteria given in Table 2.2. The crown evolution shown in Figure 7.1 for Case A is relatively stable with no finger formations due to the low momentum, and high viscous and surface tension forces. The cavity is clearly visible for Case A demonstrating the cylindrical shape behavior for drop impingements on thin liquid films. It becomes conical in shape as surface and gravity forces cause it to begin to recede ($t = 17.8$ ms), consistent with the literature discussed in Section 2.4. Case B ($We = 633$, $Re = 17,100$, $Fr = 115$, and $h_0^* = 0.113$) had more momentum, and lower viscous and surface tension forces to overcome resulting in splashing as shown in Figure 7.1. This splashing behavior agrees well with the single drop splashing criteria. The film thickness ($h_0^* = 0.113$) utilized for Case B was too thin to visually observe the cavity evolution.

Figure 7.1: Sequence of video images for (left to right) initial drop impact, initial crown formation, maximum crown height, and crown collapse for Case A (top) and Case B (bottom) (Hillen *et al.*, 2012)

Figures 7.2 a) and b) show the measured dimensionless bottom crown radius versus dimensionless time for five separate data runs for Cases A and B. The results were computed via image processing as documented in Section 4.3. Bottom crown radii were normalized with the impinging droplet diameter via

$$R_b^* = R_b/d, \quad 7.1$$

and dimensionless times were computed using Equation 2.8. Bottom crown radii for both Cases A and B follow the general $t^{0.5}$ crown growth rates from the literature reviewed in Section 2.3.1. Excellent data run-to-run repeatability is observed for the bottom crown radius. Ideally, the bottom crown radius should be 0 at the initial time in Figures 7.2 a) and b), but the desynchronization is due to the lack of measuring capabilities at the point of contact for these preliminary data. Maximum crown radii were observed in Figures 7.2 a) and b) of nominally $R_b^* = 3.4$ at $\tau \approx 12$, and $R_b^* = 2.5$ at $\tau \approx 11$, respectively.

a) b)
Figure 7.2: Dimensionless bottom crown radius histories for five runs. a) Case A: $We = 141$, $Re = 5,700$, $Fr = 103$, and $h_0^* = 0.614$. b) Case B: $We = 633$, $Re = 17,100$, $Fr = 115$, and $h_0^* = 0.113$ (Hillen *et al.* 2012).

The dimensionless crown height histories for the respective Case A and B are depicted in Figures 7.3 a) and b). The crown height was also normalized with the initial droplet diameter through the dimensionless expression:

$$H_{crown}^* = H_{crown}/d \quad 7.2$$

Maximum crown heights were observed in the respective Figures 7.3 a) and b) are $\sim 0.6d$ at $4 < \tau < 5$, and $\sim 1.6d$ at $\tau \approx 6$. The higher Weber number of the impinging droplet for Case B generates a larger crown with a slightly longer total lifetime than that of Case A, consistent with results from Cossali *et al.* (2004) covered in Section 2.3.

Figure 7.3: Dimensionless crown height histories for five runs. a) Case A: $We = 141$, $Re = 5,700$, $Fr = 103$, and $h_0^* = 0.614$. b) Case B: $We = 633$, $Re = 17,100$, $Fr = 115$, and $h_0^* = 0.113$ (Hillen *et al.* 2012).

Centerline sub-cavity liquid film thickness histories for five repeat data runs are shown in the respective Figures 7.4 a) and b). Figure 7.4 a) shows that drop-to-drop liquid film thickness measurements have excellent repeatability for Case A. This repeatability is also generally good in Figure 7.4 b) for Case B. However, some inconsistencies in the minimum liquid film thickness readings due to a subsequent satellite drop are observed. These satellite drops are a product of the primary droplet detachment process from the needle and only observed for droplets with large masses ($d > 4$ mm). Figure 7.4 shows that a nearly constant minimum sub-cavity film thickness was established during initial moments of drop impingements. This minimum film thickness was maintained until subsequent cavity retraction phase. These observations were consistent with results by Van Hinsberg *et al.* (2010) discussed in Section 2.4.1. For Case A shown in Figure 7.4 a), an average minimum sub-cavity film thickness of approximately $70\ \mu\text{m}$ was observed at 20 msec. Both Cases A and B had sub-cavity film thickness histories measured radially outward from the centerline. These film thickness histories also displayed similar excellent repeatability (outer radial measurements for Case B were generally not affected by the satellite droplets). A minimum sub-cavity film thickness of nominally $81\ \mu\text{m}$, or 1.25% of the initial droplet diameter, was measured for

the film thickness reading that was not affected by a satellite drop for Case B in Figure 7.4 b). This was less than the 2% minimum liquid sub-cavity film thickness reported by Nikolopoulos *et al.* (2007) for numerical simulations of a single drop under the same impingement conditions as the current Case B. This was believed to be due to a maximum resolution of two computational cells making up the sub-cavity film thickness in their simulations as previously discussed in Section 2.4. The consistency of the sub-cavity film thickness and crown dimensions data of Cases A and B justified the analysis of only one film thickness history per radial location for the subsequent data presented in Sections 7.5 - 7.8.

a) b)
Figure 7.4: Centerline sub-cavity liquid film thickness histories for five runs. a) Case A: $We = 141$, $Re = 5,700$, $Fr = 103$, and $h_0^* = 0.614$. b) Case B: $We = 633$, $Re = 17,100$, $Fr = 115$, and $h_0^* = 0.113$ (Hillen *et al.* 2012).

A major flaw with utilizing the bottom crown radius to construct the CHR optical probe traverse was discovered in the preliminary investigation. Traversing based on the bottom crown radius resulted in only four relevant sub-cavity liquid film thickness histories for Case A and five for Case B as shown in Figures 7.5 a) and b) respectively. This lack of cavity resolution resulted in reduced accuracy of the sub-cavity volume calculations for these preliminary data.

a) b)
Figure 7.5: Sub-cavity history carpet. a) Case A: $We = 141$, $Re = 5,700$, $Fr = 103$, and $h_0^* = 0.614$. b) Case B: $We = 633$, $Re = 17,100$, $Fr = 115$, and $h_0^* = 0.113$ (Hillen *et al.* 2012).

Section 7.2.1: Experimental and 2D Simulation Comparison

Companion 2D axisymmetric numerical simulations were also reported in detail in Hillen *et al.* (2012). Comparisons had been performed with the experimental data to check for consistency to at least perform an initial validation check of one against the other. As depicted in Figure 7.6, the dimensionless bottom crown radius histories for the experiments and simulations are in very good agreement. The small discrepancies between the simulations and experiments may be attributed to image processing not capturing the full bottom crown radius due to the wall meniscus. Crown heights were not available from the simulations for comparison since most of the simulations were 2D. Thus the crown height definition used for the results presented in Figure 4.3 could not be applied.

a) b)
Figure 7.6: Comparison of the bottom crown radius histories from the experiment and 2D simulation. a) Case A: $We = 141$, $Re = 5,700$, $Fr = 103$, and $h_0^* = 0.614$. b) Case B: $We = 633$, $Re = 17,100$, $Fr = 115$, and $h_0^* = 0.113$ (Hillen *et al.* 2012).

Dimensionless centerline sub-cavity liquid film thickness histories are presented in Figure 7.7 comparing experimental and simulation results. Comparisons between the experiment and simulation results demonstrated excellent agreement for Case A, as shown in Figure 7.7 a). Both results have consistent sub-cavity film thicknesses and similar cavity durations. Figure 7.7 b) also shows good agreement for the sub-cavity film thickness between experiments and simulations of Case B. However, for Case B the simulation cavity begins receding approximately 4τ to 6τ sooner than the corresponding experiment, as depicted in Figure 7.7 b). It is unknown as of this time the reason for this discrepancy, but plausible explanations include discrepancies in the initial drop conditions (We , Re , Fr , h_0^* , and impact surface properties) between the simulations and experiments, limitations in the 2-D simulations, or unknown limitations with the experimental apparatus. It should be noted that the longer sub-cavity duration at higher Weber numbers are consistent with results by Berberovic *et al.* (2009) and Van Hinsberg *et al.* (2010).

Figure 7.7: Comparison of the centerline sub-cavity liquid film thickness histories from the experiment and 2D simulation. a) Case A: $We = 141$, $Re = 5,700$, $Fr = 103$, and $h_0^* = 0.614$. b) Case B: $We = 633$, $Re = 17,100$, $Fr = 115$, and $h_0^* = 0.113$ (Hillen *et al.* 2012).

