DETERMINATION OF THE SPLASH PROPERTIES OF VARIOUS LIQUIDS USING HIGH-SPEED PHOTOGRAPHY

by

LISA CAROL GLITSCH

Submitted in Partial Fulfillment

of the Requirements for the

Degree of Bachelor of Science

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June, 1976

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ABSTRACT

The dynamics of the splashing process for various liquids has been investigated using high-speed photography. A dimensional-analysis method is used to correlate the height of the Rayleigh jet and the degree of crown disintegration to the Weber ($\rho V_0^2 R/\gamma$) and Reynolds ($\rho V_0 R/\eta$) numbers of the liquids where ρ, γ, and η are respectively the fluid properties of density, surface tension, and viscosity, R is the radius of the impingement droplet, and V_0 is the droplet impact velocity. In addition the effect of the splash-pool depth on the jet height and the degree of crown disintegration were studied. Extensive data were taken for dyed water and several data points were taken for toluene, ethanol, glycerin, olive oil, and mercury.

It has been found that the jet height increases as the liquid viscosity and surface tension decrease, that the jet height is proportional to approximately the square of the droplet impact velocity, and that the degree of crown disintegration is related to the jet height. It was also found that the jet height is related to the splash-pool depth when this depth is less than 15 mm for a water droplet 1.5 mm in radius. More explicitly, the jet height is zero at zero pool depth, approaches a constant value at a depth of 15 mm, and exhibits a maximum at the intermediate depth of approximately 9 mm.

Thesis Supervisor: Harold E. Edgerton
Institute Professor of Electrical Engineering

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CHAPTER I

INTRODUCTION

The phenomena associated with liquid drop splashes play important roles in many naturally occurring events such as soil erosion and the dispersal of seeds and microorganisms. In addition, the electrical charges which are separated during splashing are responsible for waterfall electrification and probably also play a role in separating electrical charges in natural clouds.

The first quantitative studies of splashes were conducted by Rayleigh (1879) and Worthington (1900, 1908), who first photographed the process. In the century following their studies much additional work, both theoretical and experimental, has been done to further define the process. Numerical solutions to the Navier-Stokes equation in two dimensions have been obtained to describe the dynamics of the fluid during the splash (Harlow, June, 1967; September, 1967). Experimentally, relations have been determined for the maximum crater depth produced by the impact (Engel, 1966, 1967; van de Sande, et al, 1974) and for the number of spray droplets ejected during the splash (Hobbs and Kezweeny, 1967). Also, the effect of pool depth on the nature of the splash has been investigated (Hobbs and Osheroff, 1967; Macklin and Hobbs, 1969).

Briefly, the events that occur during splashing are the following. A drop impacts the surface of a liquid; a crater is formed; and the displaced liquid is thrown up and around the drop in a circular wall. The wall rises in height to a maximum level as the drop penetrates the surface and then collapses. The downward flow of liquid into the crater results in the ejection of a large column of liquid known as the Rayleigh jet. The crater wall often pinches off into separate drops producing a crown. Smaller droplets are also seen to spray from the crown and jet. These droplets are responsible for the dispersal of microorganisms and for soil erosion. The results of the work which has been done to more completely describe the process are outlined in the subsequent paragraphs.

In Harlow's numerical solutions of the Navier-Stokes equations, the system is modeled on the size of drop to depth of pool ration and the impact velocity of the drop, neglecting both surface tension and viscosity effects. His findings are summarized as follows: 1) When a drop impinges on a flat plate, no upward motion of liquid is observed, instead the drop spreads across the plate in a lateral sheet at 1.6 times its impact speed. 2) When a drop splashes into a shallow liquid, an upward motion is observed. Even a very thin film of liquid is enough to interact appreciably with the lateral sheet to produce a crown. However, no jet is observed. 3) In a deep pool splash the crucial parameter is the impact velocity. As the velocity increases above a critical value, the drop breaks into separate pieces upon impact and the splashing is changed. Below this critical value, the process is normal, a crown and jet both forming. 4) Shortly after the drop hits the surface of the liquid it is greatly distorted. The mass in the drop is divided into three principle regions. Most of the drop is in the base of the crater waiting to be pushed up into the Rayleigh jet. A small amount is carried up the crater wall, and some is pushed down through the crater to form a downward jet. This downward jet was first observed experimentally by Hodgin (1975).

The experimental and theoretical studies of Engel and van de Sande describe the maximum crater depth in terms of the energies of the splashing drop. The theoretical results are based on solving Laplace's equation in cylindrical coordinates, invoking conservation of energy. The equation derived by Engel to give R_m, the maximum radius of the cavity in the target liquid is,

$$R_m = \left[\left(\frac{d^3 \rho_d V^2}{6.6667\, g \rho_t} + \frac{311.49\, \gamma^2}{g^2 \rho_t^2} \right)^{\frac{1}{2}} - \frac{17.649\, \gamma}{g \rho_t} \right]^{\frac{1}{2}} \qquad \text{(I-1)}$$

where ρ_d is the density of the drop liquid and ρ_t that of the target liquid; d is the drop diameter; V is the impingement velocity; g is the acceleration due to gravity; and γ is the surface tension of the target liquid. Although the experimental data agree well with the theory, tests have been made only for drops with very high velocities. It is not certain that the equation holds for low velocity impacts.

Hobbs and Kezweeny, experimenting with a milk-water solution, found a linear relation between the number of spray droplets produced from the crown and the distance of fall of the drop. They also determined that the number of droplets produced was related to the amount of time that the crater wall remained above the surface. Their results seem reasonable in light of the fact that the kinetic energy of the drop is linearly proportional to its distance of fall and that the amount of time the crater wall remains above the surface is related to the energy given to the liquid by the drop. Hobbs and Osheroff, experimenting again with a milk-water solution, were the first to study the number of spray drops produced in splashes on shallow liquids. When a drop impacts a shallow liquid the nature of the splash process is greatly altered because the boundary at the bottom of the pool modifies the force configuration. Since a fluid is incapable of withstanding shear stresses, the force exerted by a fluid at any given instant must always be perpendicular to its surface. The presence of the rigid boundary at the bottom of the liquid creates a surface where the condition of perpendicular forces must be satisfied and thus the pressures which cause the rise of the crater wall and Rayleigh jet are different in a shallow liquid than in a deep liquid. Their results indicate that, for a drop radius of 1.5 mm, the depth at which the bottom of the pool becomes noticeable is approximately 15 mm. Below this depth the maximum height of the Rayleigh jet and the number of drops broken off from the jet increases with decrease in depth to a depth of about 8 mm at which point both fall off rapidly. The average number of drops into which the jet disintegrates was found to be approximately 3.5. Below 2 mm, no jet is formed. The crown is extremely unstable and tends to disintegrate completely into rather large drops. Unfortunately as they counted only the number of large, observable drops and did not try to record the number of smaller spray droplets produced, their results are of limited usefulness since it is the small drops which are most important in transport processes. Repeating their experiments with dyed water, which has a higher surface tension than the milk-water solution, they found no essential difference in the results except that the dyed water tended to rise much higher although producing approximately the same number of jet drops.

