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Modeling Large-scale Drop Impact: Splash Criteria and Droplet Distribution

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Abstract

Models for the splashing of drops upon impact on a solid surface have not yet matured to a point where they are reliably predictive for a wide range of drop sizes, materials, and velocities. This is in part due to the complexity of the phenomena that occur during a drop impact, and the lack of complete data. There is a particular lack in data for the drop impact on an inclined wall and in the high Weber number regime. The high Weber number regime is of particular interest in relation to transportation accidents where large tanks of liquid may impact at high velocity. There is a general interest also in being able to model a broad range of drop impacts with a single model. Some recent data have been acquired which have been analyzed for splash mass fraction and fingering, or number of ejected jets. Additionally, tests with glycerin were conducted to verify models for a fluid of significantly different properties than those commonly tested. Combined with other datasets, a new empirical relation for the splash mass percent is presented that relates measured splash parameters from water tests to the drop Weber number. The relation is a fit based uniquely on the Weber number, and is shown to fit water impact data for a wide range of Weber numbers. This empirical correlation is compared with other existing empirical models designed to determine the presence of splash. Reasonable consistency was found between the models, suggesting that they can be used in concert with a degree of confidence. The glycerin data are presently not well described by existing models. Using the recent data obtained for splash criteria and fraction, a submodel for splash was developed and implemented into the Sandia's fire suppression code, Vulcan. Preliminary computational results are presented.

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Introduction

Modeling of spray shattering upon wall impact is a challenge for several reasons. First, there is a lack of data due in part to the focused range of applications for which this problem is of high importance. Spray studies are most commonly motivated by practical applications such as ink jet printing, fuel injection, and suppression, with many other applications as reviewed by Rein [1]. In most of these, the shattering of drops upon surface impact is undesirable, or considered a minor effect. The shattering model is also complicated by other factors. The quality of the surface being impacted has been shown to be significant to the resulting shattering. The surface roughness, the angle of incidence, the rigidity of the surface, and whether or not the surface is wetted contribute to the characteristics of the resulting spray. Whether multiple particles are present is also important.

We are particularly interested in the large Weber number regime characteristic of large sized and high velocity drops, as might be found for impacting tanks of liquid. We would like to have a model that can span a broad range of conditions with a reasonable expectation of accuracy. Data are increasingly sparse for Weber number drops above 10^4. Existing models have been found to be lacking, particularly outside regimes of original interest [2]. A good model should replicate data regarding 1) the mass of material ejected in the splash, 2) particle size distributions of the ejected material, and 3) velocity of the new droplets.

Present knowledge of spray impact was reviewed in some detail in a recent article by Cossali et al. [2]. Six models were reviewed in that work. Four of the model citations have been obtained. These include work by Mundo et al. [3-4], Stanton and Rutland [5], Park and Watkins [6], and Bai et al. [7-9]. Reviews on single drop impact are available in Rein, [1] and Yarin [10]. The work of Cossali et al, [2] is significant in that it points out large disagreement points between the various codes and model formulations, which in turn suggests the need for improvements. What follows is a brief overview of the various existing models.

Bai and Gosman [7] presented a model for impact splashing. The splash transition regime is dictated by a critical Weber number determined as a function of the Laplace number and some empirical constants. The number of splashing particles is determined empirically, and two sizes for particles are allowed. Splash mass is determined randomly. The velocity and mass distributions are random within constraints, as is the mass involved in the splash. Velocity magnitudes are based on empirical relations and simple energy conservation relations. The regime of validity for this model is not specified.

Park and Watkins [6] describe modifications to their previous work on the basis of the Mundo [3-4] and Bai and Gosman [7] work. Their model is distinguished by a concern for the spread of the film on the substrate. Additionally, there are some variants to the empirical relations for velocities compared to other work.

The Stanton and Rutland model [5] assumes a probability distribution for the splashing particles, and uses a correlation to determine the splash threshold and the mass splashed. The probability density function (PDF) employs constants that are functionally related to the Weber number and were generated from the Mundo et al. [3] and Yarin and Weiss [11] data. Instead of two particle sizes allowed as in the former work, a third is allowed to better approximate the distribution. Mass fraction involved in the splash comes from a curve fit in the range of the same data that were used to develop the PDF. Velocities are predicted from a similar PDF distribution. Reflection direction is governed by the reflection angle, which is from an empirical model. An energy balance correction is used to determine the final velocities by correcting the correlation values to maintain the balance. The concept of an impact frequency is employed, which necessitates some historical knowledge to be retained for predicting the response. The regime of validity is not detailed, but since it is based on fits of the Mundo et al. [3] work, it is likely valid in a similar regime.