Section 7.3: Single drop Sub-cavity Initial Droplet Parameters

The final dimensionless conditions computed from the Case 1 to Case 5 experiments in terms of We , Re , Fr , and h_0^* are listed in Table 7.1. Also included are the corresponding percent errors with respect to the target results in Table 6.17. Values are computed as an average of the initial drop parameters and film thicknesses for all of the radial profiles for each particular test case. Initial average droplet parameter values and respective standard deviations used to compute the values in Table 7.1 are located in Appendix E. Larger deviations of the We and Re numbers from the target values can be contributed to a lack of control of the environmental temperature. Lab conditions never varied more than 1.75%, 1.08%, and 3.72% for the respective ambient air temperature, absolute atmospheric pressure, and relative humidity during the completion of an individual test case. For consistency, all test cases were completed within the same day they were started. The larger deviations in We and Re listed in Table 7.1 are a combination of not obtaining the correct impinging droplet parameters and a lack of temperature control in the laboratory. This is especially evident in the Reynolds numbers since the viscosity is highly dependent on temperature. Average

ambient conditions of the test environment and respective standard deviations are also listed in Appendix E.

Table 7.1: Dimensionless parameters measured in the experiments and their respective percent error to the target values.

Case	Experimental Results					Percent Error		
	h_0^*	h_0^*	We	Re	Fr	h_0^*	We	Re
1	1.0	1.00	145	1,190	100	-0.297%	-3.44%	-1.75%
	0.5	0.50	146	1,290	99.0	-0.196%	-2.64%	6.33%
	0.2	0.24	135	1,180	94.0	19.5%*	-10.1%	-2.82%
2	1.0	1.01	410	2,250	217	0.749%	2.60%	-0.783%
	0.5	0.51	413	2,270	219	1.36%	3.35%	0.0320%
	0.2	0.21	414	2,290	217	2.67%	3.38%	0.903%
3	1.0	1.00	622	2,670	415	0.324%	3.61%	3.99%
	0.5	0.50	621	2,640	415	0.454%	3.58%	2.84%
	0.2	0.19	667	2,740	439	-2.54%	11.1%	6.68%
4	0.9	0.90	762	3,080	398	-0.484%	-4.81%	10.0%
	0.5	0.50	771	3,090	407	-0.173%	-3.65%	10.5%
	0.2	0.20	780	3,100	413	0.289%	-0.249%	10.8%
5	0.9	0.90	993	3,570	510	-0.224%	-0.670%	-7.08%
	0.5	0.50	984	3,560	499	-0.988%	-1.64%	6.78%
	0.2	0.20	984	3,560	407	0.583%	-1.64%	6.53%

*Operator error in obtaining the correct initial target liquid layer thickness.

Section 7.4: Sub-cavity Radius Results and Discussion

Sub-cavity radius measurements were performed for each case listed in Table 6.17 for $h_0^* = 1.0, 0.5$, and 0.2 (with $h_0^* = 0.9$ instead of 1.0 for Cases 4 and 5) to determine the radial sub-cavity traverse locations. Sub-cavity radii presented were normalized with the impinging droplet diameter by the following:

$$R_c^* = R_c/d \quad 7.3$$

Sub-cavity radius histories measured via the two video techniques for varying the h_0^* and We are shown in Figures 7.8 and 7.9, respectively. Figure 7.8 shows that the maximum value of the sub-cavity radius does not change significantly with the variation in h_0^* . However, the lifetimes do significantly increase with increasing h_0^* . Maximum sub-cavity radii of $2.02d$ at $\tau = 18.9$, $2.10d$ at $\tau = 30.7$, and $2.10d$ at $\tau = 21.3$ have been observed for the respective $h_0^* = 1.0, 0.5$, and 0.2 in Figure

7.8 a). Maximum R_c^* measured from the side-view in Figure 7.8 b) for the respective $h_0^* = 1.0, 0.5$, and 0.2 are $2.46d$ at $\tau = 27.7$, $2.43d$ at $\tau = 20.7$, and $2.32d$ at $\tau = 19.0$.

a) b)
Figure 7.8: Sub-cavity radius histories varying h_0^* for Case 3 ($We = 621, Re = 3,090, Fr = 415$).
a) Bottom-view measurements. b) Side-view measurements.

Figure 7.9 shows that, within the studied parameters, there is a weak correlation between the We and maximum R_c^* . Initially the maximum R_c^* increases with increasing We until the effect dampens to negligible influence at higher We . For example in Figure 7.9 a maximum R_c^* for nominally $We < 600$ for the BV results and $We < 400$ for the SV results display a significant, but small dependence on the Weber number. A consistent trend observed for both the BV and SV results was that the sub-cavity radius increases with Weber number more prominently than varying h_0^* . These results are consistent with the literature reviewed in Section 2.4. Also consistent with the literature was the observed initial R_c^* growth of rate $t^{0.5}$ until the onset of the retraction phase for all scenarios. Similar trends for the influence of the initial drop conditions and initial dimensionless film thickness on the sub-cavity radius lifetime are expected to apply to the sub-cavity volume histories.

There are observed peaks in R_c^* in most of the data shown in Figures 7.8 and 7.9 during the cavity retraction phase. These peaks are a result of the cavity capillary wave propagating to the impact surface temporally increasing the sub-cavity radius. This was consistent with cavity radius

histories presented by Berberovic *et al.* (2009). This propagating cavity capillary wave will be discussed in further detail in the subsequent Section 7.5. Sub-cavity radius histories for the impingement scenarios not shown exhibit similar behavior to those discussed in this section and can be found in Appendix E.

a) b)
Figure 7.9: Sub-cavity radius histories varying We at a constant $h_0^* = 0.5$. a) Bottom-view measurements. b) Side-view measurements.

Sub-cavity radii measured via the SV technique resulted in larger measurements than corresponding BV measurements, as shown in Figures 7.8 and 7.9. The coefficient of variance between the maximum R_c^* measured in Figures 7.8 a) and b) ranged from 7% to 14%. It is believed that larger results from the SV method was due to the combination of lack of resolution at the impact surface/bottom cavity interface, and the sub-cavity radius being the average of the last five rows of pixels above the impact surface (see Section 4.4.1). Additional variation in data between the two methods could be contributed to the acrylic mirrors utilized in the BV apparatus. The mirrors tended to slightly warp with use leading to faintly distorted bottom-view cavity videos. Bottom-view sub-cavity radii were an average of the two major axes, with the typical variance in the measurement ranging from 2% to 7% of the average. Figure 7.10 depicts the Case 3, $h_0^* = 0.5$ color contour plot of the measured sub-cavity liquid film thickness histories. The film thicknesses have been profiled to

the largest radial location in which sub-cavity film thicknesses were measured. Superimposed on the contour plot are the analogous BV and SV R_c histories including their average. Both the SV and BV R_c match the general sub-cavity film contour (mostly the blue region). Also, it is noted that the bottom cavity R_c history under predicts and SV R_c over predicts the actual thin sub-cavity liquid film region. The average of the two R_c measurements provided the best fit to the data. These observations are generally applicable for all the impingement scenarios. However results for Cases 4 and 5 show closer convergence of BV and SV sub-cavity radii. Contour plots corresponding to Figure 7.10 for the remaining impingement scenarios may also be found in Appendix E.

Figure 7.10: Sample contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 3, $h_0^* = 0.5$ ($We = 621$, $Re = 3,090$, $Fr = 415$).

Section 7.5: Single Drop Cavity Flow Visualization

Flow visualization of crown and cavity morphology evolution encompassing the entire test matrix listed in Table 6.17 and full range of h_0^* was performed. In general the observed cavity and crown behavior follows the same behavior described in literature as discussed in Chapter 2. Since the present work focuses primarily on the cavity behavior, crown behavior discussion herein is limited. A more detailed description of the crown behavior has been presented in Section 2.3. As

previously discussed in Chapter 2, the crown and cavity are interdependent on each other. This is demonstrated in the sequenced video images of the droplet impingement process for varying the We and h_0^* shown in the respective Figures 7.11 and 7.12.

The general cavity trend observed experimentally for all cases consisted of a droplet impinging upon the free surface generating a cavity. The cavity would propagate downward until contacting the impact surface forming a nearly cylindrical shape and creating the sub-cavity liquid film thickness distribution and sub-cavity volume. The cavity then continuously expanded outward along with the crown again illustrating the well established $t^{0.5}$ behavior. During crown collapse the cavity would cease to expand becoming nearly conical in contour before receding and deviating from $t^{0.5}$. These two observations demonstrate the interdependency of the crown and cavity evolution.

Images for drop impingement scenarios shown Figures 7.11 and 7.12 are sequenced to capture the times of the droplet before impact, the cavity during contact with the impact surface, the maximum crown height, and the last stages of crown collapse and cavity retraction. The red horizontal line noted on the images represents the location of the true free surface bottom. Optical distortion was created on the bottom of the free surface due to having aligned the line of sight with the impact surface. The cavity receding phase was always observed to initiate shortly after the crown began to collapse. Consistent with the literature, increasing the Weber number delayed the onset of the receding phase of both the crown and cavity. It also led to an increased crown height as shown in Figure 7.11. In addition, the crown became more susceptible to finger formations and splashing. Higher We had little effect on the initial cavity propagation towards the impact surface.