Despite the amount of work which has been done on studying the splash process, no one has as yet determined the functional relation between the fundamental fluid properties, density, viscosity, and surface tension and the nature of the splash involved, that is, the maximum rise of the Rayleigh jet and the size and height of the crown. Harlow tries to dismiss the effects of surface tension and viscosity as unimportant. Others have made generalized assumptions regarding their effect which have been justified neither theoretically nor experimentally. In this thesis an attempt has been made to clarify the importance of fluid properties by experimentally testing liquids of varying properties. In addition, the effect of the depth of the target pool was studied. In all cases the splashes tested were made with the drop and target liquids the same. A theory is developed based on a dimensional analysis model to quantitatively describe the general importance of fluid properties. It is the author's hope that the empirical relation developed in this thesis will be of help to others who try to study the phenomena of splashing in the future.

CHAPTER II

APPARATUS AND PROCEDURES

Basically, the experimental apparatus consisted of a hypodermic needle and syringe which produced uniform droplets, a tank in which the splash was made, and the photographic set-up which recorded the splash, A total of six liquids were used as described in Table II-1. In all cases, the drop and target liquid were identical.

Liquid	Density($\frac{gm}{cc}$)	Viscosity(cpoise)	Surf. tension($\frac{dyne}{cm}$)
Water	1.000	1.053	72.05
Toluene	.88	.590	28.5
Glycerin	1.26	1490.	63.4
Ethanol	.90	1.20	22.7
Olive oil	.918	84.0	41.5
Mercury	13.546	1.534	476.

Table II-1 Properties of Liquids Used In Thesis

The procedure for producing splashes in all liquids except mercury was fairly similar. To produce a drop of reasonably constant size, the liquids were forced under a constant pressure head through a hypodermic needle fitted on a graduated syringe. The syringe was mounted in a clamp which could be moved vertically on a ringstand. For all liquids except ethanol, a 26 gauge needle was used which created drops ranging from 2.9 to 3.1 mm in diameter. For ethanol a 22 gauge needle was used producing drops from .8 to 1.2 mm in diameter. The tank in which the splashing occurred was a cylindrical metal can which was 5 cm deep and 6 cm in radius.

The procedure for mercury was different for two reasons. First it is very difficult to make a large drop with mercury, and second extra care must be taken to avoid contaminating the laboratory. Mercury cannot be contained in a syringe. It sprays out the needle in many tiny drops under its own weight. To form the splash drops, a measured amount of mercury was placed in a funnel plugged with a wooden rod. The rod was removed quickly so that the mercury would fall out as one drop. The splash was made in a rectangular, transparent plastic box 3" deep by 3" long by 1" wide. The box was placed in a large tank with a glass front, and the floor was covered with a heavy cloth to catch any extra drops which might escape.

Two different stroboscopic set-ups were used. All of the pictures of the water splashes were taken with a 35 mm camera fitted with extension tubes for close focusing and using a General Radio 1540 strobolume for illumination. With this light source the maximum f-stop which could be attained using Tri-X film was f-8. Since at this aperture setting the depth of field when focusing on an object 3 cm away is only a few millimeters, the resulting pictures were unsatisfactory. To remedy this situation, a brighter light source was found. For all of the later pictures an EG&G 4000 v flash lamp hooked into a 6 μf capacitor was used. With this bright source pictures could be taken with a 4x5 camera using Plus-X film at f-32. To trigger the flash, a pen light was aimed through the path of the drop at a photocell. When the drop passed through the light beam, the photocell emitted a negative electrical pulse which triggered the strobe. A delay unit was added to the system so that various stages of the splash could be photographed.

Many pictures were taken of the crown and jet in order to study their size and shape. To measure the height of the jet, a ruler was placed in the pool and the delay was carefully adjusted visually until the flash caught the jet at its maximum height. When the jet remained intact, the height of the jet was determined by measuring the height of the jet body. However when the jet disintegrated or pinched off into one or more drops, the height of the jet was determined by the ascent of the first drop of radius larger than 1 mm. To avoid parallax problems, the camera was positioned as closely as possible in a horizontal plane even with the markings on the ruler. Several pictures were taken to accurately determine the average height of the jet.

