INCIPIENT BREAKUP OF LIQUID DROPS IMPACTING ON DRY SURFACES

A graduate project submitted in partial satisfaction of the requirements for the degree of Master of Science in Engineering

by

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NOMENCLATURE

Symbols

D - drop diameter
Fr - impact Froude number
$\Delta \Delta$ - height increment step size
h - drop height
$h_i$ - incipient breakup drop height
$\Delta h$ - uncertainty of drop height
n - drop count
$\Delta n$ - uncertainty of drop count
Re - impact Reynolds number
$Re_i$ - incipient breakup Reynolds number
$\Delta Re_i$ - uncertainty of incipient breakup Reynolds number
We - impact Weber number
$We_i$ - incipient breakup Weber number
$\Delta We_i$ - uncertainty of incipient breakup Weber number
$\delta$ - film thickness
$\delta^*$ - dimensionless film thickness ($\delta/D$)
$\mu$ - viscosity
$\sigma$ - surface tension
$\rho$ - density
k - surface roughness
ABSTRACT

INCIPIENT BREAKUP OF LIQUID DROPS
IMPACTING ON SMOOTH DRY SURFACES
by
Constantine Peroulias
Master of Science in Engineering

An experimental study has been performed to study incipient breakup of impacting liquid drops for condition of dry surface splash. The study was performed to determine the functional relationship between Reynolds number and the Weber number at incipient breakup. The experimental results suggest that the incipient breakup of droplets on dry surfaces may be correlated using the Reynolds number (Re), Weber number (We), and surface relative roughness (k/D).
CHAPTER I

INTRODUCTION

Numerous studies of the liquid splashing event have been made and the fields of interest in which the phenomenon is of importance are quite varied. In the early phases, Worthington (17) investigated this event through the then relatively new technique of spark photography.

Liquid droplet splash is defined as the sequence of events which take place during the impact of liquid drops onto a liquid pool, a thin film on a solid surface or on a dry solid surface. Depending on certain characteristics (such as fluid density, surface tension, velocity, drop diameter), splash can occur with or without breakup. Droplet breakup is defined as occurring when distinct secondary droplets are ejected radially during splash.

Developments in the fields of cloud physics, atmospheric electricity, soil erosion, plant diseases, and more recently, the aerospace industry have shown that the process of splashing is often a crucial event requiring serious study. Almost without exception, recent investigations of splashing have concentrated on the observation of the hydrodynamics of the impact itself. Dimensional analysis shows that the occurrence of breakup depends on the Reynolds number (Re), the Weber number, and the relative roughness k/D of a dry surface.
The purpose of this study is to investigate the functional relationship between the Reynolds number and the Weber number, for incipient breakup of a droplet upon impact with a dry surface of a fixed roughness.
CHAPTER II
LITERATURE REVIEW

2.1 INTRODUCTION

A search of literature has not uncovered any studies which have determined the necessary conditions for droplet breakup. However, the literature did provide a wealth of information describing and analyzing the liquid drop splash phenomenon. A survey of major studies and conclusions found during the literature search are presented. It should be noted that there were some references as to when breakup did not occur during splash, and these references are discussed.

2.2 OBSERVATIONS ON SPLASH

The effect of various physical parameters are emphasized in the review of the literature. The liquid droplet splash phenomenon is classified as pool splash, thin film splash, or dry surface splash.

2.2.1 POOL SPLASH

A good number of studies have been concerned with the impact of liquid drops on deep liquid pools. In these cases, as shown by the original work of Worthington and Cole (18), the following sequence of events takes place. After a drop has collided with the surface, a thin film of liquid approximately cylindrical in shape is thrown upward and outward from the periphery of the drop. The height of this cylindrical film increases as the drop penetrates further into the liquid, and small
jets of liquid are shot out from the upper rim of the film giving it the appearance of a crown. These jets break up into numerous small liquid fragments. At the same time, the cavity which forms beneath the surface of the liquid, due to the impact of the drop, is enlarged. As the wall of the crown begins to subside and thicken, the cavity collapses. The combined effects of the collapse of the cavity and the subsidence of the crown cause a relatively large column of liquid, known as the Rayleigh jet, to form at the base of the cavity and then rise above the surface. The Rayleigh jet may pinch off to form one or more large drops.

As the depth of the liquid into which the drop splashes is decreased, the features of the splash described above undergo changes as shown by the work of Hobbs & Osheroff (7), and Macklin & Hobbs (19). For example, if a drop of water 2.3 mm in diameter falls through a distance of 75 cm in air before it impacts on liquid water, it was found that as the depth of the water is decreased from 25 to 7 mm, the maximum height to which the Rayleigh jet rises increases and more drops break away from the Rayleigh jet. However, for depths of water less than 7 mm, both the height of the Rayleigh jet and the number of drops which break away from it fall off sharply. No drops break away from the Rayleigh jet for depths of water less than about 3 mm. In addition, it was found that the crown becomes increasingly unstable as the
depth of the water is decreased below about 5 mm. The variations in the nature of the splash with depth of liquid have been explained by Macklin & Hobbs in terms of the interaction of the subsurface cavity with the solid boundary beneath the shallow liquid.