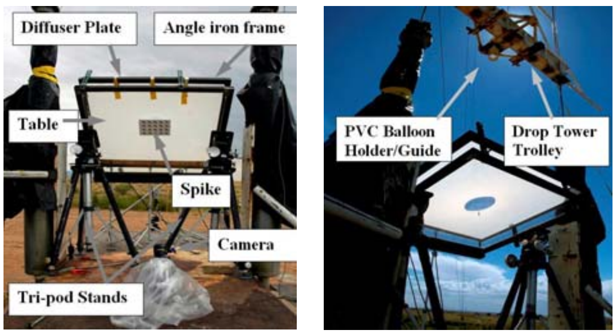
Tropea and Roisman [12] present a model for spray impact. Observing that multiple particles do not behave like the sum of individual particle impacts, they developed a methodology with a statistical basis to treat the interactions based on the assumption of interacting crown phenomena. Regimes of applicability for this model are not reported or clear, but the model is probably reasonable for the low Weber number impacts, and decreasingly accurate for higher Weber number impacts. This is inferred because high Weber number cases are not typically characterized by uniform crown-like structures intrinsic to the model development assumptions [12-13].

Existing splash models are focused on the presence or absence of splash, and less on the quantity of mass involved. Mundo et al. [3-4] presented a model for spray interactions that was validated by Particle Doppler Anemometry for spray impact data against a conical target. The model is reported as valid for $57.7 < K < 180$, and for a dimensionless surface roughness R^*=0.03 and 0.86 and dimensionless film thickness height of 0.03, where K is defined as $K=OhRe^{5/4}$ or $We^{0.5}Re^{0.25}$ (note $Oh=We^{0.5}/Re$). Their validation work suggests quite good agreement for the selected problems. This work was subsequently refined by Cossali et al [14], with new correlations for various surface conditions.

Here, we examine the large-scale impact of a wide range of drop Weber numbers subject to splash. Existing data are examined, and limited new data are also presented. Models are presented that are derived from these data and are intended to span a wider range of physical bounds than existing models as previously introduced. The new models are compared with existing models, and are demonstrated to be adequate in the range where classical data have been shown to be adequate. They also suggest trends that span a range of data outside the range of previously existing models, particularly in the high Weber number regime.

Experimental Setup

A series of drop tests were conducted from numerous drop sizes of 2 mm to 10 cm, drop heights ranging from 0.15 to 60 m high, and impact angles from 90 to 45 degrees from horizontal.



(a) (b)

Figure 1. Experimental setup for large scale impact testing.

Large liquid slugs were used to obtain very high Weber number impacts (i.e. *We* between 10^3-10^6). These slugs were spherical, about 10 cm in diameter, and were delivered to the target in a latex bladder. The bladder was removed immediately prior to impact with a blade placed on a 2 mm diameter spike 5 cm above the impact surface. The blade removes the bladder from the liquid slug in approximately 1 ms so the large slug is able to impact the target unimpeded by the bladder. The blade was mounted onto the center of a 2.5 cm thick by 1.25 m long by 1.25 m wide Lucite table top as the target. The table was smooth, with an estimated roughness below 10 μm. Approximately 25 cm above the target was a diffuser plate for backlighting the high speed video. Since the table top was rotated and setup at different angles, the spike and blade angle configuration compensated for the angle of the table. The Lucite table top and diffuser plate were supported in place by a steel angle iron frames mounted onto a set of adjustable tri-pod stands placed on top the drop tower steel target; see **Figure 1(a)**.

A 10 cm internal diameter by 20 cm long PVC tube was attached to the bottom of the tower trolley beam by 4-each 7/16-inch by 2-inch long bolts. The purpose of the PCV tube was to hold and guide the slug during the release; see **Figure 1(b)**. The bladders were placed inside the PVC tube and held in place by a thin sheet of aluminum foil that was taped to the bottom of the tube. The aluminum foil was scared with a small incision approximately 1-inch by 1-inch long cross-shape located directly below the balloon. The incision on the foil provided minimum resistance on the slug during the release therefore minimizing the bladder distortion and rotation.

The bladders were weighed before each test. After the test was completed, the test fluid that remained on the top of the impact table and tray were collected and weighed. The pre-test and post-test fluid quantities were compared for each test.