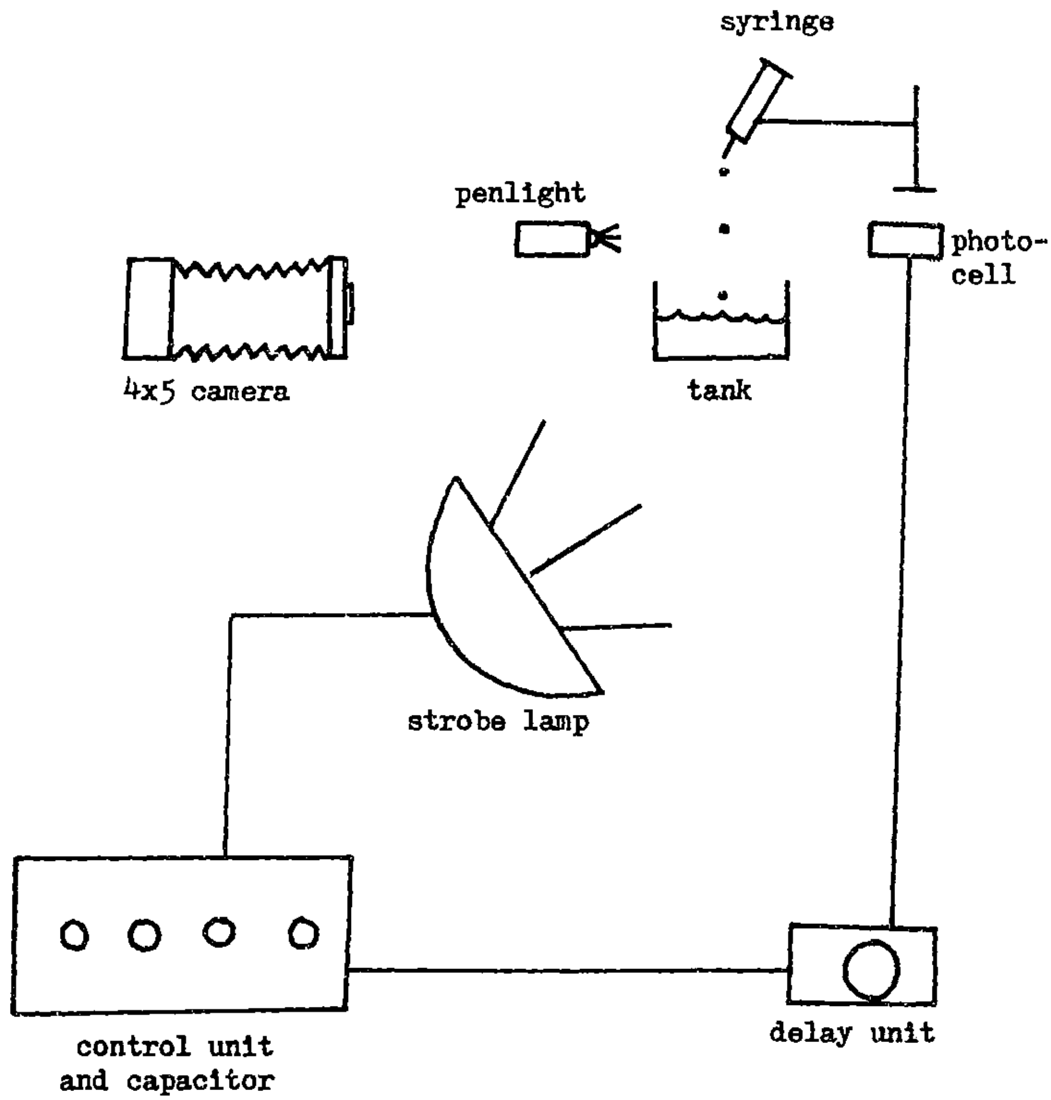


Figure II-1 Experimental Apparatus

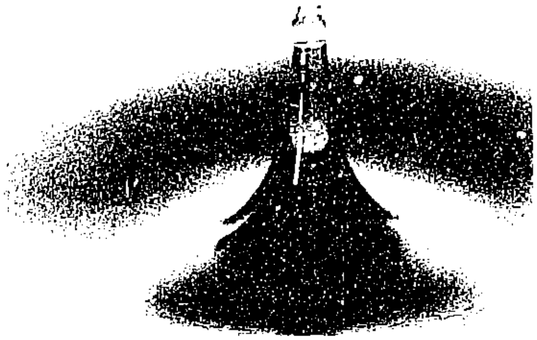
CHAPTER III

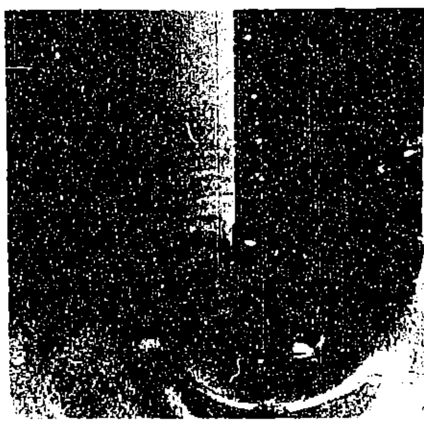
RESULTS

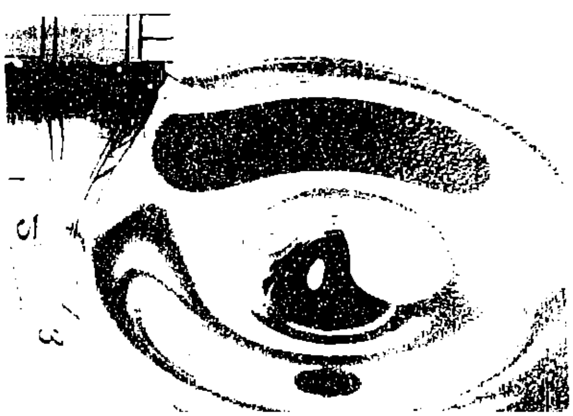
As Hobbs and Kezweeny (1966) have already shown that the number of minute spray droplets ejected from the jet is linearly proportional to its maximum rise, the measurement of the maximum jet height is sufficient to characterize the splashing process. In all cases the maximum height of the Rayleigh jet was determined by measuring either the maximum rise of the jet body, if the jet stayed intact, or the maximum ascent of the first drop of radius larger than 1 mm, if the jet disintegrated. There are two reasons for choosing this particular drop size to determine the height of the jet. In pictures which show the jet before it disintegrates completely, the head is seen to pinch off into a drop of approximately 1 mm radius. Since the jet is composed of the original drop fluid and contains very little, if any, target fluid, it cannot rise to arbitrarily large heights in one piece without breaking into smaller drops. Thus, measuring the height of the first large drop is equivalent to measuring the height of the jet. Furthermore, since drops of various sizes are seen to shoot out of the head of the jet, it is necessary to standardize the size of the reference drop. Smaller drops carrying the same momentum as large drops rise much higher. Measuring the height of the first observable drop without taking into account its size would give meaningless results.

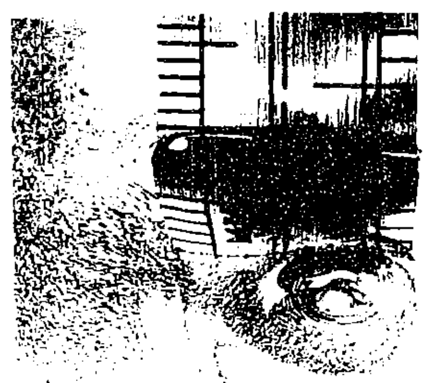
Because it is much more difficult to determine the height of the crown than that of the jet, as the crater wall rises at most only 1 or 2 mm above the liquid surface and may or may not break into several drops, the author chose to establish a scale from 0-4 to define the degree of disintegration of the crater wall, which is also proportional to the number of spray droplets ejected. The scale is defined as such: 0 - no break-up of the wall whatsoever, wall remains smooth; 1 - top of wall begins to wrinkle but does not coalesce; 2 - crater wall forms bulges which do not break away as drops, small drops are seen to spray from crown; 3 - large drops of diameter greater than 1 mm break away from crown but most of crown remains; 4 - entire crown disintegrates. Although mildly subjective, this scale provides a reasonable description of the degree of crown disintegration and probably gives the best estimate of the number of spray droplets efected outside of counting them directly.

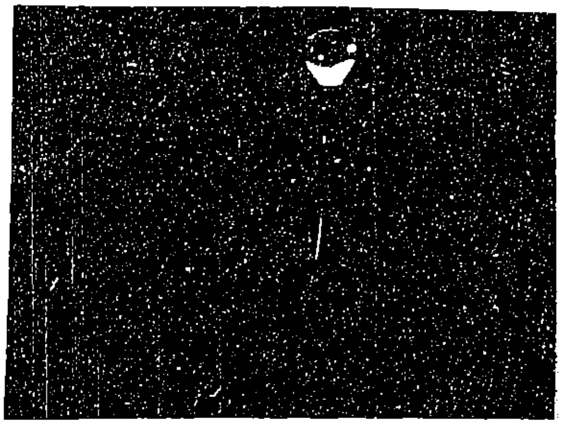
Approximately 250 experimental conditions were photographed and analyzed for the jet height and crown disintegration. Typical photographs for each of the six experimental liquids are displayed in Figure III-1. The ranges of drop heights (h), pool depths (D), and droplet sizes (R) for each liquid are presented in Table III-1. A summary of the results indicating the average jet height (H) and crown disintegration (CD) obtained at the given experimental conditions is displayed in Table III-2. These results indicate that the jet height increases with drop size and splash height, decreases as the surface tension and viscosity increase, and increases from approximately zero at small pool depths to a maximum before decreasing to an essentially constant value at large pool depths. This last result is consistent with Harlow's calculations (1967) for small pool depths