Figure 7.11: Images taken from high-speed videos showing the cavity formation over time at an $h_0^* = 0.5$ for Cases 1, 3, and 5 test conditions. The red dashed line is the true free surface interface. a) $We = 146, Re = 1,290, Fr = 99.0$. b) $We = 621, Re = 2,640, Fr = 415$. c) $We = 984, Re = 3,560, Fr = 499$ (Hillen *et al.* 2013).

No significant changes were observed for varying the h_0^* of Case 1 other than a slightly larger crown height. The corresponding cavity evolution images for $h_0^* = 1.0$ and 0.2 for Case 3 and $h_0^* = 0.9$ and 0.2 for Case 5 are shown in Figure 7.12. As expected, the film thickness had a dramatic influence over the crown formation and splashing. Thinner initial film thickness cases were more susceptible to splashing and produced thinner crowns and larger crown angles. For a given h_0^* the general cavity shape was not generally affected other than the cylindrical shape occurring earlier for thinner h_0^* . During the initial stages of cavity formation for thicker h_0^* , the cavity generally displayed a more spherical shape consistent with deep pool behavior. These observations were all consistent with the literature reviewed in Chapter 2. Other than the bottom cavity diameter not much on the cavity morphology can be discerned when $h_0^* = 0.2$ in Figures 7.12 b) and d) because the thin film lacks visual sharpness.

Figure 7.12: High-speed video images showing the crown and cavity formation over time at varying h_0^* for Cases 3 and 5. The red dashed line is the true free surface interface. a) $We = 145, Re = 1,190, Fr = 100.0$. b) $We = 135, Re = 1,180, Fr = 94$. c) $We = 993, Re = 3,570, Fr = 510$. d) $We = 984, Re = 3,560, Fr = 407$ (Hillen *et al.*, 2013)

During the cavity recession period when the crown is collapsing a noticeable wave on the inside surface of the upper portion of the cavity propagates downward to the impact surface (Berberovic *et al.*, 2009). This wave temporarily expands the sub-cavity radius as it recedes as evident in the results shown in Figures 7.8 and 7.9. The wave has been defined as a capillary wave in the literature (Fedorchenko and Wang, 2004, Roisman *et al.*, 2008, and Berberovic *et al.*, 2009), but is referred to herein as a cavity wave since it is believed to also be driven partially by gravity. A cavity wave is clearly visible at the last time steps in Figures 7.12 a) and c). Figure 7.13 shows a more detailed example of the cavity wave propagation for Case 3 at $h_0^* = 1.0$. The images are sequenced beginning with the maximum crown height before collapse ($\tau = 16.0$), the time immediately before the cavity wave is visible ($\tau = 30.7$), and its propagation to the impact surface ($30.7 \leq \tau \leq 38.5$). Gravity is believed to be a major contributor to the cavity wave along with surface tension, due to its occurrence coincides with the collapse of the crown mass. It should be noted that

for the current data the Weber and Froude number are the same order of magnitude while this would not be true for the corresponding Weber number spray droplets. Also, capillary waves generally consist of multiple short wavelength waves, but it was observed experimentally that most of these waves were single events with no more than three occurring at the higher Weber numbers. These two observations support the theory that gravity at least partially drives the termed “capillary” wave (Fedorchenko and Wang, 2004, Roisman *et al.*, 2008, and Berberovic *et al.*, 2009). Cavity wave propagation was observed to occur rapidly with the example contacting the surface in nominally 7.8 dimensionless time units. This propagation agrees well with respective the sub-cavity radius plots in Figure 7.8 b) in which the cavity wave is evident for at least $5 \leq \Delta\tau \leq 6$.

Figure 7.13: Examination of cavity wave denoted as a capillary wave in literature. Case 3: $We = 145$, $Re = 1,190$, $Fr = 100.0$, and $h_0^* = 1.0$. The red dashed line is the true free surface interface and the red arrow highlights the cavity wave.

Section 7.5.1: Additional Splashing Observations

Splashing behavior has been analyzed for droplet impingement conditions and the results have been presented in Table 7.1. The splashing criteria K and Y have been computed for each test scenario using the respective Equations 2.9 and 2.10 (Cossali *et al.* 1997, Yarin, 2006). Table 7.2 summarizes the resulting splash criteria and whether consistent splashing was observed from the experiments. To reiterate, splashing would be expected for values of $K > 57.1$ for a dry surface and Y

> 1 for a thin initial liquid film (see Section Table 2.2). Generally, the Y splashing criteria (Cossali *et al.* 1997) predicted the splashing outcome.

Table 7.2: Computed splashing limits based on Cossali *et al.* (1997) compared with experimental observations.

Case	h_0^*	K	Y	Observed Splash?
1	1.0	911	0.114	No
	0.5	944	0.221	No
	0.2	855	0.319	No
2	1.0	2700	0.338	No
	0.5	2720	0.637	No
	0.2	2740	1.02	Delayed Splash
3	1.0	4040	0.506	No
	0.5	4020	0.941	Prompt Splash
	0.2	4310	1.61	Prompt and Delayed Splash
4	0.9	5020	0.701	Prompt Splash
	0.5	5070	1.19	Prompt and Delayed Splash
	0.2	5130	1.92	Prompt and Delayed Splash
5	0.9	6600	0.922	Prompt Splash
	0.5	6530	1.53	Prompt and Delayed Splash
	0.2	6530	2.44	Prompt and Delayed Splash

An interesting crown formation phenomenon was consistently observed for nearly every test condition for Cases 2 – 5 at $h_0^* = 0.2$. An example of this unique crown formation is presented Figure 7.14 for a sequence of images for Case 4 ($We = 762$, $Re = 3,080$, $Fr = 398$) at $h_0^* = 0.9$. During the initial droplet impingement an initial crown would form ($\tau = 0.265$). As the droplet continues to penetrate the initial liquid layer a secondary larger crown is formed propagating at a faster speed ($\tau = 0.617$). This new larger crown quickly over takes the slower and smaller initial crown essentially engulfing it ($\tau = 1.06$). However, this initial crown does not immediately merge with the main crown existing on the inside of its rim and continues to propagate upward ($\tau = 2.56$). When the main crown begins to slow as it reaches its maximum height, the initial crown over takes it and completely merges with its rim ($\tau = 7.76$). This process typically resulted in a prompt splash that

originates from this initial film as shown in Figure 7.14 at $\tau = 7.76$. Prompt splashing due to this behavior was observed to occur on occasion even for Case 2 for $h_0^* = 1.0$. It is also responsible for some the discrepancy between the splashing criteria prediction and the observed predictions in Table 7.2.

Figure 7.14: Example of unique prompt splash for Case 4, $h_0^* = 0.9$ ($We = 762$, $Re = 3,080$, $Fr = 398$). The initial splash is highlighted by the dashed ellipse.

Section 7.6: Single Drop Centerline Sub-cavity Film Thickness

Centerline sub-cavity results presented in this section consist of the improved single drop sub-cavity experiments based on the test plan developed in Section 6.5. The effects of varying the Weber number and initial film thickness on the resulting centerline sub-cavity film thickness histories have been analyzed. Dimensionless sub-cavity film thickness and times were computed via Equations 1.5 and 2.8, respectively. Figure 7.15 shows the measured dimensionless centerline sub-cavity liquid film thickness histories for the middle Weber number of 640 with $0.2 < h_0^* < 1.0$ (Case 3), and for the middle dimensionless film thickness of $h_0^* = 0.5$ for $142 < We < 987$ (Cases 1 - 5). It was found that the varying h_0^* for a constant We , Re , and Fr had a negligible effect on minimum sub-

cavity h^* as observed for Case 3 in Figure 7.15 a) with minimum films measured from $\sim 3.2\%$ to 4.5% of the initial drop diameter at this Weber number. Earlier initiation versus time of the thin sub-cavity film thickness was found to occur with decreasing h_0^* for a specific impact (We, Re), although this is a minor effect. For an increasing h_0^* the respective dimensionless nominal times to form the constant minimum h^* were $\tau = 4.0, 4.3$, and 8.0 in Figure 7.15 b). However, h_0^* has a very pronounced effect on the onset of the cavity collapse, with thinner h_0^* resulting in shorter cavity durations ($\tau = 50.0, 42.5$, and 27.9 for decreasing h_0^*). The contributions of the dimensionless drop parameters (primarily, variation in We) for a constant h_0^* on the minimum h^* and cavity evolution are shown for $h_0^* = 0.5$ in Figure 7.15 b). Increasing the Weber number also is seen to have a negligible effect on the minimum sub-cavity h^* . Minimum sub-cavity film thicknesses of between 4.1% to 3.0% of the initial droplet diameter were measured in Figure 7.15 b) as the Weber number is increased. Figure 7.15 b) does demonstrate the cavity duration to be strongly dependent on the Weber number. The cavity collapse time is dramatically increased for higher Weber numbers. Although the Weber number's influence on the total cavity lifetime is comparable to that of h_0^* , it had essentially no influence on the dimensionless cavity formation time. All these observations are consistent with similar previous work as reviewed in Section 2.4. The dependence of the centerline sub-cavity film thickness lifetimes on We and h_0^* have been found to be consistent with sub-cavity radius results and flow visualization discussed in the respective Sections 7.4 and 7.5.

a) **b)**
Figure 7.15: The effects of varying the h_0^* and We on the centerline dimensionless film thickness. a) Varying h_0^* for a constant $We \approx 640$, $Re \approx 2,700$, $Fr \approx 430$ of Case 3 for. b) Varying the We at a constant $h_0^* = 0.5$ (Hillen *et al.*, 2013).