The photographic results obtained during this test series were recorded by two high speed digital *Phantom* cameras running at 4,800 up to 17,000 frames per second. The two Phantom cameras were positioned at two different locations to capture the desired test information on each test. The main and most important camera on these tests was the camera that recorded the fluid dispersal pattern. This camera (#1) was position under the Lucite table top directly below the puncturing spike setup to run at 10,000 frames per second; see **Figure 1(a).** The second camera (#2) was positioned on the south and east side of the table and setup at 4,800 frames per second to capture the balloon as it passed through the hole on the diffuser plate. It further captured the fluid as it made contact with the spike, the balloon latex peeling off from the fluid, and the fluid droplet making contact with the surface of the impact table.

Additional test data are also considered for model development from historical tests performed at Sandia National Laboratories. For smaller droplets of 2 to 4 mm, tests were done on the lab bench top onto a smooth plexiglass surface. Drops were released individually from a syringe and impact velocities were determined by drop height just as the drop tower tests were done. The very high Weber number tests ($We > 10^6$) were done by impacting a 1 m diameter aluminum tank propelled by a rocket sled with an unyielding concrete wall.

Separate experimental methods were conducted to determine the amount of splash. For large (10 cm) water slugs, photometrics from views underneath the impact were used to verify that splash separated from the spreading fluid and that the spreading fluid remained on the impact table for the duration of the test. The remaining fluid was collected and weighed. The amount of splash for this case was the original weight minus the amount collected from the spreading fluid. For smaller droplets in which very little splash was measureable, photometric data taken from a side view determined the shape of the collapsing droplet once splash had ceased and a volume was determined from that shape.

Experimental Results

Photometric data collected from the tests were used to determine the number of fingers generated upon impact. Tests were done from low enough Weber numbers that no fingers were observed up to high enough *We* that several hundred fingers were observed. **Figure 2** shows a frame at 11 ms after impact for a water drop of ~10^6 *We* at the drop tower. Photo data such as this were used to compile the plot of fingers vs. *We* shown in **Figure 3**. Fingers were hand counted from visual observation of a still frame for the spreading edge approximately 4 to 5 radial diameters from impact. In many high Weber number cases, only a small portion of the spreading circumference was available to count because of poor depth focus or obscuration due to splash. In these cases, the angle of measureable fingers within a wedge was determined and extrapolated to 360 degrees for the total number of fingers. Since many tests were repeated 3 to 5 times, it allowed some statistical analysis of the counting method. The standard deviation was never more than 20% of the total number of fingers for repeats and was independent of the individual conducting the counting measurements.

In addition to determining the number of fingers for the range of Weber numbers tested, the amount of splash was measured by recovering the liquid remaining on the table. **Figure 4** shows the amount of splash for Weber numbers of 10^3 up to 10^8. Also added to **Figure 4** were data from Tieszen [13] for high speed impact of water filled wing structures. At low Weber numbers between 10^3 and 10^4, the splash can be visually spectacular and important in processes such as ink jet printing and coating. However at these levels, only minor amounts of the original drop actually separate and splash into satellite droplets. It is not until a Weber number >10^4 that a significant mass fraction of splash is observed and becomes important for processes such as fuel dispersion.

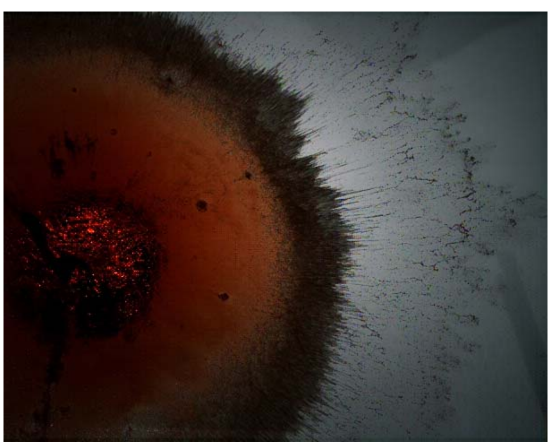


Figure 2. Impact of a 10 cm red-dyed water drop at 30 m/s.

Limited tests were done for glycerin in which fingers and splash amount were measured. The data from a single test show that glycerin does not generate fingers or splash at a Weber number of 2 x 10^5. At a Weber number of 10^6, approximately 40 fingers were observed from two tests, and this was associated with less than 20% of the fluid mass fraction in splash. Stills from the photography of the 2 x 10^5 *We* drop are found in **Figure 5**. We have observed that finger counts are generally repeatable to +/- 5% for a single standard deviation. Therefore, a fluid with similar surface tension but much higher viscosity than water appears to cause a shift in the relationship of fingers and splash vs. the Weber number significantly to the right on **Figures 3** and **4**. Both the splash models [3, 14] predict the glycerin drop with Weber number of 2 x 10^5 will splash. This is the case despite the Cossali [14] work including mixtures of glycerin and water in the formulation of their model.