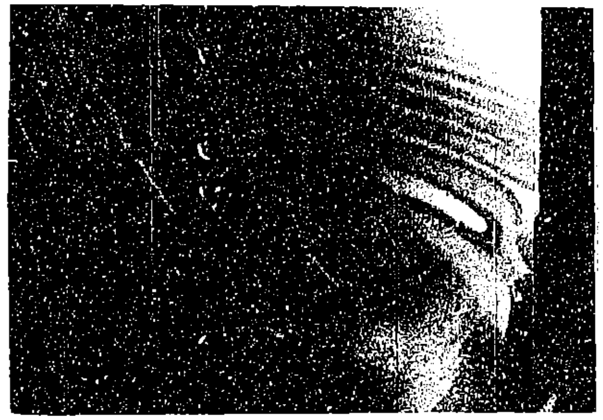




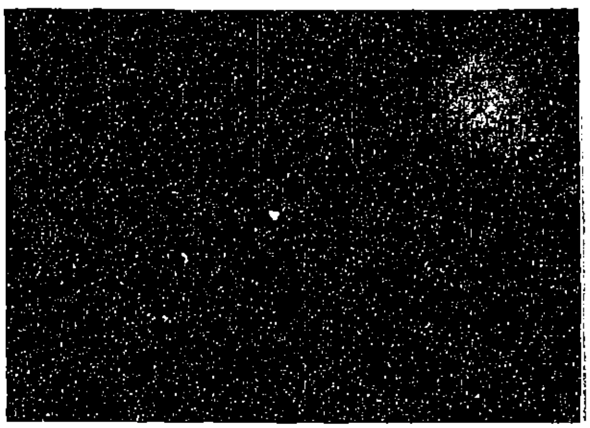




Water jet before complete pinch-off



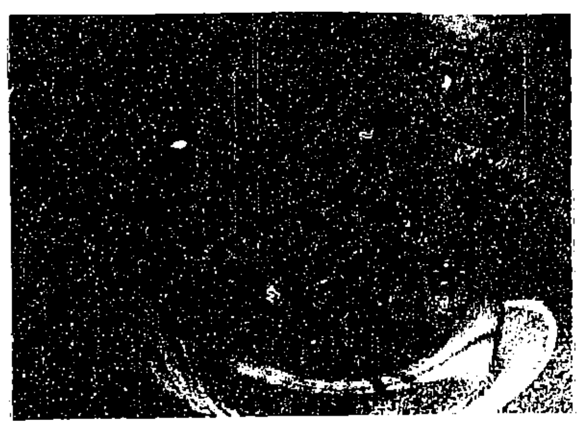
Toluene, h = 23 cm



Ethanol, h = 20 cm

Mercury crown

Glycerin, h = 100 cm



Olive oil, h = 100 cm

Figure III-1 Photographs of Typical Splashes and Hobbs and Osheroff's experimental findings (1967) at large pool depths. It should also be noted that mercury did not form a jet at the presented drop heights and pool depths, possibly because the small container used to hold the mercury may have restricted the liquid motion.

Table III-1 Range of Experimental Variables

Liquid	h (cm)	D (cm)	R (cm)
water-permanent red ink	0-100	0 - 2.5	.29-.31
toluene-red paint	10, 23	.5, .9	.29-.31
glycerin-washable blue ink	100	.5, .9	.29-.31
ethanol-washable blue ink	10, 20	.5, .9	.08-.12
olive oil	100	.5, .9	.29-.31
mercury	40	.9	---

Table III-2 Summary of Experimental Data

I. Water - γ = 72.05 dyne/cm η = 1.053 cpoise ρ = 1.000 gm/cc

h (cm)	D (cm)	H (cm)	CD
2.6	0	0	-
2.6	.5	.33	0
2.6	.9	.25	0
5.3	0	0	-
5.3	.5	.50	0
5.3	.9	.42	0
10.0	0	0	0
10.0	.5	.60	0
10.0	.9	.80	0
15.0	0	0	1
15.0	.5	.80	0
15.0	.9	1.62	1
15.0	1.5	1.52	0
15.0	2.5	1.50	0

h (cm)	D (cm)	H (cm)	CD
20.0	0	0	1
20.0	.5	1.00	1
20.0	.9	2.00	1
20.0	1.5	1.70	1
20.0	2.5	1.63	1
30.0	0	0	2
30.0	.5	1.43	1
30.0	.9	5.12	2
30.0	1.5	3.52	1
30.0	2.5	3.52	1
50.0	0	0	3
50.0	.5	2.02	2
50.0	.9	6.95	2
50.0	1.5	4.67	2
50.0	2.5	4.70	2
75.0	0	0	4
75.0	.5	3.00	2
75.0	.9	9.37	3
75.0	1.5	6.27	2
75.0	2.5	6.30	2
100.0	0	0	4
100.0	.5	3.97	3
100.0	.9	11.97	3
100.0	1.5	7.50	3
100.0	2.5	7.50	3

II. Toluene γ = 28.5 dyne/cm η = .590 cpoise ρ = .88 gm/cc

h (cm)	D (cm)	H (cm)	CD
10.0	.9	1.09	0
23.0	.9	2.25	1
23.0	.5	1.95	1

III. Glycerin γ = 63.4 dyne/cm η = 1490 cpoise ρ = 1.26 gm/cc

h (cm)	D (cm)	H (cm)	CD
100.0	.5	.35	0
100.0	.9	.50	0

IV. Ethanol γ = 22.7 dyne/cm η = 1.20 cpoise ρ = .90 gm/cc

h (cm)	D (cm)	H (cm)	CD
10.0	.5	.50	0
10.0	.9	1.05	0
20.0	.5	1.05	1
20.0	.9	4.00	1

V. Olive oil γ = 41.5 dyne/cm η = 84.0 cpoise ρ = .918 gm/cc

h (cm)	D (cm)	H (cm)	CD
100.0	.5	.22	0
100.0	.9	.40	0

VI. Mercury γ = 476 dyne/cm η = 1.534 cpoise ρ = 13.546 gm/cc

h (cm)	D (cm)	H (cm)	CD
40.0	.9	0	3

CHAPTER IV

ANALYSIS OF RESULTS

Because the splashing mechanism depends in a complex way on geometric and flow parameters, one expects a functional relation for the jet height of the following form:

$$H = f(\gamma, \rho, \eta, V_o, R, D) \qquad \text{(IV-1)}$$

where: H = the Rayleigh height, cm

γ = the fluid surface tension, dyne/cm or gm/sec^2

ρ = the fluid density, gm/cc

η = the fluid viscosity, poise or gm/cm-sec

V_o = the drop impact velocity which depends on the drop height, cm/sec

R = the drop radius, cm

D = the pool depth, cm

However, an experimental determination of this relation as stated is virtually an impossible task as one would have to make tests at all possible combinations of independent-variable values, which would require utilizing liquids with all combinations of surface tensions, viscosities, and densities.