The centerline sub-cavity film thickness has also been analyzed as a ratio of the initial film thickness, (h/h_0) . Effects of varying the h_0^* and Weber number on this ratio are shown in Figures 7.16 a) and b) respectively. It was found that for the studied range of conditions, the initial dimensionless film thickness does influence the h/h_0 ratio at a value of $h_0^* = 0.2$ as shown in Figure 7.16 a). The minimum sub-cavity film thicknesses for this example were measured to nominally increase from 4.6% to 16% of the initial film thickness for decreasing h_0^* . Thinner films ($h_0^* = 0.2$) are more susceptible to the larger viscous frictional forces in the thin film boundary layer. This results in the sub-cavity film thickness being a higher percentage of the initial layer thickness. It is believed that this particular thin film is comprised mostly of the impinging droplet liquid. As discussed in Section 2.5, numerical simulations tracking the impinging droplet and initial layer fluids were performed in Hillen *et al.* (2012) for the conditions listed in Table 4.1. Simulation results for a similarly thin initial liquid layer of $h_0^* = 0.113$ for Case B showed the sub-cavity to consist almost entirely of droplet liquid. Additional observations found that Weber number had a negligible influence on h/h_0 in Figure 7.16 b) consistent with Figure 7.15 b). Minimum sub-cavity film thicknesses between 8.4% and 6.1% of the initial liquid film thickness were measured in Figure 7.16

b) with increasing Weber number. Sub-cavity lifetime behavior was found to be consistent with that observed for Figure 7.15 b).

a) b)
Figure 7.16: The effects of varying the We and h_0^* on the centerline film thickness ratio h/h_0 . a) Varying h_0^* for a constant $We \approx 640$, $Re \approx 2,700$, $Fr \approx 430$ of Case 3. b) Varying the We at a constant $h_0^* = 0.5$ (Hillen *et al.*, 2013).

Trends consistent with those discussed for Figures 7.15 and 7.16 were observed for all Cases at every h_0^* . These additional centerline sub-cavity film thickness history plots are presented in Appendix E.

Section 7.7: Single Drop Cavity Film Thickness Surface Contour Maps

Cavity liquid film thickness surface contour plots have been constructed from the sub-cavity liquid film thickness versus time and radius. The surface plots are comprised of the film thickness histories using data smoothing and interpolation methods described above in Section 5.4.

The resulting cavity liquid film thickness surface plots are presented below in Figure 7.17 for the entire test matrix given in Table 7.1. A color contour range of $0 \leq h \leq 250 \mu\text{m}$ has been employed to most effectively highlight the sub-cavity contours. The sub-cavity generally displayed a uniform distribution of the liquid film thicknesses. However, a noticeably thinner region of liquid was consistently observed at the outer radial locations for every impingement scenario shown in

Figure 7.17. These thinner regions occur at the latter stages of the cavity propagation and are expected to influence the sub-cavity volume results. It is thought that the viscous frictional forces in the sub-cavity boundary layer are damping the radial outward momentum of the sub-cavity film as the cavity expands. Increased inertia makes all of the sub-cavity film thicknesses smaller so that the change in the maximum versus minimum h is reduced. Even with the increased drop inertia this thinner region is prominent except for the most extreme drop impingement scenario (Case 5, $h_0^* = 0.2$, $We \approx 987$, $Re \approx 3,560$, and $Fr \approx 472$). This suggests that for the studied cases the Reynolds number (inertial and viscous effects) is the dominant variable in sub-cavity film flow propagation ($Re \leq \sim 2,270$). Cases 2 - 5 were expected to produce smooth sub-volume histories due to their uniform distribution of the sub-cavity film while Case 1 was expected to provide less clean trends, due to the unevenness of its contours. Examining Case 1 ($We \approx 142$, $Re \approx 1,220$, and $Fr \approx 98.0$) at $h_0^* = 1.0$ the impinging droplet lacks the momentum for the bulk of the sub-cavity film flow to overcome viscous forces and spread radially outward. Initial film thicknesses of $h_0^* < 1.0$ for Case 1 appear to lead to more uniform sub-cavity liquid film thickness distribution.

Additional investigations of the surface plots depicted in Figure 7.17 show that the maximum cavity radius is nearly constant for a significant portion of the cavity lifetime. The best examples of this occur at the higher We and Re at $h_0^* = 0.5$. This behavior is fully plausible since it is consistent with the sub-cavity radius measurements presented in Section 7.4.

For the lower Weber number cases and thicker initial liquids films the minimum film thickness histories located at large radius are actually initiated at small times before the minimum film thickness histories near the centerline are established. This phenomenon is due to the “top tail end” of the impinging droplet not fully transitioning into a thin film as the sub-cavity is formed. This was also evident in some of the sub-cavity radius histories in Appendix E due to the image

processing measuring part of the impinging drop for early times. This resulted in a peak in the data before it transitioned to the smooth $t^{0.5}$ initial sub-cavity radius growth rate.

The cavity wave discussed in the previous Sections 7.4 and 7.5 clearly influenced the surface contour liquid film thickness results. Again referring to Figures 7.8 to 7.10 the peak of the sub-cavity radius due to the cavity wave is typically near the maximum radius that occurs just prior to the onset of the receding phase. It was nearly impossible to capture the transition of the cavity wave contacting the impact surface. This was due to the aforementioned combination of drop-to-drop variability combined with the discrete CHR optical probe traverse method. It is believed that the nearly constant maximum sub-cavity radius is evidence of this cavity wave contacting the surface and delaying the onset of the receding phase. However, measurements of the liquid thickness of the cavity wave propagation via the CHR sensor was obtained for every initial droplet impingement condition of $h_0^* = 0.2$, as shown in Figure 7.17. It occurs near the onset of the receding phase and temporally expands the sub-cavity radius and thus the sub-cavity thin film region. Surface plots for Cases 3 and 5 at $h_0^* = 0.2$ clearly show that upon full contact with the impact surface the cavity wave results in the thinnest liquid film region at the outer most radius (the small dark blue region). This occurs at times of nominally 14 to 17.8 msec and 17.3 to 22.5 msec for Cases 3 and 5, respectively. Further examination of the respective nominal time ranges of $12.8 < t < 14.5$ msec and $9.25 < t < 13.5$ msec for Cases 1 and 3 for $h_0^* = 0.2$ shows the transition of the cavity wave contacting the surface. Its thin film is initially evident “behind” the corresponding original film thicknesses at the maximum radial location. Due to these results, it is expected that computed sub-cavity volumes for the impingement scenarios of $h_0^* = 0.2$ will have larger volumes when the cavity wave film thickness merges with the original sub-cavity film region.

Figure 7.17: Sub-cavity liquid film thickness surface plots for Cases 1 - 5 at a fixed 0 - 250 μm contour color scale. Note for cases 4 and 5 $h_0^* = 0.9$ in the left hand column.

A summary of the cavity values are presented in Table 7.3 which have been extracted individually from each Case presented in Figure 7.17. The absolute minimum, absolute maximum, and average sub-cavity liquid film thickness have been computed for the thin sub-cavity region and listed in Table 7.3. The sub-cavity region was defined based on the film thickness constraint limit used to compute sub-cavity volumes (Section 5.5). Therefore, the computed maximum h is similar in thickness to the film thickness constraint limit used for a particular test scenario. They were typically located in the outer radial region where the sub-cavity region begins to transition into the cavity wall. The absolute minimum sub-cavity film thickness was generally consistent between each test scenario and typically located in the thinner sub-cavity regions located radially outward, as previously discussed. However, significantly thinner absolute h_{min} are listed in Table 7.3 for Cases 1, 3, and 5 for $h_0^* = 0.2$ and Case 1 for $h_0^* = 1.0$. The location and time that these smaller absolute h_{min} occur corresponds to the time when the cavity wave fully merges with the original sub-cavity liquid film before the onset of retraction. An overall average of the sub-cavity film thickness has also been computed for the sub-cavity region for each test scenario. The h_{mean} values computed for each test scenario are the same order of magnitude in thickness and follow trends consistent with the centerline sub-cavity film thickness histories. The average sub-cavity film thickness is mostly insensitive to the Weber number, but a noticeable decrease in h_{mean} with decreasing h_0^* is observed (excluding Case 1). Table 7.3 also contains the duration of the nearly constant minimum film thickness of the cavity. These times are generally consistent with the trends for varying the We and h_0^* discussed in the previous Sections 7.3 - 7.6. The maximum sub-cavity radius has also been computed based on the radial sub-cavity film thickness distribution. These results are also listed in Table 7.3 and have trends consistent with the sub-cavity radii measured from the SV and BV

methods in Section 7.4. It should be noted that for Cases 1, 3 and 5 for $h_0^* = 1.0$ the transition of the sub-cavity region to the cavity wall was not captured with the CHR sensor.