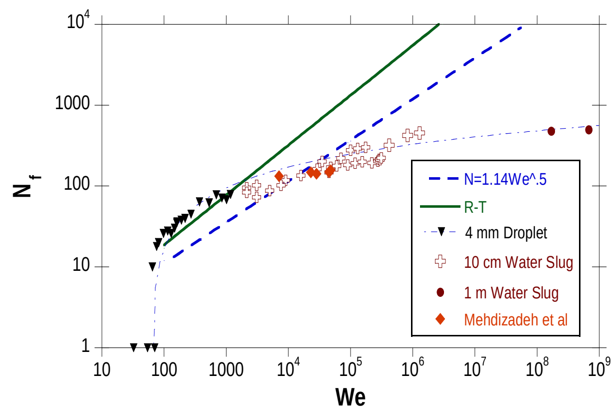


Figure 3. Number of fingers (N_f) vs. Weber number for water.

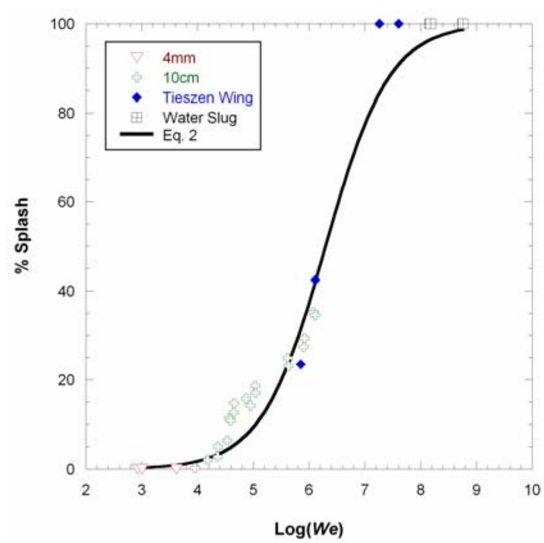
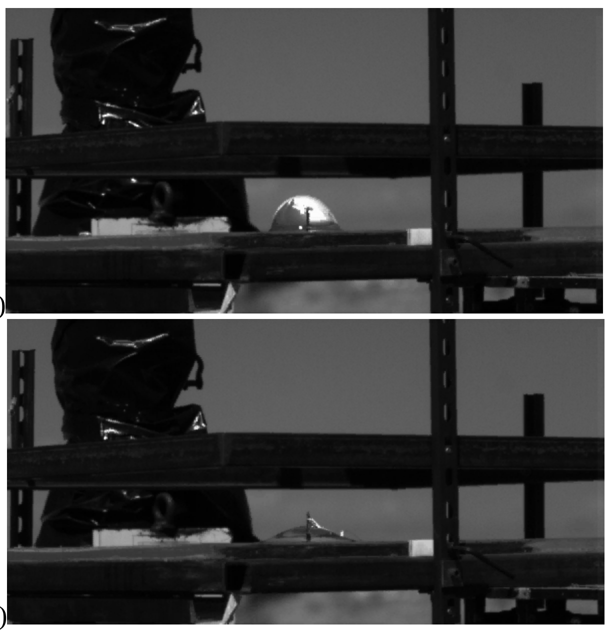


Figure 4. Amount of splashed water upon impact as a function of the Weber number.

Modeling

Splash Criteria, mass, and Finger Number

Drops are often characterized by dimensionless groups, the Reynolds number ($Re=\rho VD/\mu$) and the Weber number ($We=\rho V^2 D/\sigma$). These have been found to be useful for relating behavior for arbitrary fluids. To a first order, the various drop impact regimes can be classified on the basis of the Weber number. At very low Weber numbers (<< 50), there is a tendency towards bouncing. As the Weber number increases, rather than bounce, the particles may stick. At even higher Weber numbers (~1000+), shattering may begin to occur. The mass fraction involved in the shatter is thought to increase functionally with an increase in the Weber number, as suggested in the previous section.



(a) (b)

Figure 5. Stills from the high-speed photography of a $We = 2 \times 10^5$ drop of glycerin with no splash or fingers.