Fortunately, the use of dimensional analysis obviates these difficulties by grouping the dependent variables into sets of dimensionless ratios and products which are varied by changing the values of only one variable, naturally the one most easily manipulated. Mathematically, the method is based on the following theorem. Given a function of n-1 variables, $g_1 = f(g_2, g_3, \ldots, g_n)$, which may be stated in the equivalent form $g(g_1, g_2, \ldots, g_n) = 0$, if m is the minimum number of independent dimensions required to specify the dimensions of all the parameters g_1, then the g's may be frouped into n-m independent dimensionless ratios, called Π parameters, expressible in fundtional form by $G(\Pi_1, \Pi_2, \ldots, \Pi_{n-m}) = 0$ or $\Pi_1 = F(\Pi_2, \Pi_3, \ldots, \Pi_{n-m})$. A parameter is independent if it cannot be expressed as a product or quotient of any of the other parameters. The rigorous proof of this theorem is straightforward, but too complicated to merit being described in detail. The essentials of the proof consist of writing the total derivative of g in terms of its partial derivatives with respect to the m separate dimensions. As there are m dimensions to describe n variables, a maximum of n-m independent dimensionless ratios can be attained.

In this problem, there are a total of four independent dimensionless parameters as there are seven variables with three independent dimensions (mass, length and time). Although only a finite number of independent dimensionless parameters exist, the set of all possible parameters which can be formed from any set of variables is very large. Hence some care must be taken in choosing exactly the right groups to ensure that the determined relation is meaningful and logically consistent. Since the primary purpose of this study was to determine the relation of the height of the Rayleigh jet to the fluid properties of surface tension and viscosity, these two properties were grouped into the separate parameters, $\rho V_o^2 R/\gamma$ (the Weber Number, We) and $\rho V_o R/\eta$ (the Reynolds Number, Re). As Hobbs and Osheroff (1967) have already determined that the height is is sensitive to the pool depth, the third parameter was chosen to be R/D and the independent parameter was of course H/D. Thus the functional relation which was determined was,

$$H/D = F(R/D,\ \rho V_o^2 R/\gamma\ ,\ \rho V_o R/\eta\ ) \qquad \text{(IV-2)}$$

Figure IV-1 is a plot of H/D vs the Weber number ($\rho V_o^2 R/\gamma$) for four different values of R/D. This figure indicates that H/D for water is proportional to the Weber number for all pool depths tested with the exception of a discontinuity between the low and high Weber-number lines. The discontinuity marks the point where the head of the jet pinches off into a separate drop which rises higher than the jet body since the drop has a smaller mass and carries the same momentum as the jet. Unfortunately as extensive data was obtained only for water and not for the other liquids, which have different surface tensions, viscosities, and densities, Figure IV-3 merely indicates that H/D is proportional to V_o^2, as a change in the Weber number also implies a change in the Reynolds number, which is proportional to V_o. Nevertheless, Figure IV-1 does indicate that if the jet height is proportional to $We^a Re^b$, $2a + b$ must equal 2, because We is proportional to V_o^2 while Re is proportional to V_o.

It should be noted that the exact dependence of H/D on the Reynolds number could be obtained from a Figure IV-1 type plot if extensive data for the other five liquids had been obtained. In this case, H/D would be plotted versus the Weber number at a constant R/D. Then the Reynolds numbers for the six liquids would be calculated at a constant Weber number and plotted versus H/D. After several such curves were obtained at various Weber numbers, the dependence of H/D on the Reynolds number would be found.

An initial inspection of the limited data for the five liquids other than water indicates that H/D increases as the Reynolds number increases, as the data points in Figure IV-1 for the low viscosity liquids (water, ethanol, and toluene) are well above the data points for the high viscosity liquids (olive oil and glycerin). This result is consistent with the basic physics of the splashing process, as to a first order approximation, the viscous force on a moving body in an incompressible fluid is given by $F = -bv$, where b is some geometrically-determined constant which depends on the viscosity, and v is the velocity of the body. Integrating the dynamical equation, one obtains an exponential decrease in velocity with increasing viscosity as follows:

$$F = m\frac{dv}{dt} = -bv \tag{IV-3}$$

$$\frac{dv}{v} = -\frac{b}{m}\,dt$$

$$v = v_o\, e^{-bt/m}$$

Thus since the rebound velocity of the jet decreases exponentially with the viscosity, the maximum jet height---which should depend on the rebound velocity---should decrease as the viscosity decreases, or as the Reynolds number $(\rho V_o R/\eta)$ increases.

Figure IV-2 displays the dependence of the jet height on the Reynolds number for various values of R/D. This figure also demonstrates that the jet height is approximately proportional to $V_o^{\,2}$ as the slopes of the curves for water are approximately two. The dependence of the jet jeight on the Weber number can be determined from this figure by plotting H/D versus the Weber numbers for the six liquids at a constant Reynolds number. As the limited data for the