Using high-speed photography, Hobbs & Alkezweeny (8) also studied the deep-water splash. They measured the times required for the formation of the initial crown and the Rayleigh jet. They also made a cursory study of splash products and noted that the number of products increased with impact velocity and that a velocity existed below which no splash products could be observed.

2.2.2 THIN FILM SPLASH

Thin film splash is the limiting case of the pool splash where the pool thickness is significantly reduced so that the Rayleigh jet does not form. In this case the drop formation is entirely due to the breakup of the crown. Macklin & Metaxas (1) found that the cavity formed during thin film splash is approximately cylindrical. Levin & Hobbs (10) in a high-speed photographic study showed that a crown is formed when water drops impact on a water film about .5mm in depth. In addition, jets develop on the periphery of this crown with the jets becoming unstable and breaking into fragments.

Ji (22) performed measurements of the conditions for incipient drop breakup for several liquids and liquid film thicknesses. He presented the results graphically
in the form of a curve of Reynolds number vs Weber number for each constant value of the dimensionless film thickness. The drops breaking off at Weber numbers less than approximately 80 were small, and the heights of the crown were low. For the Weber numbers greater than 80, the size of the drops breaking off appeared to be significantly larger, and the crown was higher.

During a study of the dispersal of fungus spores, Gregory, Guthrie, & Buncy (5) investigated the splashing of water drops into thin liquid layers containing a suspension of spores. They varied the depth of their water layers over a range from 0.2 mm to 1.0 mm and noted that the numbers of splash products decreased as the depth of the layer was increased. Regardless of the conditions, a negligible proportion of ejected droplets were found at distances greater than 70 cm from the point of impact.

Stow & Stainer (15) observed the physical products of splashing water drops with respect to several parameters such as, impact velocity, drop size, surface tension, radius of curvature and roughness of the target surface, and the depth of liquid film covering the surface of the target. They concluded that the number of droplets produced by a splash increases with surface roughness, impact velocity and drop size, but decreases with an increase in liquid film depth and with a reduction in surface tension of the drop.
Studies of splashing on solid surfaces were initiated by Worthington (17). He investigated the patterns left by the ejected drops of various liquids after they had struck a horizontal smoked-glass plate. Most of the recent work which has been done on splashing on solid surfaces has been concerned with the erosion caused by the impact. Engle (2,3) chemically mapped the radial flow of a splashing water drop by placing a crystal of sodium dichromate in the bottom of a drop before allowing it to fall onto treated filter paper. She found that no crown formed and that the water which contacted the surface first was washed to the periphery of the flow, and that water which impacted last essentially did not flow.

Levin & Hobbs (10) investigated the impact of drops on a dry copper surface, with roughness characteristics ranging from very smooth to comparatively rough. They observed that when water drops impact onto a very smooth dry copper surface a crown is not formed. The drop simply spreads out radially over the surface. When water drops impact on a rough dry copper surface the liquid flows radially outward from the bottom of the drop to form a thin liquid layer on the solid surface. On the periphery of this layer a liquid crown forms and extends upward. As the drop collapses the liquid layer increases in area and the crown increases in height.
Cheng (1) conducted a theoretical and experimental study of the behavior of drops impacting onto a dry solid surface. He observed that the impacting drop forms a flat disk, and derived a theoretical maximum dynamic spread factor in terms of the Weber number and a correction factor C, which depends upon the drop size and velocity and the nature of the drop and target surface.

Wachters & Westerling (16) studied the heat transfer when a liquid drop impinges upon a very hot plate. They observed that a crown is not formed, instead a vapour layer forms under the drop which causes the drop to behave like a rubber ball and rebounds from the surface after a short contact time.

2.3 ANALYTICAL AND NUMERICAL APPROACH ON SPLASH

2.3.1 ANALYTICAL WORK

Numerous theoretical and analytical studies have been performed on droplet splash. Engel (4) derived approximate theoretical expressions for the spread of the liquid drop and the pressure within the drop after impact. She based her analysis on a combination of flow and pressure wave arguments.

She also studied the cavity that is produced when a liquid drop impinges against the surface of a liquid and the cylinder of liquid that rises at the periphery of this cavity. She derived an expression for the cavity depth as a function of time and impact energy. Her calculations were based upon the energy conservation law.
DeSande, Smith, & Oord (13) developed and presented a mathematical model for the prediction of the crater depth in target liquids following the impact of liquid drops. This model is based upon the energy conservation law and experimental verification fits very well. The analytical approach is similar to that used by Engle.

Macklin & Metaxas (11) developed equations in dimensionless form to predict the crater depth and cavity size for both the deep-pool splash and the thin film splash. Macklin & Metaxas concluded that deep-pool splash could be characterized by the Froude number and the Weber number. The Froude number which is the ratio of the gravitational force to the inertia force can be neglected for thin film splash, because the splash bowl is low and the fraction of the impact energy converted into gravitational potential energy is negligible. The viscosity effects are also neglected due to the low viscosity of liquids modeled.