Existing literature models for splashing suggest a critical regime. Mundo et al. [3] define a constant $K=OhRe^{1.25}$ that is a function of the Reynolds and Ohnesorge, $Oh=\mu/(\rho\sigma D)^{1/2}$, numbers with a critical value of 57.7 above which shattering occurs under given wall roughness. The relation is derived from analysis of a large number of data-points. In a more recent review, Cossali et al [14] suggested different splashing criteria which appear to be quite similar to that of Mundo et al. [3], except that Cossali et al.'s criterion of K is approximately an order of magnitude larger because of greater power constants for We and Re. Both criteria for shattering (below) will be employed and compared:

$$K \equiv Oh\,\mathrm{Re}^{1.25} = We^{0.50}\,\mathrm{Re}^{0.25} > K_{crit} = 57.7 \qquad (1a)$$

$$K \equiv Oh\,\mathrm{Re}^{-0.4} = We^{0.80}\,\mathrm{Re}^{0.40} > K_{crit} = 649 + \frac{3.76}{(R^*)^{0.63}} \qquad (1b)$$

The variable R^* is the nondimensional substrate roughness defined as R/D, where R is the roughness and D the drop diameter.

Many of the impact measurements in the literature neglect to quantify the residual mass or the mass of fluid sprayed. Some of the previous work assumes any shattering results in full re-entrainment of the liquid mass. Recent work at Sandia National Laboratories has attempted to provide a range of data that can be generally employed in formulating such a model. A compilation of data from various sources has suggested a logistic fit to the fraction of mass involved in the splash for increasing Weber numbers, expressed as an equation below from the plot in **Figure 4**:

$$\%Splash = \frac{100We}{We + 10^6} \qquad (2)$$

It is assumed that the splashed mass fraction of Eq. (2) is a function of the Weber number only, which may be a reasonable assumption for low viscous fluids such as water and others similar thereto. However, an increase in viscosity should result in an increase in deposition, according to Rioboo et al. [15] and the data described above. As suggested by our glycerin tests, an increase in liquid viscosity would shift the logistic curve, shown in **Figure 4**, to the right as it could require up to two orders of magnitude greater Weber number to cause the liquid to splash.

A series of simulation impact scenarios has been composed for the fluids listed in **Table 1** (from [16,17]). Diameters and velocities were varied across a wide range of practical values. For model comparisons, 15,000 drops are used with randomly selected drop diameter ranging from 1 micron to 16 m, covering a range of drop velocities from 0.01 m/s to 150 m/s. The splash fraction according to Eq. (2) has been calculated for each particle. Also, the occurrence of splash following the Mundo and Cossali criteria [3, 14], Eq. (1), are calculated. **Figure 6** represents a cross-section between the two models of Eqs. (1-2). The surface roughness used in this parametric study is R=0.1 mm.

Table 1. Assumed ambient properties for several fluids of interest. [16,17].

Fluid	Density	Surface Tension	Viscosity
Units	*[kg/m^3]*	*[N/m]*	*[Pa s]*
Water	998	7.28e-2	1.00e-3
Gasoline	680	2.16e-2	2.92e-4
Methanol	791	2.25e-2	5.98e-4
Kerosene	820	2.68e-2	1.2e-3
Glycerin	1260	6.33e-2	1.49