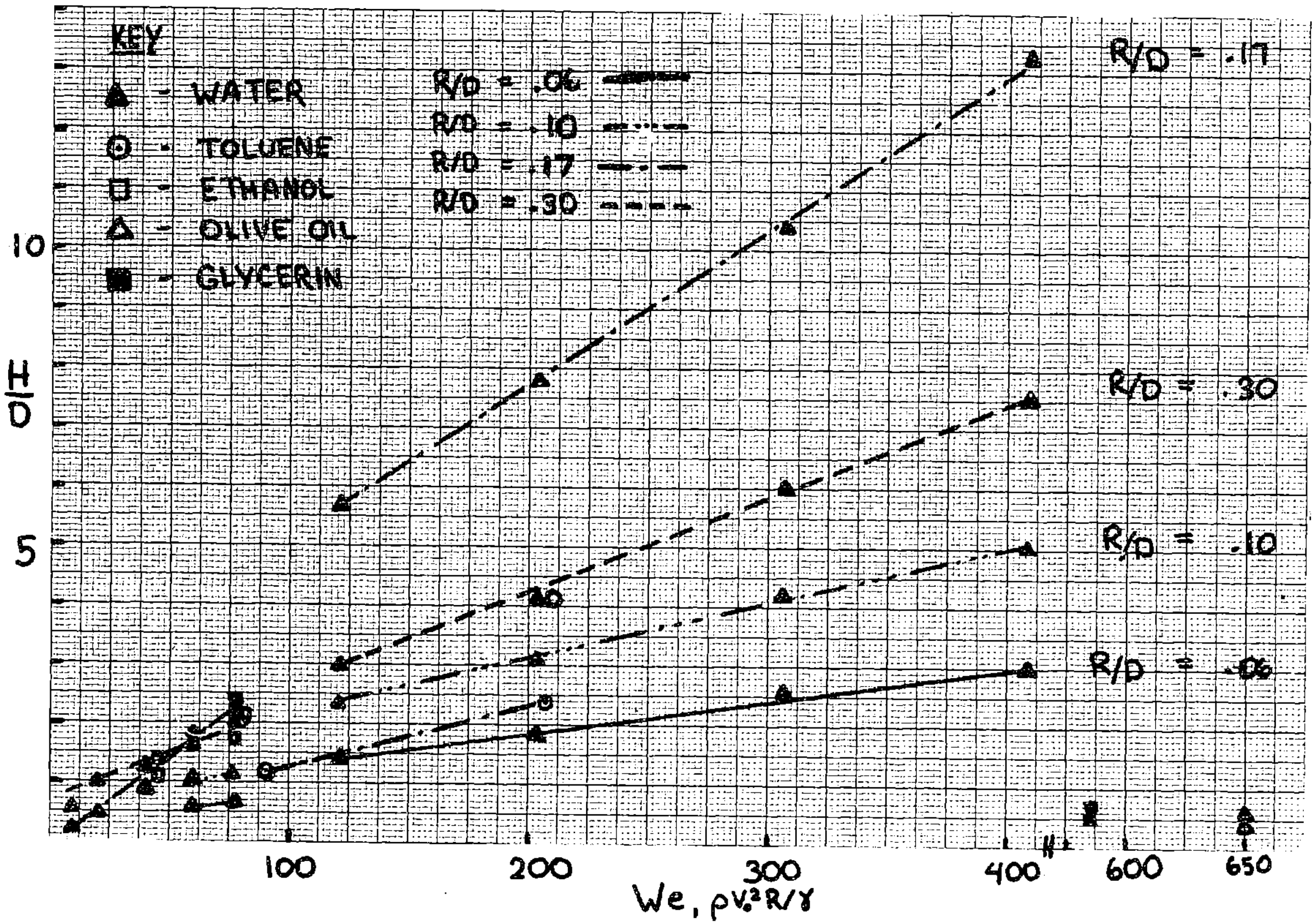


Figure IV-1 Jet Height Versus the Weber Number

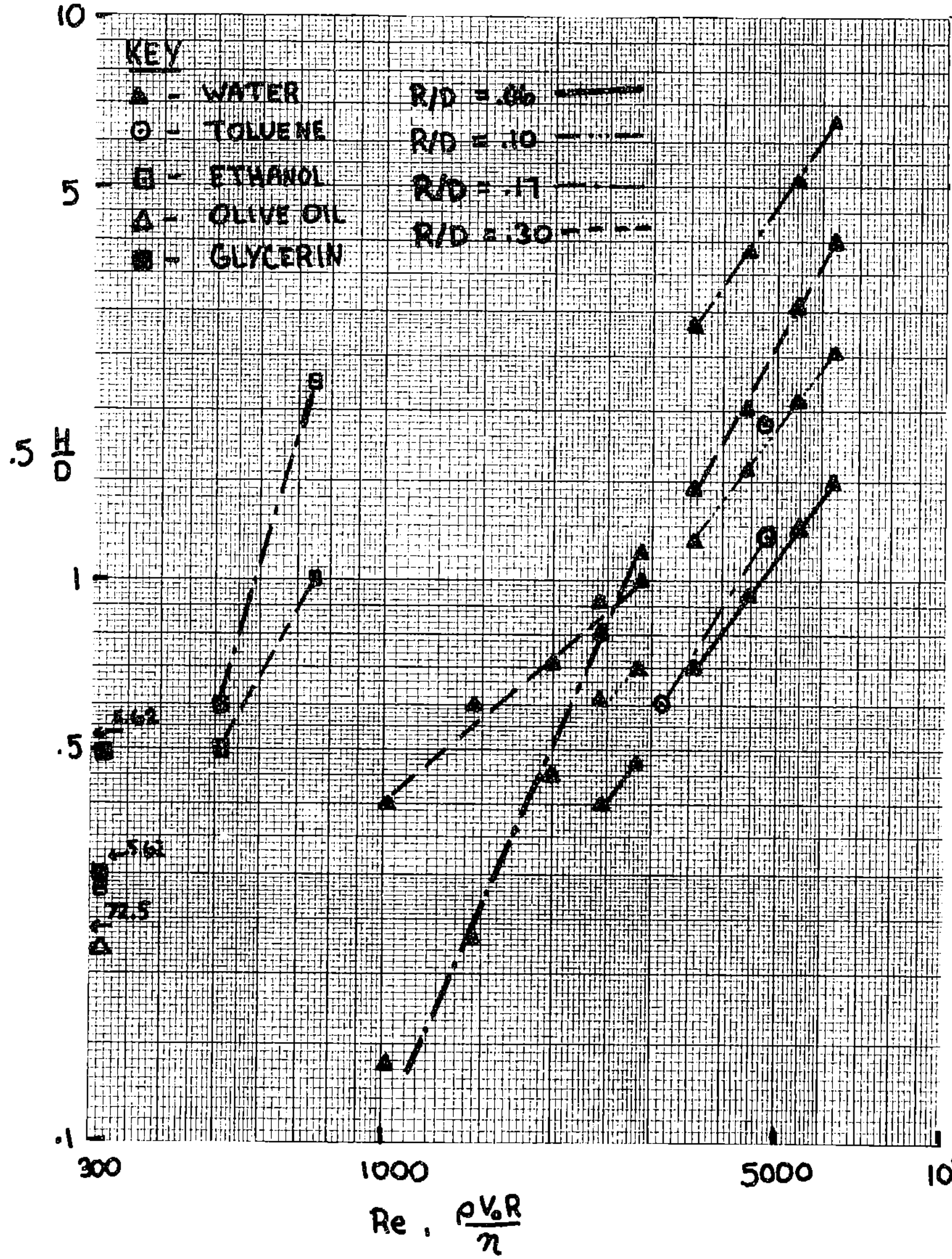


Figure IV-2 Jet Height Versus the Reynolds Number liquids other than water indicate that H/D is higher for the lower surface tension liquids (toluene, ethanol) than for the higher surface tension liquids (water, mercury), Figure IV-2 suggests that the jet height increases as the Weber number increases. This result is consistent with the physical feeling that the jet should go higher when less energy is wasted as surface energy. It should be noted that although these results appear to be inconsistent with Hobbs and Osheroff's finding (1967) that the jet rises higher in dyed water---surface tension of 72.75 dyne/cm---than in a milk-water solution---surface tension of 65.07 dyne/cm, they may not be as these authors failed to take in account the fact that the milk-water solution has a higher viscosity than the dyed-water solution has.