2.3.2 NUMERICAL WORK

Numerical work, on droplet splash, is very limited. Harlow & Shannon (6) have applied a method of numerically solving the complete Navier-Stokes equation to the problem of a drop splashing on a deep-pool, a thin film, and a dry surface, and produced computer animated results. They found that the solution was sensitive to the Froude number. The effect of surface tension, and therefore, the Weber number was not considered in the numerical
calculations.

Foote (2) used a method for studying the dynamics of liquid drops to examine the motion of colliding drops, with application to the raindrop problem. His conclusions were that the characteristics of the motion following impact, including the amount of deformation experienced and the time for rebound, can be predicted by a knowledge of only the Weber number. The calculations indicate that viscous effects upon collision should be relatively minor for all water drop sizes involved in the rain formation process.

2.4 SUMMARY

The literature survey has uncovered numerous studies, related to liquid splash. Table 1 summarizes the most significant studies related to the drop splash found in the literature. In addition, the literature survey pointed out certain dimensionless parameters associated with deep-pool, thin film, and dry surface splash. Macklin & Metaxas (11) have found that deep-pool splash can be characterized by the Weber number and the Froude number, and the thin film splash characterized by the Weber number. Ji (22) did a quantitative study of incipient breakup of liquid drops impacting on thin liquid films. He found that the film splash is characterized by Reynolds number, Weber number, and dimensionless film thickness.

Results discussed above indicate that dry surface splash on a smooth surface produces radial spreading.
without the formation of a crown. Nevertheless, it is anticipated that the conditions for incipient drop breakup will involve a Weber number-Reynolds number relationship similar to that found by Ji. However, because of the differences in the mechanism for breakup the Reynolds number-Weber number relationships for incipient breakup should be quantitatively different. The determination of this difference is the goal for this study.
# TABLE 1

## SUMMARY OF LITERATURE

### A. OBSERVATION OF SPLASH

<table>
<thead>
<tr>
<th>NAME OF AUTHOR</th>
<th>SUBJECT/TITLE</th>
<th>IMPORTANT CONCLUSIONS/OBSERVATIONS</th>
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<tr>
<td>Worthington (17,18)</td>
<td>&quot;A Study of Splashes&quot;</td>
<td>He initiated studies on splashing using spark photography. He observed the impact of drops on deep liquids, and the formation of the liquid crown, Rayleigh Jet (wet surface). He also investigated the patterns left by drops of liquid on smoked glass plates (dry surface).</td>
</tr>
<tr>
<td>Hobbs &amp; Alkezweeny (8)</td>
<td>&quot;Splashing of a Water Drop&quot;</td>
<td>They studied deep-water splash by measuring the time required for the formation of the initial crown and the subsequent Rayleigh Jet. They also concluded that the number of splash products increased with impact velocity and that a velocity existed below which no products could be observed.</td>
</tr>
<tr>
<td>Stow &amp; Stainer (15)</td>
<td>&quot;The Physical Products of a Splash in Water Drop&quot;</td>
<td>The physical products of splashing water drops were investigated with respect to impact velocity, drop size, surface tension, radius of curvature and roughness of the target surface and the depth of liquid film covering the surface of the target. They concluded that the number of droplets produced by a splash increases with surface roughness, impact velocity, and drop size, but decreases with an increase in liquid film</td>
</tr>
<tr>
<td>NAME OF AUTHOR</td>
<td>SUBJECT/TITLE</td>
<td>IMPORTANT CONCLUSIONS/OBSERVATIONS</td>
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<tr>
<td>Hobbs &amp; Osheroff (7)</td>
<td>&quot;Splash of a Liquid Drop&quot;</td>
<td>They found that as the liquid layer depth decreased from 25 mm to 7 mm there was an increase in the height of the Rayleigh Jet and in the number of droplets that pinched off. For depths less than 7 mm both effects were diminished and no drops were ejected for depths of 3 mm or less.</td>
</tr>
<tr>
<td>Gregory, Guthrie &amp; Bunce (5)</td>
<td>&quot;Experiments on Splash Dispersal of Fungus Spores&quot;</td>
<td>They investigated the splashing of water drops onto thin liquid layers containing a suspension of spores. They varied the depth of their water layers over the range from 0.2 mm to 1.0 mm and noted that the number of splash products decreased as the depth of the layer was increased.</td>
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### TABLE 1 (CONT)