Table 7.3: Nominal absolute minimum, absolute maximum, and mean liquid sub-cavity film thickness measured in the sub-cavity region. Also included is the duration of the thin liquid sub-cavity film thickness and maximum sub-cavity radius. Results are for Cases 1 - 5 at $h_0^* = 1.0, 0.5$, and 0.2 .

Case	h_0^*	h_{min} (μm)	h_{max} (μm)	h_{mean} (μm)	h_{min} Duration (msec)	$R_{c\ max}$ (mm)
1	1.0	54.4	189	135	13.8	3.68
	0.5	66.1	200	143	16.8	4.97
	0.2	54.8	189	138	16.5	4.82
2	1.0	75.0	189	145	27.8	5.80
	0.5	68.5	159	126	31.5	6.03
	0.2	70.6	145	112	22.8	6.19
3	1.0	71.5	170	127	35.6	6.18
	0.5	74.4	138	106	32.1	6.10
	0.2	35.8	129	98.4	19.8	6.05
4	0.9	71.8	170	125	40.1	7.46
	0.5	74.3	155	110	37.5	7.25
	0.2	79.3	134	103	23.0	7.29
5	0.9	75.8	170	123	50.7	7.59
	0.5	73.1	145	103	39.7	7.51
	0.2	42.6	119	98.0	26.0	7.36

Section 7.8: Sub-cavity Volume Results and Discussion

Sub-cavity volume histories have been computed for Cases 1 - 5 for the three $h_0^* \approx 1.0, 0.5$, and 0.2 through the methodology developed in Chapter 5. The same smoothed and filled sub-cavity liquid film thicknesses versus time and radius used to create the surface plots in Figure 7.17 have been employed in the sub-cavity volume calculations. Presented sub-cavity volumes in this section have been normalized with the volume of the related impinging droplet by:

$$Vol^* = Vol/Vol_{droplet} \quad 7.4$$

Figures 7.18 to 7.20 show the resulting dimensionless sub-cavity volumes including the effects of varying h_0^* and initial droplet We . For a more in-depth understanding of the presented sub-cavity plots the surface plots, refer to Figure 7.17.

Examining Figures 7.18 to 7.20 the typical trend observed for Vol^* does not follow the same $t^{0.5}$ growth rate behavior of the crown and cavity radius established in literature and the current results. Instead, the volume follows a time behavior similar to the centerline film thickness as it rapidly reaches a nearly constant plateau that lasts until the onset of the receding phase. One contributing factor to this plateau is that the sub-cavity radius becomes virtually constant during this time until the onset of the receding phase as seen in Figure 7.17. The sharp rise in the sub-cavity volume was not unexpected, since the cavity forms very quickly. Figures 7.15 and 7.16 illustrate that it takes $\tau \approx 4 - 5$ for the rear portion the droplet to reach the impact surface. The thinner regions of liquid film at the outer sub-cavity radius discussed for Figure 7.17 also contribute to the plateau. Furthermore, a slight gradual downward slope in the plateau region is typically found for $h_0^* > 0.2$ for Cases 2 - 5 as shown in Figure 7.18, and Figures 7.19 a) and b). The outer thinner film region is also believed to be the main source of this slight slope. More evidence of the contributions of the propagating cavity wave to the sub-cavity liquid volume can be seen by carefully examining Figure 7.18. The cavity wave causes small sharp dips in the dimensionless volume occur before it plateaus between nominally $5 < \tau < 15$. The peak occurs at respective approximate dimensionless times of $7.43 < \tau < 8.68$, $12.9 < \tau < 15.3$, $16.5 < \tau < 21.2$, $18.7 < \tau < 22.7$, and $19.3 < \tau < 26.4$ for Cases 1 - 5 in Figure 7.19 c). All of the sub-cavity volume data shown in Figures 7.18 to 7.20 experienced some oscillation at the times corresponding to the receding phase of the cavity. This was result of the combined effect of the downward inner cavity wave propagation and variations in sub-cavity maps shown in Figure 7.17. A primary cause of the variations in the surface plots was the drop-to-drop variations in the impact process. Surface plots were assembled from $h(t)$ data for different droplet impacts at the differing radii. The resulting assembled waves created what appeared as a “ripple effect” at the final time steps of the sub-cavity surface plots.

The effects of h_0^* on the sub-cavity volume for a constant Weber number shown in Figure 7.18 are similar to those described for the centerline film thickness data depicted in Figure 7.15 a). The sub-cavity volume lifetime is equal to the cavity duration. Thus higher initial values of h_0^* correspond to larger computed dimensionless volumes. This conclusion ignores the sub-cavity volume peaks before the receding phase for $h_0^* = 0.2$ which have a maximum volume nearly the same as the data for $h_0^* = 0.5$ in Figure 7.18, Figures 7.19 a) and b), and Figure 7.20.

Figure 7.18: Effects of varying the h_0^* on the dimensionless sub-cavity volume histories at a constant $We = 637$, $Re = 2,686$, $Fr = 432$ of Case 3 (Hillen *et al.*, 2013).

Figure 7.19 demonstrates the dimensionless sub-cavity volume dependence on the initial droplet conditions (We , Re , and, Fr). This emphasizes the effects of increased Weber and Reynolds numbers in each of the three plots. The sub-cavity volume lifetimes follow trends similar to those observed for the centerline sub-cavity film thickness profiles in Figure 7.15 a) when Weber number was varied. Consistent with the crown and cavity lifetimes, the sub-cavity volume lifetime increased with an increasing Weber number. This trend was again more prominent than that of increasing the initial film thickness. For a constant $h_0^* = \sim 1.0$ and 0.5 shown in Figures 7.19 a) and b) it was observed that the maximum value of the sub-cavity volume increased with the Weber number. This influence dampens for the $We > \sim 412$ for the studied scenarios. A negligible dependence on the

maximum values of the sub-cavity volume on the Weber number were observed in Figure 7.19 c) for $h_0^* = 0.2$.

Figure 7.19: Effects of varying We on the dimensionless sub-cavity volume histories. a) Constant $h_0^* = 1.0$ ($h_0^* = 0.9$ for cases 4 and 5). b) Constant $h_0^* = 0.5$. c) Constant $h_0^* = 0.2$.

Sub-cavity volume results presented in Figure 7.20 for Case 1 (lowest Weber number) were not consistent in behavior with the rest of the results. Figure 7.20 show that the smallest sub-cavity volumes were observed for $h_0^* = 1.0$ for a constant We , which was contrary to the previous results shown in Figures 7.18 and 7.19. Also, the sub-cavity volume for Case 1, $h_0^* = 1.0$ begins significantly later in time compared to Case 1 results for $h_0^* = 0.5$ and 0.2 . Further Case 1 deviation from the main sub-cavity volume trends can be observed for $h_0^* = 0.5$ and 0.2 results. These two trends are observed to have a very similar duration and sub-cavity volume values. The unique

behavior of the Case 1 results are due to a lack of initial droplet momentum ($We = 142$, $Re = 1,220$, and $Fr = 98.0$). The droplet's smaller kinetic energy causes it to be more susceptible to the dampening effects of the layer thickness. Therefore, less potential energy is available to effectively spread the sub-cavity liquid film.

Figure 7.20: Effects of varying the h_0^* on the dimensionless sub-cavity volume histories at a constant $We = 142$, $Re = 1,220$, $Fr = 98.0$ of Case 1 (Hillen *et al.*, 2013).

CHAPTER 8: CONCLUSIONS AND FUTURE WORK

Section 8.1: Conclusions

Sub-cavity volumes created by a single droplet impinging onto a thin initial liquid layer have been successfully computed for a range of dimensionless numbers (We , Re , and h_0^*) relevant to a spray of interest. This was accomplished by initially characterizing a full cone water spray generated by a Spraying Systems 1/8-G FullJet nozzle via PDPA for varying flow conditions. A relevant test matrix for the single drop experiments has been created from the integrated global Weber, Reynolds, and Froude numbers utilizing the spray data for the three different operating pressures. Sub-cavity liquid film thicknesses versus time and radius have been measured for each droplet condition in the test matrix utilizing a non-contact chromatic optical thickness sensor and high-speed video imagery. Time dependent sub-cavity volumes have been computed through numerical integration of the sub-cavity film thickness radial distributions.