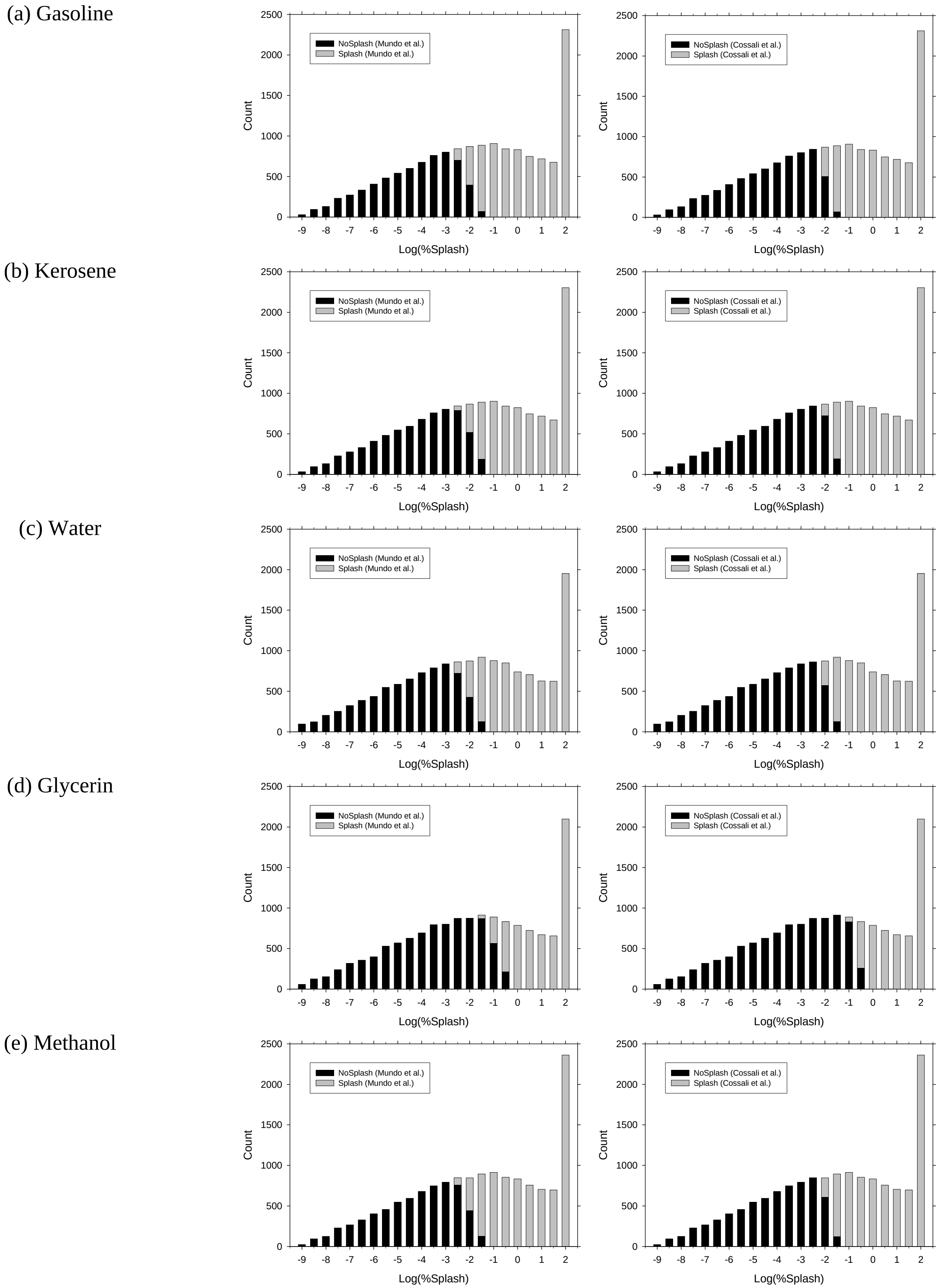


Figure 6. A comparison between the splash criteria of Mundo et al. [3] (left column) and Cossali et al. [14] models (right column) and logistic model of Eq. (2).

In general, when a high splash percent is predicted by Eq. (2), the Mundo or Cossali criteria (Eqs. 1a, 1b respectively) allow splashing. When a low splash percent is predicted, none is allowed by the two criteria. Transition regimes are generally similar between the several models for the fluids examined (around 0.01%), with the glycerin transition occurring at a higher predicted splash percent (>0.1%).

Equation 2 is probably not valid for fluids that are significantly different from water, as it is lacking a parameter to model viscous effects. It will tend to over-predict the amount of splash, which is consistent with the comparisons and findings in **Figure 6**. These two models appear to be sufficiently self-consistent on the basis of this analysis for inclusion in concert in a model designed to predict the behavior of water or common fuels.

With the quantity of material that is involved in the splash determined from the splash model, the distribution and fate of the mass must be determined. When splash occurs, there is a relationship from Yoon et al. [18] that suggests the number of fingers that are expected to form. This number of fingers (N_f) and the mass involved in the splash can be used to determine the number and size of the particles involved in the splatter. The Yoon et al. [18] empirical relationship is as follows:

$$N_f = -92.0 + 57.0 \log(We) \tag{3}$$

This relationship in Eq. 3 is shown to give a better fit to data with high Weber numbers than other theories, as illustrated in **Figure 3**.