#### B. HYDRODYNAMICS

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<th>IMPORTANT CONCLUSION/ OBSERVATIONS</th>
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<tr>
<td>Levin &amp; Hobbs (10)</td>
<td>&quot;Splashing of Water Drops on Solid &amp; Wetted Surfaces&quot;</td>
<td>They investigated the hydrodynamics of splashing onto rough solid copper hemisphere and on thin layers of liquid. They concluded that in both cases a crown is formed and jets develop on the periphery of the crown, but the time scale of the events associated with splashing on a rough surface is much shorter than for splashing into shallow liquids. They also found that when water drops impact onto a very smooth solid surface a crown is not formed and the drop spreads out radially over the surface.</td>
</tr>
<tr>
<td>Macklin &amp; Metaxas (14)</td>
<td>&quot;Splashing of Drops on Liquid Layers&quot;</td>
<td>The splashing of drops on deep and shallow liquid layers has been investigated experimentally. They concluded that a deep pool splash can be characterized by the Weber number and the Froude number. With the thin film splash characterized by the Weber number.</td>
</tr>
<tr>
<td>Engel (3,4)</td>
<td>&quot;Crater Depth Fluid Impacts&quot;</td>
<td>She performed experimental and analytical studies of water splashing onto treated filter paper. She concluded that the water which contacted the surface first was washed to the periphery of the flow.</td>
</tr>
<tr>
<td>NAME OF AUTHOR</td>
<td>SUBJECT/TITLE</td>
<td>IMPORTANT CONCLUSIONS/OBSERVATIONS</td>
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<tr>
<td>Cheng (1)</td>
<td>&quot;Dynamic Spreading of Drops Impacting onto a Solid Surface&quot;</td>
<td>He conducted a theoretical and experimental study of the behavior of drops impacting onto a dry solid surface. He observed that the impacting drop forms a flat film and derived a theoretical maximum dynamic spread factor in terms of the Weber number and a correction factor C, which depends upon the drop size and velocity. Also the nature of the drop and the target surface.</td>
</tr>
<tr>
<td>Ji (22)</td>
<td>&quot;Incipient Breakup of Liquid Drops Impacting on Thin Liquid Films&quot;</td>
<td>He performed measurements of the conditions for incipient drop breakup for several liquids and liquid film thicknesses. He presented the results graphically in the form of a curve of Reynolds number vs Weber number for each constant value of the dimensionless film thickness.</td>
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## C. HEAT TRANSFER

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<td>Wachters, Bonne &amp; Van Nouhuis (23)</td>
<td>&quot;The Heat Transfer from a Hot Horizontal Plate to Sessile Water Drops in the Spheroidal State&quot;</td>
<td>They investigated the heat transfer from a hot metal surface to a water drop resting upon it. They concluded that the critical temperature for the occurrence of the spheroidal state depended upon the volume of the drop, the amplitude of possible oscillations, and the roughness of the metal surface.</td>
</tr>
<tr>
<td>Wachters &amp; Westerlings (16)</td>
<td>&quot;The Heat Transfer from a Hot Wall to Impinging Water Drops in the Spheroidal State&quot;</td>
<td>They studied the heat transfer when a liquid drop impinges upon a very hot plate. They concluded that a crown is not formed, instead a vapour layer forms under the drop.</td>
</tr>
<tr>
<td>Kazikawa (20)</td>
<td>&quot;Supercooled Droplets on Iced Plate&quot;</td>
<td>He studied the rebound of supercooled droplets colliding with an ice plate. He concluded that the rate of rebound was 2 to 3 percent and the rebounded droplets were frozen. No formation of crown was observed.</td>
</tr>
</tbody>
</table>
CHAPTER III

THEORY

Breakup behavior on a smooth dry solid surface is influenced by several factors, such as, the size of the drop (D), its velocity of impact (V), the roughness (k), the density (ρ), and viscosity (μ) of the fluid.

The dimensionless groups related to the drop splash on a dry solid surface can be formed from the above variables and hence related to the breakup. For breakup the following expression holds:

* \( \text{Breakup Behavior} = f(\rho, \mu, \sigma, V_i, D, g, k) \)

A simple Buckingham Pi analysis leads to:

* \( \text{Breakup Behavior} = f(Re, We, Fr, k^*) \)

Where

* \( Re = \frac{\rho V_i D}{\mu} \)
* \( We = \frac{\rho V_i^2 D}{\mu} \)
* \( Fr = \frac{gD}{V_i^2} \)
* \( k^* = \frac{k}{D} \)

** See Appendix C
The relative importance of these dimensionless parameters is not evident. However, since the objective of this study is to investigate the incipient drop breakup the drop inertia prior to the impact, the surface energy, the film thickness, and shear energy dissipated, will be important in determining whether or not breakup will occur. Therefore, it is expected that the Reynolds number, the Weber number, relative roughness will be important factors. Furthermore, one might expect a functional relationship between these dimensionless parameters at the incipient breakup point to exist. This relation could be expressed functionally as:

\[ F (We_I, Re_I, k/D) = 0 \]

where \( k \) is the surface roughness.
CHAPTER IV

EXPERIMENTAL APPARATUS

4.1.1 INTRODUCTION

The major components of the experimental apparatus are:

1. High Speed Camera

2. Lighting Fixture

3. Drop Generator

4. Drop Surface

Figure 1 shows the experimental set-up and the relative position of the various components.

FIGURE 1
4.1.2 HIGH SPEED CAMERA

A high speed motion picture camera is often used in liquid drop splash studies. In the present study a Fastax
High Speed camera was used to detect whether or not drop
breakup occurs at conditions close to the point of
incipient breakup, since this is extremely difficult to
determine with the naked eye.