Figure IV-3 shows the dependence of the water jet height on R/D at the four largest values of the Weber and Reynolds numbers. The dashed lines in this figure are merely intended as a visual aid and are not meant to imply anything about the shape of the curves. Nevertheless, it is evident that the parameter H/D increases from approximately zero, to a maximum at $R/D \approx .17$, before decreasing at higher values of R/D. This result is consistent with Macklin and Hobbs' findings (1969) for dyed water, which they explained by the way the jet crater hit the bottom of the tank. Further explanation of this phenomena is given in the Introduction.

Thus, the jet-height-to-pool-depth-ratio increases as the Weber ($\rho V_o^2 R/\gamma$) and Reynolds ($\rho V_o R/\eta$) numbers increase and as the parameter R/D approaches .17 for water. It should be noted that the results of this work also apply to the amount of spray produced

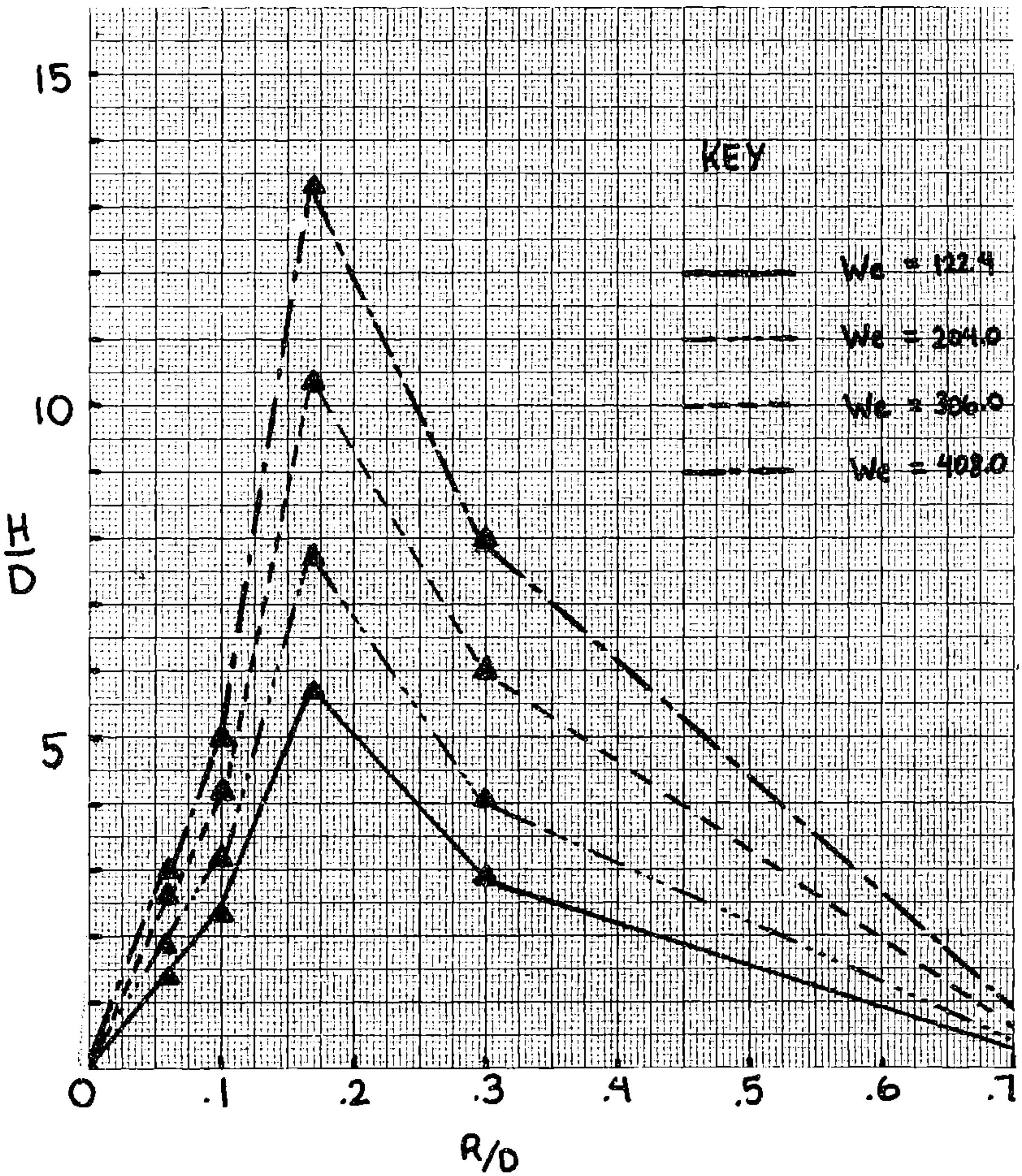


Figure IV-3 Jet-Height Dependence on the Pool Depth for Water in the splash, as Hobbs and Kezweeny (1966) have shown that the number of spray droplets is directly proportional to the maximum jet height. It should also be mentioned that the small container used for the mercury splashes may have restricted the formation of a mercury jet, due to the damping effect of this container on the splash forces.

CHAPTER V

CONCLUSIONS

1. The present data for the splashing process suggest that the jet-height-to-pool-depth ratio is correlated by the droplet-size-to-pool-depth-ratio, the Weber number $(\rho V_o^2 R/\gamma)$, and the Reynolds number $(\rho V_o R/\eta)$.

2. The jet-height-to-pool-depth ratio increases as the liquid viscosity and surface tension decrease. In other words, the relative jet height increases as the drop-fall-energy loss due to viscous and surface-energy dissipation decreases.

3. For water, the jet-height-to-pool-depth ratio approaches a maximum at a droplet-size-to-pool-depth ratio of approximately .17. This maximum in the jet-height-to-pool-depth ratio is independent of the impact velocity of the drop.

4. The jet-height-to-pool-depth ratio is proportional to approximately the square of the impact velocity of the drop.

5. The crown disintegration increases with the jet-height-to-pool-depth ratio.

CHAPTER VI

RECOMMENDATIONS

1. More data should be obtained for the splashing of liquids other than water so that the relation between the jet height and the liquid properties can be better determined.

2. The splashing of a drop of one liquid onto a pool of another liquid should be investigated. This information should better define the physics of the splashing phenomena.

3. The effect of liquid properties on the jet-height-to-pool-depth-ratio maximum with respect to the droplet-size-to-pool-depth ratio should be investigated. A theoretical study of the crater formation might help in this investigation.