Equation (3) is one of many relations found in the literature. There is wide disagreement among the models with data predominant in the range of Weber numbers from 10^3-10^5. Yoon et al. [18] make comparisons against some of these other fits, and note that they do not trend to an appropriate limit at the high and low Weber number regimes. For this study, additional comparisons have been made to existing correlations. A listing of the existing correlations is found in **Table 2** and results plotted in **Figure 7** for a practical range of drops. While most relations are in general agreement around *We* values of 1000, they widely diverge at other conditions. The Aziz and Chandra [19] model includes the Reynolds number, which explains the spread in values for similar Weber numbers in **Figure 6**.

We recognize that our glycerin drops detailed in the experimental section are not well represented by any of the models shown in **Figure 7**. Our drop with a Weber number of 10^6 yielded 40 fingers, which is well below what any of the models predict. While the Aziz and Chandra model includes effects of viscosity, none of the others do. Our data suggest it is important, and higher viscosity should shift the points in **Figure 7** to the right. This highlights the need to pay close attention to the regime of applicability for empirical drop models.

Table 2. Finger number models.

Model	Source
$\left(We\,Re^{1/2}/48\right)^{1/2}$	Aziz and Chandra [19]
$1.14We^{1/2}$	Mehdizadeh et al, [20]
$0.187We - 14.0$	Park and Watkins, [6]
$0.016We - 5.0$	Park and Watkins, [6]
$57.0\log(We) - 92.0$	Yoon et al. [18]

The number of fingers relates to the number of emerging droplets. The simplest assumption is that each finger yields a single particle. This is often true, but not always. The particle break-up model can be argued to compensate for any inadequacies related to this assumption. Assuming a single drop per finger, the break-up model describes the subsequent potential for break-up of the particles.

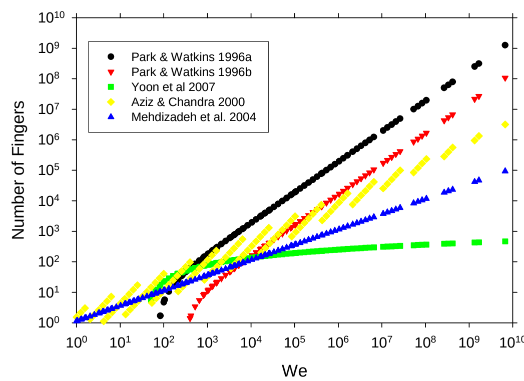


Figure 7. Finger number models plotted for a range of conditions.

Droplet Distribution, Velocity, and Future Work

With the mass and number of fingers described, the size distribution and particle velocity need description. Size distributions can be difficult to determine. We are presently working on this topic, and hope to make contributions in the near future that help define improved models, particularly for spray impacts at high Weber numbers. Ultimately, the size and number distribution of the droplets must be consistent with the mass and number of fingers already prescribed.

Also requiring implementation in an impact and splash model is the velocity of the new droplets. **Figure 8** shows a notional impact schematic of a drop on a surface area. Besides determining the magnitude of the velocity, one must distribute the drops in the ϕ

direction, and determine the appropriate elevation θ, for the newly formed droplets. A complicating factor is if the drop impacts at an oblique angle. We would like to have a model that can adequately distribute the mass with reasonable velocity approximations. A simple velocity assumption might be that the magnitude of the new droplets is equal to that of the incoming drop. More representative of the data, velocity time history might be inferred from a model based on recent applicable measurements [22]. Here, a small amount (<1%) of splashed fluid is forced from the impact region at speeds up to 4 times faster than the impact speed. This is due to the initial spreading fluid being entrained and ejected from the impact region by the air compressed underneath the collapsing droplet. The remaining fluid ejects at velocities close to the impact speed. Alternately, one may take the conservation of energy approach as demonstrated previously [5,7-9], but this approach is either missing a significant unknown that is the energy dissipated on surface impact, or employs a model of questionable reliability and uncertainty. Mass and velocity distributions might fit a distribution function like the finger distribution function described below:

$$\frac{N}{N_{total}} = \frac{\int_0^{\phi} \frac{1}{2} f(\psi) d\psi}{\int_0^{2\pi} \frac{1}{2} f(\psi) d\psi} \qquad (4)$$

In Eq. 4, ψ is an angle, and $f(\psi)$ is a function to distribute the number of particles radially. Given a number of fingers, N_f, and a finger number N, the direction of the evolving droplet may be determined by solving for ϕ. The simplest distribution approximation is appropriate for the perpendicular impact, and is that $f(\psi) = 1$. A more complex assumption might recognize the importance of the two velocity components of the incoming drop relative to the surface normal, and include this in the functional distribution. The elevation, θ, has been assumed to be randomly distributed over a narrow angle range [7,8], and appears to be somewhat consistent with observations from tests.