The Fastax camera was used with 16 mm-film and is
of the continuously moving film type, employing a four­sided compensating prism, positioned between the lens and
the direct-drive film sprocket. The prism rotates in
synchronism with the continuously moving film to compensate
for relative image to film movement. Synchronism is
achieved by direct gearing between the film drive sprocket
and the rotating prism.

The camera operating speed was determined from timing
marks exposed on the film edge. An external timing lamp
assembly was used, consisting of a neon glow lamp. The
lamp was energized by a 24 volt DC power supply and the
frequency was set at 1000 Hz.

A standard bayonette base f/2.0 50 mm Raptar lens
was used. With this lens a depth of focus of 0.25 inches
and a field of view of 2 inches x 3 inches was obtained.

The roll of film was push processed in DK-50 film
developer for 5 minutes at 20°C and stop bath (acid-coater
solution) for 1 minute and fixed in a normal fixer for
10 minutes and finally rinsed with water for 5 minutes.
4.1.3 LIGHTING FIXTURE

The lighting fixture consisted of a 300 watt flood light, placed at the optimum distance from the target surface. A translucent screen was placed between the lighting source and the target surface for uniform illumination.

4.1.4 DROP GENERATOR

Various micro-burettes were tested with diameters ranging from 0.125 to 0.375 inches. For the final experiment a 0.375 inch droplet drop generator, with 0.1 ml graduated markings and a turn valve for uniform size drops, was selected.

The drop generator was attached to a fixture having the freedom to move up and down at fixed increments so that the impact velocity (free fall velocity) could be varied.

The drops left the burette with zero initial velocity. The rate of production of drops depended on the physical properties of the liquid. The liquids used were water, 15%, 30%, 60%, 85% mixture of glycerine and water, as well as, Dow 704 (pump oil).

4.1.5 DROP SURFACE

Experimental test procedures were repeated several times using various surfaces. These surfaces included glass, smooth sheet metal and aluminum. The smooth sheet surface was selected for the final test run with the high-speed camera. The sheet metal was used with no preparation
such as, sanding or polishing. Grease was removed from the surface with water and detergent (glass cleaner).
CHAPTER V

5.0 EXPERIMENTAL PROCEDURE

5.1 EXPERIMENTAL PROCEDURE WITHOUT THE HIGH SPEED CAMERA

Since high speed photography is an expensive process, a preliminary set of experiments was conducted without the camera, to reduce the use of film.

The objective here was to establish an approximate range of experimental drop height where the breakup occurred for each liquid and to select the drop generator, as well as, the material of the impact surface. The definition of Weber number \( \left( \frac{\rho V^2 D}{\sigma} \right) \) indicates that in order to have a low experimental height, the diameter of the drop must be large.

The approximate range of experimental drop height was established for each liquid, starting with water.

Each range was established by starting from an arbitrary height where no breakup occurred to a height where the first breakup was visually observed using step changes of 2 inches for low viscosity liquids and 5 inches for high viscosity liquids. This process was repeated a number of times to assure that this range included incipient breakup.

The principal requirement for the receptable target surface was that the surface was absolutely dry when the first drop struck the surface. Special care was taken to insure that this criterion was met. After each drop splash the surface was wiped clean and a small fan blew
dry air directly on it, eliminating any moisture. Also, the target area had to be sufficiently large so that the wall boundary did not affect the splash.

5.2 EXPERIMENTAL PROCEDURE WITH THE HIGH-SPEED CAMERA

The test liquid used were water, Dow 704 (pump oil) and 15%, 30%, 60%, & 85% glycerine-water solutions. After selecting a test liquid the temperature was measured, as well as, the specific gravities of the glycerine-water solutions. These measurements were repeated for different test liquids on a given day for a single experiment. In addition, the value of density, viscosity, and surface tension were obtained from reference (24). The 300 watt flood light was turned on and aimed at the impact area. Several trial runs were performed to obtain proper lighting. The optimum distance from the base of the high-speed camera to the impact area for the f/2.0 50 Raptar lens used was 23 inches.

The drop generator was positioned at the starting drop height and the impact area was established so that the camera field of view could be determined. A paper clip was positioned at the one end of the field view and was used as a reference to determine the drop size. The camera was then prefocused on a liquid drop in the impact area. After a trial and error period, it was found that the proper position of the camera was with the surface elevation matching the camera's lens center line.

The camera was loaded in a dark room with Tri-x 430.
high-speed film. After loading, the camera was connected to the DC power supply and to the external timing lamp. As soon as a drop broke free from the drop generator, the camera switch was turned on to insure that the first drop impacting the dry surface was recorded. Subsequent drops striking the residue of the first droplet were not considered.