PDPA spray results without an impact surface installed displayed consistent trends across the flow conditions. The average droplet diameter has been observed to increase away from the centerline for each nozzle operating pressure. This corresponded to the respective increase and decrease in the spray droplet's average radial and axial velocity. Additional observations showed that the droplet diameter decreased and its average velocities increased with increasing spray nozzle flow condition (gage pressure, and flow rate). The spray data was further examined for 5% of the diameter population comprised of the largest droplets. The results showed that this diameter range contributed up to nominally 39% of the total spray mass. Accurate measured volume fluxes were not obtained due to limitations in the PDPA system, along with the very dense spray studied in the present work. This resulted in measured fluxes that deviated significantly from the actual average nozzle flux.

Additional PDPA studies were performed characterizing the splashed droplets created by the same nozzle spray impinging onto a smooth surface. Data was collected 1.6 mm above the surface, traversing along the horizontal spray centerline. These measurements were separated into the incoming spray and various splashing droplets. Results showed that the splashed droplets were similar in size to the incoming spray droplets, consistent with Kalantari and Tropea, (2006). These splashed droplets were also relatively slow, never exceeding 3 m/s, and had low trajectory angles with respect to the surface. This suggests that the spray/splash region may be more complicated than originally had been contemplated based on single drop observations. There may be more interaction between the impinging droplets and incoming spray droplets. Lower quality data was collected at measurement locations above the spray impact surface due to the increased droplet fluxes created by additional splashing droplets. Therefore, splashed droplet diameter and velocities were also measured via PDPA, traversing vertically just outside of the main impinging droplet spray cone. These splashed droplet data have been found to be in consistent agreement with the traverses that were collected above the spray impact surface. Splashing criteria have been computed for the splashed droplets showing that they are not a major contributor to cavity formation in the residual spray film.

A single drop test matrix was created from the studied spray characteristics. This test plan consisted of the following dimensionless number ranges: $150 \leq We \leq 1,000$, $1,200 \leq Re \leq 3,300$, and $0.2 \leq h_0^* \leq 1.0$. A glycerol-water solution was utilized to match the single droplet parameters to the spray data. Due to the size difference of the spray and single droplets, the Froude numbers were unable to be matched for the current apparatus.

Sub-cavity radius histories have been determined for single drop impacts using two complementary high-speed imagery techniques. Good agreement has been observed between the two

measurements. The behavior of the sub-cavity radius evolution has been shown to be consistent with results by Berberovic *et al.* (2009). It was found that the maximum sub-cavity radius was relatively insensitive to the initial liquid layer thickness for a given droplet Weber number for the given range of h_0^* studied in the current work. However, it was observed from the results that the maximum sub-cavity radius would increase with an increasing Weber number, for Weber numbers below ~ 600 for the current range. Consistent with literature, increasing the Weber number and/or the initial dimensionless film thickness will delay the onset of the cavity retraction phase (Berberovic *et al.*, 2009 and Hinsberg *et al.*, 2010). The measured sub-cavity radii were in good agreement with the radial distribution of the sub-cavity liquid film thickness.

Single drop high-speed flow visualization has been performed for the single drop impingements of the given test range. A cavity wave was observed in nearly all of the test conditions, which is termed a “capillary wave” in the literature (Fedorchenko and Wang, 2004, Roisman *et al.*, 2008, and Berberovic *et al.*, 2009). However, the high-speed imagery showed evidence that the cavity wave that occurs during the receding phase of the cavity is partially gravity driven. The effects of this cavity wave were observed in the majority of the sub-cavity measurements in the current work (R_c^* data, h surface plots, and Vol^* data). Splashing created by the single drop impacts was in good agreement with criteria developed by Cossali *et al.* (1997).

Single drop sub-cavity liquid film thickness histories have been measured, from the cavity centerline out to the maximum sub-cavity radius, for the test conditions summarized in Table 7.1. Centerline sub-cavity film thickness trends were in good agreement with similar work by Van Hinsberg *et al.* (2010). During the droplet impingement process a thin, nearly constant minimum sub-cavity liquid film thickness ($\sim 3\%$ - 4.5% of the droplet diameter) was quickly established, lasting until the onset of the cavity receding phase. The initial dimensionless film thickness and

Weber number had only minor effects on the minimum sub-cavity film thickness. However, the lifetime of the cavity increased dramatically with increasing Weber number and/or initial dimensionless layer thickness, consistent with the sub-cavity radius results. Another way to examine the sub-cavity film thickness data was to normalize it with the initial liquid layer thickness. This allowed the effects of viscous friction forces to be observed, where it was observed that $h_0^* = 0.2$ resulted in a thicker h/h_0 ratio. Surface contour plots of the sub-cavity liquid film thickness showed a nearly uniformly distributed liquid film thickness, except for thinner regions at the outer radial locations. This demonstrates that sub-cavity volumes computed using the current method provide higher quality data compared to using the sub-cavity radius and an average minimum centerline sub-cavity film thickness. Low Weber numbers of less than approximately 400 displayed uneven sub-cavity film thickness contours.

Detailed analysis of the sub-cavity volume histories has been performed. Typical sub-cavity volumes resulted in a nearly constant value until the initiation of receding. Deviations from this trend were generally observed for conditions with $h_0^* = 0.2$. For these scenarios the propagating cavity wave would result in a temporary expansion of the radial sub-cavity film thickness distribution. This resulted in significantly larger sub-cavity volumes for this time. Variations in We and h_0^* had the same effect on sub-cavity volume lifetimes as were observed for the respective centerline sub-cavity film thickness sub-cavity radii results. That is, the sub-cavity volume lifetime increased with increasing We and/or h_0^* . It was found that the maximum sub-cavity volume increased with increasing Weber number up to $We \approx 600$ for $h_0^* > 0.2$. It was also observed that for the given range h_0^* the sub-cavity volume also increases with thicker initial dimensionless film thicknesses. Plateau regions of the computed sub-cavity volume as percentage of the initial drop volume were nominally 70% to 90% for $h_0^* \approx 1.0$, 60% to 75% for $h_0^* = 0.5$, and 57% to 65% $h_0^* = 0.2$. However, sub-cavity

volumes for $h_0^* = 0.2$ would generally increase to a maximum of nominally 80% of the initial drop volume when the cavity wave propagated to the floor.

Section 8.2: Future Work

The presented sub-cavity volume results for the We , Re , Fr , and h_0^* studied herein will be incorporated into the current Monte-Carlo spray cooling model (Kreitzer, 2010) to improve its predictive capabilities. Sub-cavity volumes can be scaled to the spray of interest, and may be treated as a constant over the sub-cavity volume lifetime in the MC model, thus simplifying the computation. Local wall heat fluxes can be computed by applying the localized heat flux enhancement levels computed by Sarkar and Selvam (2009) to the sub-cavity volumes. Including the contributions of these localized cavity heat fluxes is anticipated to improve the accuracy of the MC model.

Also, the contributions of the cavities to the onset of boiling and subsequent CHF for relevant spray conditions can be investigated. Localized wall heat fluxes that would be needed for the onset of boiling and subsequent dry out in the drop impact cavity can be computed utilizing the measured sub-cavity volumes and their lifetimes. It is hoped that this might lead to an accurate estimate of the overall average heat flux required for onset of CHF.

It is suggested that CFD simulations of the present single droplet test parameters listed in Table 7.1 be performed. Single drop Froude numbers can then be matched to actual spray results to investigate its influence on the sub-cavity region. Also, with the use of CFD the percentage of impinging droplet liquid and initial layer liquid can be computed for Table 7.1. Knowledge of the concentration of the cool droplet liquid in the sub-cavity film would be beneficial. This data would not only improve predictive capabilities of the MC spray cooling model, but also contribute to a greater understanding of the spray cooling heat transfer mechanisms.

Additional sub-cavity experiments based on the methods developed in the current work should be performed. This includes examining the effects that a single droplet train impinging on a wetted surface would have on the liquid sub-cavity results. It would also be beneficial to investigate the effects of multiple single droplets impinging near the vicinity of each other. In addition, it is suggested that heated sub-cavity single droplet experiments be performed. These data would also contribute to a more accurate MC model.

The PDPA splashed droplet data presented in Chapter 6 can also be incorporated into the initial MC model. If proper volume fluxes can be obtained from this data, it would greatly improve the liquid spray film mass conservation in the MC model. This author recommends that future PDPA be performed for a less dense spray. This would provide smaller drop number fluxes and improve the quality of the PDPA data, ultimately leading to more accurate volume fluxes.

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Appendix A: CAD DRAWINGS

This Appendix contains the CAD drawings with dimensions of the major components of the single drop apparatus. Units are in inches.

Figure A.1: Base mounting plate (0.25 in thick stainless steel sheet) used to attach to the leveling plate to the structural frame (units in inches).