APPENDIX A

CALCULATION OF DATA

h = height of fall, cm

H = observed height of Rayleigh jet, cm

D = depth of pool, cm

R = radius of drop, cm

V_o = impact speed, cm

ρ = density of fluid, gm/cc

γ = surface tension, dynes/cm

η = viscosity, poise

Re = Reynolds number, $\rho V_o R/\eta$

We = Weber number, $\rho V_o^2 R/\gamma$

I. Water - γ = 72.05 dyne/cm η = 1.053 x 10^{-2} poise ρ = 1.000 gm/cc
R = .15 cm

h	H	D	H/D	R/D	We	Re
2.6	.23	.9	.25	.17	10.61	1.02×10^3
2.6	.25	.9	.28	.17	10.61	1.02×10^3
2.6	.27	.9	.30	.17	10.61	1.02×10^3
2.6	.28	.5	.55	.30	10.61	1.02×10^3
2.6	.31	.5	.61	.30	10.61	1.02×10^3
5.3	.40	.9	.44	.17	21.63	1.45×10^3
5.3	.43	.9	.48	.17	21.63	1.45×10^3
5.3	.48	.5	.96	.30	21.63	1.45×10^3
5.3	.50	.5	1.00	.30	21.63	1.45×10^3
10.0	.80	.9	.89	.17	40.80	2.00×10^3
10.0	.81	.9	.90	.17	40.80	2.00×10^3
10.0	.60	.5	1.20	.30	40.80	2.00×10^3
10.0	.62	.5	1.24	.30	40.80	2.00×10^3
15.0	1.47	2.5	.59	.06	61.21	2.44×10^3
15.0	1.50	2.5	.60	.06	61.21	2.44×10^3
15.0	1.55	1.5	1.03	.10	61.21	2.44×10^3

h	H	D	H/D	R/D	We	Re
15.0	1.60	1.5	1.08	.10	61.21	2.44×10^3
15.0	1.60	.9	1.78	.17	61.21	2.44×10^3
15.0	1.65	.9	1.83	.17	61.21	2.44×10^3
15.0	.80	.5	1.60	.30	61.21	2.44×10^3
15.0	.83	.5	1.65	.30	61.21	2.44×10^3
20.0	1.63	2.5	.65	.06	81.61	2.82×10^3
20.0	1.70	2.5	.68	.06	81.61	2.82×10^3
20.0	1.70	1.5	1.13	.10	81.61	2.82×10^3
20.0	1.80	1.5	1.20	.10	81.61	2.82×10^3
20.0	2.00	.9	2.22	.17	81.61	2.82×10^3
20.0	2.01	.9	2.23	.17	81.61	2.82×10^3
20.0	1.00	.5	2.00	.30	81.61	2.82×10^3
20.0	1.03	.5	2.06	.30	81.61	2.82×10^3
30.0	3.52	2.5	1.41	.06	122.4	3.54×10^3
30.0	3.55	2.5	1.42	.06	122.4	3.54×10^3
30.0	3.50	1.5	2.33	.10	122.4	3.54×10^3
30.0	3.55	1.5	2.37	.10	122.4	3.54×10^3
30.0	5.10	.9	5.67	.17	122.4	3.54×10^3
30.0	5.15	.9	5.72	.17	122.4	3.54×10^3
30.0	1.42	.5	2.84	.30	122.4	3.54×10^3
30.0	1.45	.5	2.90	.30	122.4	3.54×10^3
50.0	4.67	2.5	1.87	.06	204.0	4.46×10^3
50.0	4.70	2.5	1.88	.06	204.0	4.46×10^3
50.0	4.65	1.5	3.10	.10	204.0	4.46×10^3
50.0	4.70	1.5	3.13	.10	204.0	4.46×10^3
50.0	6.90	.9	7.67	.17	204.0	4.46×10^3
50.0	7.00	.9	7.78	.17	204.0	4.46×10^3
50.0	2.00	.5	4.00	.30	204.0	4.46×10^3
50.0	2.05	.5	4.10	.30	204.0	4.46×10^3
75.0	6.27	2.5	2.51	.06	306.0	5.46×10^3
75.0	6.30	2.5	2.52	.06	306.0	5.46×10^3
75.0	6.27	1.5	4.18	.10	306.0	5.46×10^3
75.0	6.30	1.5	4.20	.10	306.0	5.46×10^3
75.0	9.35	99	10.39	.17	306.0	5.46×10^3
75.0	9.40	.9	10.44	.17	306.0	5.46×10^3

h	H	D	H/D	R/D	We	Re
75.0	3.00	.5	6.00	.30	306.0	5.46×10^3
75.0	3.05	.5	6.10	.30	306.0	5.46×10^3
100.0	7.45	2.5	2.98	.06	408.0	6.29×10^3
100.0	7.50	2.5	3.00	.06	408.0	6.29×10^3
100.0	7.47	1.5	4.98	.10	408.0	6.29×10^3
100.0	7.50	1.5	5.00	.10	408.0	6.29×10^3
100.0	11.96	.9	13.29	.17	408.0	6.29×10^3
100.0	12.00	.9	13.33	.17	408.0	6.29×10^3
100.0	3.95	.5	7.90	.30	408.0	6.29×10^3
100.0	4.00	.5	8.00	.30	408.0	6.29×10^3

II. Toluene - γ = 28.5 dynes/cm $\quad \eta$ = $.590 \times 10^{-2}$ poise
ρ = .88 gm/cc $\quad$ R = .15 cm

h	H	D	H/D	R/D	We	Re
10.0	1.10	.9	1.22	.17	90.78	3.13×10^3
10.0	1.05	.9	1.17	.17	90.78	3.13×10^3
23.0	2.20	.9	2.44	.17	208.8	4.74×10^3
23.0	2.30	.9	2.56	.17	208.8	4.74×10^3
23.0	1.90	.5	3.80	.30	208.8	4.74×10^3
23.0	2.00	.5	4.00	.30	208.8	4.74×10^3

III. Glycerin - γ = 63.4 dynes/cm $\quad \eta$ = 1490×10^{-2} poise
ρ = 1.26 gm/cc $\quad$ R = .15 cm

h	H	D	H/D	R/D	We	Re
100.0	.50	.9	.56	.17	584.3	5.62
100.0	.35	.5	.70	.30	584.3	5.62

IV. Ethanol - γ = 22.7 dynes/cm $\quad \eta$ = 1.20×10^{-2} poise
ρ = .90 gm/cc $\quad$ R = .05 cm

h	H	D	H/D	R/D	We	Re
10.0	1.0	.9	1.11	.056	38.85	525.0

h	H	D	H/D	R/D	We	Re
10.0	1.1	.9	1.22	.056	38.85	525.
10.0	.5	.5	1.00	.10	38.85	525.
20.0	4.0	.9	4.44	.056	77.71	742.
20.0	1.0	.5	2.0	.10	77.71	742.
20.0	1.1	.5	2.2	.10	77.71	742.

V. Olive oil - γ = 41.5 dyne/cm η = 84.0×10^{-2} poise
ρ = .918 gm/cc R = .15 cm

h	H	D	H/D	R/D	We	Re
100.0	.40	.9	.444	.17	650.3	72.5
100.0	.22	.5	.440	.30	650.3	72.5

VI. Mercury - γ = 476 dyne/cm η = 1.534×10^{-2} poise
ρ = 13.546 gm/cc h = 40 cm

It should be noted that whenever two values of the jet height are listed for a given pool depth, the numbers correspond to the maximum and minimum heights observed. Generally, five to ten experiments were performed at each pool depth.

APPENDIX B

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