Data reduction was accomplished using a stop/start motion picture projector which allowed the image of a single frame to be kept on the screen indefinitely.
CHAPTER VI
RESULTS AND DISCUSSION OF RESULTS

6.1 RESULTS

6.1.1 INTRODUCTION

The point of incipient breakup was found by examining the motion picture film. The incipient breakup condition was assumed to occur when the first sign of particles being ejected was detected. The incipient breakup drop height was defined to be the midpoint between the drop height where breakup was first detected and this height reduced by the value of the step size used to increment the drop height. The values of the Reynolds number and the Weber number at the incipient breakup point were calculated by using the incipient breakup drop height. The values of the incipient Reynolds number and Weber number with their corresponding uncertainties are listed in Table 2, and the data is plotted in Figure 2. Appendix B shows the experimental data.

<table>
<thead>
<tr>
<th></th>
<th>We&lt;sub&gt;I&lt;/sub&gt;</th>
<th>Re&lt;sub&gt;I&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1,089 ± 5.6</td>
<td>27,500 ± 207</td>
</tr>
<tr>
<td>15% Glycerine Sol</td>
<td>1,285 ± 5.7</td>
<td>20,000 ± 115</td>
</tr>
<tr>
<td>30% Glycerine Sol</td>
<td>1,698 ± 6.0</td>
<td>14,140 ± 94</td>
</tr>
<tr>
<td>60% Glycerine Sol</td>
<td>2,110 ± 11.0</td>
<td>3,746 ± 31</td>
</tr>
<tr>
<td>85% Glycerine Sol</td>
<td>4,300 ± 39.0</td>
<td>1,269 ± 9</td>
</tr>
<tr>
<td>DOW 704</td>
<td>38,939 ± 42.0</td>
<td>1,200 ± 8</td>
</tr>
</tbody>
</table>
PLOT OF REYNOLDS NUMBER VS WEBER NUMBER
FOR INCIPIENT BREAKUP ON A DRY SURFACE

FIGURE 2
6.1.2  NATURE OF SPLASH AND BREAKUP

Figures 3, 4, and 5 show a sequence of photographs of the splash produced by water, 30%, and 85% Glycerine solution respectively.

These photographs reveal the main features of splashing on smooth solid surfaces. After impact the liquid flows radially outward from the bottom of the drop to form a thin liquid layer on the solid surface. As the drop collapses the liquid layer increases in area forming a flat disk with liquid particles attached at the periphery of the disk. The formation of a liquid crown or a Rayleigh jet never materialized for the conditions and type of liquids investigated.

It should be noted that there are marked differences between the splashing of drops on smooth dry solid surfaces and splashing on wet surfaces (deep liquids or thin film liquids). When drops impact onto a smooth dry solid surface, a liquid crown or Rayleigh jet are not formed but in the case of splashing on wet surface a liquid crown is formed.

6.2  DISCUSSION OF RESULTS
6.2.1  COMPARISON TO LITERATURE

The results of this study can be most directly compared with that of Ji (22) who measured incipient breakup for several liquids and liquid film thicknesses. The results have been plotted in the form of Reynolds number vs Weber number for two fixed values of the
FIGURE 3
SEQUENCE OF PHOTOGRAPHS OF SPLASH BREAKUP
PRODUCED BY WATER
FIGURE 4

SEQUENCE OF PHOTOGRAPHS OF SPLASH BREAKUP PRODUCED BY 30% GLYCERINE SOLUTION
FIGURE 5
SEQUENCE OF PHOTOGRAPHS OF SPLASH BREAKUP
PRODUCED BY 85% GLYCERINE SOLUTION
dimensionless film thickness.

The curves show that the incipient breakup of droplets on thin films may be correlated using the Reynolds number and the Weber number.

Several features should be noted in Figure 2, which is the plot of the incipient Reynolds number vs Weber number for a dry surface. At low Weber numbers less than 1300 the values of the Reynolds number are very sensitive to the value of the Weber number and hence independent of the Reynolds number. A small change in the Weber number results in a large change in the Reynolds number. At values of Weber number greater than 2110, the Reynolds number remains fairly constant with respect to the Weber number and hence independent of the Weber number. Also, for the Weber number between 1300 and 2110, there is an intermediate zone linking the two asymptotic regions of the curve. This is demonstrated in Figure 6.

Figure 7 shows the plot of the incipient Reynolds number vs Weber number for a dry surface, as well as, the plot of the incipient Reynolds number vs Weber number for a thin film. For comparison, it can be seen that both curves have the same characteristics, although the magnitudes of Reynolds number vs Weber number are notably larger for a dry surface than for thin films.
REI

BEHAVIOR OF INCIPENT BREAKUP CURVE

Independent of Reynolds number

Breakup

Independent of Weber number

FIGURE 6
PLOT OF REYNOLDS NUMBER VS WEBER NUMBER
FOR INCIPIENT BREAKUP ($\delta/D = 0.1$) AND ON A DRY SURFACE

+ $\delta/D = 0.1$

* DRY SURFACE

FIGURE 7
Ji (22) observed the formation of a liquid crown during the incipient breakup for thin films, where as in this study no formation of a crown was found.