Figure A.2: Leveling plate (0.25 in thick stainless steel sheet) used to level the single droplet tank (units in inches).

Figure A.3: Base plate (0.25 in thick stainless steel sheet) used to attach the acrylic tank to the micro-traverse (units in inches).

Figure A.4: Acrylic impact stand used for sub-cavity liquid film thickness experiments (units in inches).

A.5: Acrylic impact stand with larger viewing port used for the BV sub-cavity radius experiments (units in inches).

Figure A.6: Acrylic tank (units in inches).

a)

b)

Figure A.7: Final Single drop test facility Assembly. a) Backlit configuration. b) Tank and impact surface fixed to the micro-traverse.

Appendix B: ADDITIONAL PDPA SPRAY DATA (NO IMPACT SURFACE)

This Appendix contains the additional basic spray (no spray impact surface installed) PDPA data results for the various flow conditions not presented in Chapter 6. Included are the raw droplet diameter and velocity PDPA data histograms, and the average droplet diameter and velocity distributions. It should be noted that y-traverse profiles have been only measured at $z = 3.81$ cm.

Figure B.1: Spray droplet diameter, speed, axial velocity, and radial velocity for a 2.76 bar and 43.5 L/hr at $z = 3.81$ cm. a) Center of the spray, $R_s = 0$ cm. b) Edge of spray, $R_s = 2.47$ cm.

Figure B.2: Spray droplet diameter, speed, axial velocity, and radial velocity for a 1.38 bar and 29.5 L/hr at $z = 3.81$ cm. a) Center of the spray, $R_s = 0$ cm. b) Edge of spray, $R_s = 2.47$ cm.

Figure B.3: Average droplet velocity magnitude profiles at a constant $z = 3.81$ cm for the different pressure cases $\blacktriangle \triangle$ 1.38 bar, 29.5 L/hr; $\bullet \circ$ 2.76 bar, 43.5 L/hr; $\blacklozenge \diamond$ 4.14 bar, 54.5 L/hr; — x -plane data; ---- y -plane.

Figure B.4: Variation of the standoff distance of the measuring profile to the nozzle for a spray flow condition of the average velocity magnitude for 4.14 bar and 54.5 L/hr.

c) **Figure B.5: Average droplet characteristic profiles at a constant $z = 3.18$ cm for the different pressure cases. a) Arithmetic mean diameter. b) Sauter mean diameter. c) Average axial velocity. d) Average radial velocity. e) Average velocity magnitude. $\blacktriangle$ 1.38 bar, 29.5 L/hr; $\bullet$ 2.76 bar, 43.5 L/hr; $\blacklozenge$ 4.14 bar, 54.5 L/hr.**

Figure B.6: Average droplet characteristic profiles at a constant $z = 4.45$ cm for the different pressure cases. a) Arithmetic mean diameter. b) Sauter mean diameter. c) Average axial velocity. d) Average radial velocity. e) Average velocity magnitude. $\blacktriangle$ 1.38 bar, 29.5 L/hr; $\bullet$ 2.76 bar, 43.5 L/hr; $\blacklozenge$ 4.14 bar, 54.5 L/hr.

Appendix C: ADDITIONAL PDPA SPLASHING DATA (WITH IMPACT SURFACE)

Contained within this appendix are additional plots of the spray PDPA data collected with the spray impact surface installed to generate splashing. Additional PDPA data of the droplet diameter and velocity histograms separated into the spray, ejected splash, return splash, and absolute splash components for flow conditions listed Table 3.3 are contained herein. Also included are the PDPA splashed droplet characteristic profiles for both the x -axis and vertical edge traverses

Figure C.1: Histograms of the incoming spray droplet data for 4.14 bar, 54.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.2: Histograms of the ejected splashed droplet data for 4.14 bar, 54.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.3: Histograms of the returning splashed droplet data for 4.14 bar, 54.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.4: Histograms of the absolute splashed droplet data for 4.14 bar, 54.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.5: Histograms of the incoming spray droplet data for 2.76 bar, 43.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.6: Histograms of the ejected splashed droplet data for 2.76 bar, 43.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.7: Histograms of the returning splashed droplet data for 2.76 bar, 43.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.8: Histograms of the absolute splashed droplet data for 2.76 bar, 43.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.9: Histograms of the incoming spray droplet data for 1.38 bar, 29.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.10: Histograms of the ejected splashed droplet data for 1.38 bar, 29.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.11: Histograms of the returning splashed droplet data for 1.38 bar, 29.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.12: Histograms of the absolute splashed droplet data for 1.38 bar, 29.5 L/hr at $z = 3.65$ cm at a single point. a) $R_s = 0$ cm. b) $R_s = 2.47$ cm.

Figure C.13: Droplet velocity magnitude of the spray, ejected, return, and absolute splash data with the impact surface installed for a flow condition of 4.14 bar, 54.5 L/hr at a constant $z = 36.5$ mm. $\diamond$ Impinging spray droplets, $\triangle$ ejected splashed droplets, $\square$ returning splashed droplets, $\bullet$ absolute splashed droplets.

Figure C.14: Absolute splashed droplet mean velocity magnitude profile for varying pressures at a constant $z = 36.5$ mm.

Figure C.15: PDPA data of the mean velocity magnitude versus z at $R_s = \pm 2.68$ cm.

Figure C.16: Comparison of the spray droplet characteristics with and without the impact surface installed a flow condition of 2.76 bar, 43.5 L/hr at a constant $z = 36.5$ mm. a) Arithmetic mean diameter. b) Sauter mean diameter. c) Mean axial velocity. d) Mean radial velocity. e) Mean velocity magnitude. $\diamond$ Impinging spray droplets, $\triangleleft$ ejected splashed droplets, $\square$ returning splashed droplets, $\bullet$ absolute splashed droplets.

Figure C.17: Comparison of the spray droplet characteristics with and without the impact surface installed a flow condition of 1.38 bar, 29.5 L/hr at a constant $z = 36.5$ mm. a) Arithmetic mean diameter. b) Sauter mean diameter. c) Mean axial velocity. d) Mean radial velocity. e) Mean velocity magnitude. $\diamond$ Impinging spray droplets, $\triangleleft$ ejected splashed droplets, $\square$ returning splashed droplets, $\bullet$ absolute splashed droplets.

Figure C.18: Ejected splashed droplet characteristics at varying pressures at a constant $z = 36.5$ mm. a) Arithmetic mean droplet diameter. b) Sauter mean droplet diameter. c) Mean axial velocity. d) Mean radial velocity. e) Mean velocity magnitude.

Figure C.19: Returning splashed droplet characteristics at varying pressures at a constant $z = 36.5$ mm. a) Arithmetic mean droplet diameter. b) Sauter mean droplet diameter. c) Mean axial velocity. d) Mean radial velocity. e) Mean velocity magnitude.

Appendix D: GLYCEROL-WATER SOLUTION METHODOLOGY AND CHR THICKNESS VALIDATION

Appendix D contains further explanation of how the glycerol-water solution by mass was computed to match the single drop and spray dimensionless numbers (We and Re). Also, included is a comparison of the of a static liquid layer thickness measured manually from the videos and by the CHR sensor.

The correct glycerol-water mass fraction, calculated from Equation D.1, was solved iteratively starting with the target Weber number. The process for computing the viscosity and density of different glycerol-water concentrations follows procedure described by Cheng (2008). The corresponding volume fraction (Equation D.2) was initially computed for pure water (0% volume fraction of glycerol in water). The “Goal Seek” Excel function was used to iterate the necessary volume fraction of glycerol to produce the proper Reynolds number. Then the droplet velocity was iterated using same function to match the Weber number with the target value again. The Droplet velocity and volume fraction of the solution was iterated until their respective errors converged. Surface tensions were computed from Equation D.3, which was extracted from a data base (Glycerol Producer’s Society, 1963) plotted versus mass fraction in Figure D.1.

Equation D.1 was used to compute the mass percentage of the water-glycerol solution.

$$C_m = \frac{m_G}{m_G + m_W} \quad D.1$$

Equation D.2 was used to compute the volume percentage of the water-glycerol solution.

$$\Phi_m = \frac{Vol_G}{Vol_G + Vol_W} \quad D.2$$

Figure D.1: Surface tension versus glycerol-water solution percent concentration by mass for $T = 20^\circ$.

Surface tension for the glycerol-water mixture where computed using the linear curve fit from Figure D.1 given by Equation D.3.

$$\sigma_{sol} = -0.0804C_m + 73.591 \quad D.3$$

Figure D.2: Viscosity prediction from Cheng (2008) compared with data from Glycerol Producer's Association (1963).

Figure D.3: Density prediction from Cheng (2008) compared with data from Glycerol Producer's Association (1963).