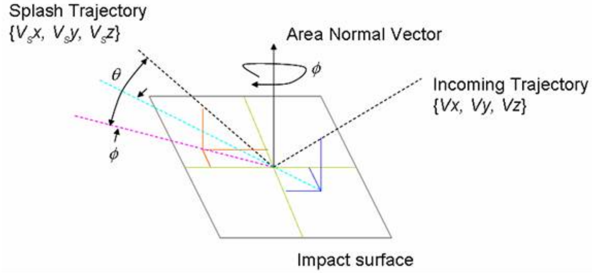


Figure 8. An illustration of variable definitions for the impact spray model.

The modeling described above is implemented in the Vulcan fire simulation code. The model is tested versus several notional cases. One is described herein. A 4 cm diameter drop is periodically released from several meters above a complex platform (about 2 m square) geometrically described in **Figure 9**. A snap-shot of the relative droplet sizes and distributions from the impact at a fixed time can be seen in **Figure 10**. Drop sizes are magnified to be visible, and are not to scale. The initial drop shatters to form hundreds of secondary drops. These impact the obstacles, and further shatter to form tiny, short-lived droplets that quickly evaporate.

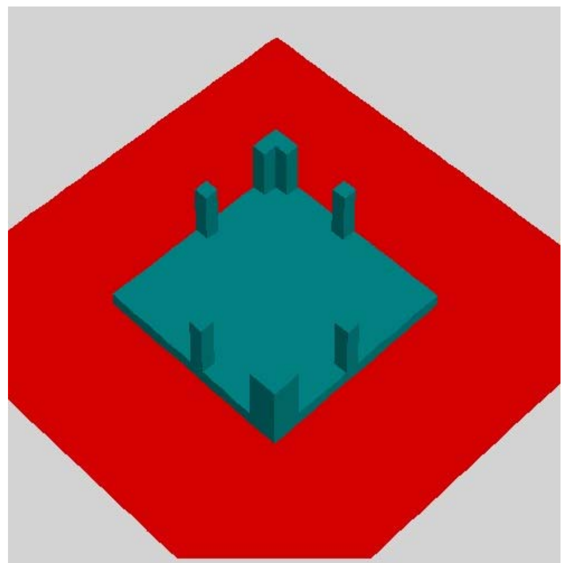


Figure 9. Impacting substrate geometry.

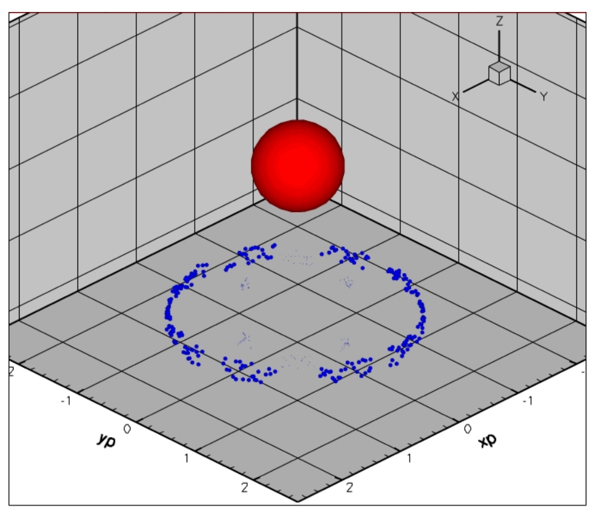


Figure 10. Modeling splashed droplet generation upon drop impact. Only a minor fraction of the incoming drop is splashed into secondary droplets.

Conclusions

1. A new empirical model for liquid splash percent is formulated from data for water and similar liquid impact on a surface that shows good agreement with data for a wide range of Weber numbers.

2. The empirical model for splash percent is relatively consistent with existing models for predicting the presence of splash. The splash criteria generally suggest that splash is present when the presented empirical model suggests splash mass percents greater than 0.01.

3. The 10 cm glycerin drop impact tests suggest inadequacies in existing finger and splash mass models probably related to the treatment of the viscosity in the models. The splash criteria models from the literature are also found to be inadequate, as they do not describe drop-tower observations. Additional work is required to resolve these issues.

4. The mass fraction and the number of fingers models form the backbone of a splash model that is implemented in the Vulcan fire/spray code. Some simplified assumptions regarding the number and size of droplets as well as droplet velocity are presently required. These topic areas merit further study if accurate and representative models are required.

Acknowledgement

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