This observation is consistent with the results reported by Levin & Hobbs (10), who found that a crown does not form when water drops impact onto a very smooth solid surface, the drop simply spreads out radially over the surface. Cheng (1) also found that drops impacting onto a dry smooth solid surface spread without a crown.
CHAPTER VII

CONCLUSIONS

Measurements were made of the conditions for the incipient breakup for several liquids on smooth dry surfaces. The results have been plotted in the form of Reynolds number vs Weber number.

Although the curves were based on limited selection of liquids and drop diameters, the curves suggest that the breakup of droplets on dry surfaces may be correlated using the Reynolds number and Weber number.

Even though the experimental curves found for the incipient breakup on smooth surfaces have the same characteristics, (not magnitude) with the incipient breakup on thin films the nature of splashing and breakup is different.

Also, a liquid crown and Rayleigh jet never formed during a liquid-solid impact.
CHAPTER VIII

RECOMMENDATION

Additional experimental work should be performed to verify and expand the reported results.

The experimental tests should be performed by using different combinations of drop diameter, impact velocity, and liquid properties.

A reasonable test range would extend from dry surface splash to a ratio of film thickness to the drop diameter equal to 1.0. During future tests additional flood lights, should be added to improve the illumination.

Also the influence of surface roughness, on drop breakup during splash and crown formation needs further investigation.
BIBLIOGRAPHY


(22) Hyun-Chul, J., "Incipient Breakup of Liquid Drops Impacting on Thin Liquid Films", Master Project, California State University, Northridge, (1985).


APPENDIX A

DATA REDUCTION AND ERROR ANALYSIS

A.1 INTRODUCTION

High speed photography was used to define the point of incipient breakup of the droplet splash. The incipient breakup condition was defined to occur when the first sign of particles being ejected was detected. The incipient breakup drop height was interpolated and defined to be the midpoint between the drop height where breakup was first detected and this height reduced by the value of the step size used to increment the drop height. The values of Reynolds number and Weber number at the incipient breakup point were calculated by using the incipient breakup drop height.

A.2 DATA REDUCTION

The impact velocity was calculated by using the free fall formula such that

\[ V_i = \sqrt{2gh} \]

where \( h \) is the distance from the center of the drop hanging under the burette to the surface of the target film. With the value of the drop height and the liquid properties, the values of the Reynolds number and Weber number at the incipient breakup point could be calculated as:
A.3 ERROR ANALYSIS

A.3.1 INTRODUCTION

The primary factors contributing to the uncertainty of the Reynolds number and Weber number at the incipient point are the uncertainty of the experimental height, drop diameter, and the impact velocity. The uncertainty of the physical properties of the liquid in comparison is negligible.

A.3.2 UNCERTAINTY DUE TO DROP SIZE AND IMPACT VELOCITY

Assuming that the uncertainty of the liquid properties is negligible, the uncertainty due to the drop height, drop diameter, and the impact velocity is calculated by using the formula recommended by Kline & McClintock (9).

\[ W_R = \sum_{i=1}^{n} \left( \frac{\partial R}{\partial r} \right) W_i \]
\( W_R \) is the uncertainty of the desired value \( R \) and \( W_1 \) is the uncertainty of the variable \( r_1 \). When the expressions for the drop diameter, impact velocity, and the expressions for their uncertainties which are obtained by differentiation are put into the equation of Kline & McClintock, one gets:

\[
\Delta W_{\epsilon I} = \left[ \frac{2g\rho (D)^{1/3}(\Delta h + \Delta H/2)}{6} + \frac{4g\rho h \nu (D)^{-2/3} \Delta \eta}{\pi \sigma \eta^2} \right]^{1/2}
\]

\[
\Delta R_{\epsilon I} = \left[ \frac{\rho}{\mu} \left( \frac{g/2h}{D} \right)^{1/2} (D)^{1/3}(\Delta h + \Delta H/2) \right]^{1/2} + \left[ \frac{2(2g\rho) h^{1/2} \nu (D)^{-2/3} \Delta \eta}{\pi \mu \eta^2} \right]^{1/2}
\]

The symbols \( \Delta n \) and \( \Delta h \) represent the uncertainty of the drop and the measured drop height. The symbol \( H \) represent the drop height increment step size.

A.4 SAMPLE CALCULATION

A sample calculation is provided to demonstrate the calculation procedure for the values and errors of the Reynolds number and Weber number at the incipient point. This calculation uses the water as the test liquid. The following data are known at 20\(^{\circ}\)C.

* Density = 998.2 Kg/M3
* Viscosity = 1,005 Cp
* Surface Tension = 73.9 dyne/cm
* Incipient Breakup = 0.423 \( \pm \) 0.01
* Drop Height
The impact velocity can be calculated as follows:

* $D = 0.00952 \text{ m}$

* $V_i = \sqrt{2 \times 9.81 \times 0.423} = 2.880 \text{ m/s}$

* $V_i = 2.880 \text{ m/s}$

The value of the Reynolds number and the Weber number at the incipient point is calculated as shown.