Equations D.4 - D.6 are curve fits of measured refractive indexes and were used to compute the refractive index of the water-glycerol solution based on percent mass (Glycerol Producer's Association, 1963).

$$\eta_{sol} = 1.3303 + 0.001124C_m + 0.00000605C_m^2 - 0.000000555C_m^3, \quad \text{for } C_m: 0 - 44\% \quad \text{D.4}$$

$$\eta_{sol} = 0.00149C_m + 1.32359, \quad \text{for } C_m: 45-79\% \quad \text{D.5}$$

$$\eta_{sol} = 0.90799 + 0.0154C_m - 0.000155C_m^2 + 0.000000576C_m^3, \quad \text{for } C_m: 80 - 100\% \quad \text{D.6}$$

Figure D.4: Comparison of the predictive capability of curve fits from Glycerol Producers Association (1963) with available refractive indices of glycerol-water mixtures.

Undisturbed static film thickness measurements were performed by manually measuring an image in the Photron FASTCAM Viewer software. This was compared with the CHR sensor readings using the refractive index computed for glycerol-water solution of 46.2% by mass using Equation D.5. Figure D.5 shows that the distance was measured to the bottom of the wall meniscus.

Figure D.5: Initial film thickness manual measurements.

Table D.1 lists the measured liquid film thickness computed from the respective video analysis and CHR sensor readings. Indexes of refraction were back computed using Equation 4.1, and the variance was compared with the refractive index used for the CHR sensor. The CHR refractive index was 1.39 computed for a 46.2% water-glycerol solution using Equation D.5. The variance was negligible thus the curve fits from Equations D.4 - D.6 are acceptable. The variance that does occur can be contributed to the 50.7 μm pixel resolution in the video analysis.

Table D.1: Target liquid film thickness measured by the CHR sensor and by video. Included is the refractive index calculated by the video analysis for a glycerol-water mixture of 46.2%.

CHR Sensor		Video Analysis		
h (μm)	h_0 (μm)	h_0 (μm)	η	$c_v(\eta)$
2,304	3075	3,093	1.40	$\pm 0.40\%$
2,254	3005	3,042	1.38	$\pm 0.77\%$
2,141	2848	2,890	1.41	$\pm 1.0\%$
2,315	3104	3,093	1.39	$\pm 0.26\%$
2,310	3083	3,093	1.40	$\pm 0.23\%$

Appendix E: ADDITIONAL SINGLE DROPLET SUB-CAVITY RESULTS

Contained herein are the single drop sub-cavity results for Cases 1 - 5 not presented in Chapter 7. Included are the respective sub-cavity radius and centerline sub-cavity liquid film thickness histories. Also included are the average measured droplet characteristics used to compute the dimensionless numbers in Table 7.1.

Table E.1: Measured sub-cavity single drop parameters and standard deviations for Cases 1 - 5 for each h_0^* .

Case	h_0^*	h_0 (μm)	D (mm)	V (m/s)	$std(d)$ (mm)	$std(v)$ (m/s)	$std(xc)$ (mm)
1	1.0	3,020	3.03	1.73	0.0689	0.0115	0.0931
	0.5	1,530	3.06	1.73	0.0326	0.0244	0.0551
	0.2	724	3.03	1.67	0.0341	0.0462	0.0939
2	1.0	3,500	3.47	2.72	0.0106	0.00460	0.0270
	0.5	1,760	3.47	2.73	0.0101	0.00370	0.0397
	0.2	714	3.48	2.72	0.00940	0.00790	0.0457
3	1.0	3,010	3.09	3.55	0.0359	0.00520	0.0859
	0.5	1,550	3.08	3.55	0.0288	0.0128	0.0666
	0.2	606	3.11	3.66	0.0278	0.00578	0.430
4	0.9	3,120	3.49	3.69	0.00633	0.00676	0.0770
	0.5	1,730	3.47	3.72	0.0170	0.00925	0.0621
	0.2	695	3.46	3.75	0.0213	0.00892	0.0661
5	0.9	3,160	3.52	4.20	0.00682	0.00562	0.0770
	0.5	1,750	3.54	4.16	0.00925	0.00662	0.0689
	0.2	707	3.52	4.18	0.0350	0.00456	0.0950

Table E.2: Average ambient conditions and respective variance recorded during the Single drop experiments for Cases 1 – 5 for each h_0^* .

Case	h_0^*	T ($^{\circ}\text{C}$)	Abs(P) (inHg)	RH	$std(T)$ (mm)	$std(Abs(P))$ (m/s)	$std(RH)$
1	1.0	N/A	N/A	N/A	N/A	N/A	N/A
	0.5	22.0	28.6	47.6%	0.109	0.0209	1.77%
	0.2	20.7	27.3	41.6%	0.115	0.0154	1.07%
2	1.0	21.4	29.1	28.4%	0.311	0.0140	0.505%
	0.5	21.6	29.1	27.3%	0.302	0.0156	0.480%
	0.2	21.8	28.9	43.6%	0.298	0.0104	0.756%
3	1.0	22.0	29.1	<20.0%	0.255	0.314	N/A
	0.5	21.7	29.3	<20.0%	0.380	0.242	N/A
	0.2	21.7	28.6	46.1%	0.250	0.0722	1.290%
4	0.9	21.4	29.1	36.5%	0.132	0.0189	0.0519%
	0.5	21.5	30.0	34.5%	0.210	0.0132	0.00660%
	0.2	21.4	29.9	27.0%	0.302	0.00832	0.000%
5	0.9	21.8	28.8	44.3%	0.163	0.0249	0.0467%
	0.5	21.7	28.8	45.5%	0.262	0.000	0.522%
	0.2	21.8	28.8	44.7%	0.163	0.0767	0.467%

a) b)
Figure E.1: Sub-cavity radius histories varying for Cases 1 – 5 at $h_0^* = 1.0$ ($h_0^* = 0.9$ for Cases 4 and 5). a) Bottom-view results. b) Side-view results.

a) b)
Figure E.2: Sub-cavity radius histories varying for Cases 1 – 5 at $h_0^* = 0.2$. a) Bottom-view results. b) Side-view results.

Figure E.3: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 1, $h_0^* = 0.2$ ($We = 135$, $Re = 1,180$, $Fr = 94.0$).

Figure E.4: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 1, $h_0^* = 0.5$ ($We = 146$, $Re = 1,290$, $Fr = 99.0$).

Figure E.5: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 1, $h_0^* = 1.0$ ($We = 145$, $Re = 1,190$, $Fr = 100$).

Figure E.6: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 2, $h_0^* = 0.2$ ($We = 414$, $Re = 2,290$, $Fr = 217$).

Figure E.7: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 2, $h_0^* = 0.5$ ($We = 413$, $Re = 2,270$, $Fr = 219$).

Figure E.8: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 2, $h_0^* = 1.0$ ($We = 410$, $Re = 2,250$, $Fr = 217$).

Figure E.9: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 3, $h_0^* = 0.2$ ($We = 667$, $Re = 2,740$, $Fr = 439$).

Figure E.10: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 3, $h_0^* = 1.0$ ($We = 621$, $Re = 2,640$, $Fr = 415$).

Figure E.11: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 4, $h_0^* = 0.2$ ($We = 780, Re = 3,100, Fr = 413$).

Figure E.12: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 4, $h_0^* = 0.5$ ($We = 771, Re = 3,090, Fr = 407$).

Figure E.13: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 4, $h_0^* = 0.9$ ($We = 762, Re = 3,080, Fr = 398$).

Figure E.14: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 5, $h_0^* = 0.2$ ($We = 984, Re = 3,560, Fr = 407$).

Figure E.15: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 5, $h_0^* = 0.5$ ($We = 984$, $Re = 3,560$, $Fr = 499$).

Figure E.16: Contour plot of with the bottom-view (dashed line), side-view (dotted line), and averaged (solid line) sub-cavity radius overlaid for Case 5, $h_0^* = 0.9$ ($We = 993$, $Re = 3,570$, $Fr = 510$).

a)

b)

Figure E.17: Dimensionless sub-cavity liquid film thickness (h^*) histories for varying the initial droplet condition (We , Re , and Fr) at a constant h_0^* . a) $h_0^* = 1.0$ for Case 1 – 3 and $h_0^* = 0.9$ for Cases 4 - 5. b) $h_0^* = 0.2$.

a)

b)

Figure E.18: Sub-cavity liquid film thickness ratio h/h_0 histories for varying the initial droplet condition (We , Re , and Fr) at a constant h_0^* . a) $h_0^* = 1.0$ for Case 1 – 3 and $h_0^* = 0.9$ for Cases 4 - 5. b) $h_0^* = 0.2$.

Figure E.19: Dimensionless sub-cavity liquid film thickness (h^*) histories for varying the h_0^* at a constant initial droplet condition (We , Re , and Fr). a) Case 1. b) Case 2. c) Case 3. d) Case 4.

Figure E.20: Sub-cavity liquid film thickness ratio h/h_0 histories for varying the h_0^* at a constant initial droplet condition (We , Re , and Fr). a) Case 1. b) Case 2. c) Case 3. d) Case 4.