* $Re_i = \frac{[998.2] \times [2.88] \times [0.00952]}{1.005 \times 10^{-3}}$
  $Re_i = 27,500$

* $We_i = \frac{[998.2] \times [2.88]^2 \times [0.00952]}{0.0739}$
  $We_i = 1,089$

The uncertainty of the Weber number and the Reynolds number at the incipient breakup point is calculated below.

* $\sqrt{\left( \frac{0.0254}{0.0739} \right) \left( \frac{998}{998} \right) \left( \frac{0.00952}{0.425} \right) \left( 6 + 2.5 \right)^{1/3} \left( \frac{998}{998} \left( 5 \times 10^{-6} \right) \left( 0.00952 \right)^3 \left( 0.0739 \right)^{13} \right)}$

$We_i = 5.6$
The values of the Reynolds number and the Weber number at the incipient breakup point are

* \( \text{Re}_I = 27,500 \)
* \( \text{We}_I = 1,089 \)
APPENDIX B

EXPERIMENTAL DATA

<table>
<thead>
<tr>
<th></th>
<th>Temp. (°C)</th>
<th>S. Gravity</th>
<th>Drop Height (in)</th>
<th>Step Size (in)</th>
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<tbody>
<tr>
<td>Water</td>
<td>20</td>
<td>-</td>
<td>15 - 20</td>
<td>1</td>
</tr>
<tr>
<td>15% Glycerine</td>
<td>20</td>
<td>-</td>
<td>18 - 25</td>
<td>1</td>
</tr>
<tr>
<td>30% Glycerine</td>
<td>24</td>
<td>1.0716</td>
<td>22 - 28</td>
<td>1</td>
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<td>24</td>
<td>1.1495</td>
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</tr>
<tr>
<td>85% Glycerine</td>
<td>24.5</td>
<td>1.2120</td>
<td>34 - 46</td>
<td>2</td>
</tr>
<tr>
<td>DOW 704</td>
<td>30</td>
<td>-</td>
<td>40 - 60</td>
<td>5</td>
</tr>
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TABLE 3

EXPERIMENTAL VALUES

<table>
<thead>
<tr>
<th></th>
<th>Dia. (in)</th>
<th>Density (Kg/M3)</th>
<th>Viscosity (Cp)</th>
<th>S. Tension (dyne/cm)</th>
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<tr>
<td>Water</td>
<td>0.375</td>
<td>998</td>
<td>1.005</td>
<td>73.9</td>
</tr>
<tr>
<td>15% Glycerine</td>
<td>0.375</td>
<td>1034</td>
<td>1.510</td>
<td>72.7</td>
</tr>
<tr>
<td>30% Glycerine</td>
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<td>1068</td>
<td>2.155</td>
<td>72.0</td>
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<tr>
<td>60% Glycerine</td>
<td>0.375</td>
<td>1146</td>
<td>8.248</td>
<td>69.0</td>
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<td>0.375</td>
<td>1208</td>
<td>53.08</td>
<td>66.5</td>
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<tr>
<td>DOW 704</td>
<td>0.375</td>
<td>1069</td>
<td>39.00</td>
<td>37.3</td>
</tr>
</tbody>
</table>

TABLE 4

PHYSICAL PROPERTIES OF LIQUIDS

51
APPENDIX C

BUCKINGHAM PI ANALYSIS

Theorem: For n variables and m = 3 fundamental dimensions (F,L,T) there will be at least (n-m) dimensionless groups.

For thin film splash one expects that

* Breakup Behavior = f (ρ,μ,σ,k,g,v₁,D)

According to the Buckingham Pi theorem

* Breakup Behavior = f (π₁,π₂,π₃,π₄)

The values of the 4 Pi groups can be determined by assuming

* π₁ will contain - ρ,v₁,D, and μ

* π₂ will contain - ρ,v₁,D, and σ

* π₃ will contain - ρ,v₁,D, and k

* π₄ will contain - ρ,v₁,D, and g

In order for these Pi groups to be dimensionless, any one quantity in each may appear to the first power and the others appear to the unknown powers which must be determined.
Four sets of algebraic equations can be written and solved to determine the values of the constants. It can be shown that the 4 Pi groups are

\[ \pi_1 = [FT^2/L^4]^{a_1}[L/T]^{a_2}[L]^{a_3}[FT/L^2] = L^0F^0T^0 \]
\[ \pi_2 = [FT^2/L^4]^{b_1}[L/T]^{b_2}[L]^{b_3}[F/L] = L^0F^0T^0 \]
\[ \pi_3 = [FT^2/L^4]^{c_1}[L/T]^{c_2}[L]^{c_3}[L] = L^0F^0T^0 \]
\[ \pi_4 = [FT^2/L^4]^{d_1}[L/T]^{d_2}[L]^{d_3}[L/T^2] = L^0F^0T^0 \]

The Reynolds number represent the ratio of the inertia force to the viscous force, the Weber number represent the ratio of the inertia force to the surface tension force, the Froude number represent the ratio of the gravitational force to the inertia force, and k/D represent the ratio of the surface roughness to the drop diameter.