Extreme Impact Events for Glycerin Provide new Insights for Splash Dynamics

Alexander L. Brown and Richard A. Jepsen*
Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185-1135

Abstract

In the wake of terrorist attacks on civil and governmental structures with transportation vehicles, Sandia National Labs has been actively working to better understand the complex dynamics of large, high-speed liquid impact as it relates to the subsequent thermal insult. This necessitates knowledge of the break-up and transport of the fluid as this relates directly to the fate of the fluid. Such fate varies from rapid consumption in a fireball, to later consumption in a longer-term surface fire. Accurate predictive capabilities allows for improved vulnerability assessments and critical safety design. We find that the size of the body of evidence tends to be inversely proportional to the scale of droplet impact, which means that there are few reports for large-scale impacts. We have therefore focused on experimental testing of fluid dynamics in this large-scale test regime. Single large-scale impacts rapidly disintegrate into many smaller-scale drop problems. The continuum capability to model a wide range of scales is therefore important to the accuracy of a generic impact model.

Motivated by the need for data, we have performed many tests with a variety of fluids and scales into dry, rigid surfaces. In particular, a few tests at large scale with a high viscosity fluid, glycerin, have produced remarkable results. The results of our testing were very different than any theory or empirical relationships heretofore presented would suggest. The subsequent analysis of the existing theoretical models in light of these findings expose shortcomings in the most current models. Many models using non-dimensional parameters such as Weber number and/or Reynolds number appear to be insufficient for the broad range of regimes of interest. Further, this new data and analysis helps define methods for subsequent research that should help improve the applicability of subsequent model development to a broader range of drop conditions.

Introduction

Impact of liquid at large scale, as is the case for transportation accidents, primarily motivates this study. Historically, the smaller scale problems have been better studied and much of the accepted modeling and theory is demonstrated accurate for these smaller scale regimes. Current models tend to rely on similarity arguments to extrapolate beyond tested ranges or provide theoretical validity. There are few careful and instrumented studies at larger scales that are useful for validation, which challenges the progress in this regard. Tieszen conducted a well instrumented test series designed to simulate the impact of an aircraft into the ground [1]. Large-scale tanks of liquid have also been tested impacting into barricades [2]. Video evidence also exists for high profile incidents like the September 11, 2001 attacks [3-5] and others.

We have described in the past a series of tests that we have conducted in an intermediate scale regime [6,7]. The tests involved dropping latex encapsulated 10 cm diameter parcels of liquid from a droptower at velocities of 10-30 m/s. Most of our tests have focused on water, as it is relatively similar to common fuels in viscosity and in surface tension. Motivated by a desire to better understand the relevant physics, we conducted a few tests with glycerin, chosen because it has a significantly different viscosity than water. The outcome of the tests was particularly unexpected given the preponderance of information in the literature on predicting this class of events. Here we present some of the fundamental measurements from these tests and compare these to models found in the most recent literature. The subsequent discussion is meant to suggest methods that can be employed in the future to provide engineering models that will better approximate wide ranging datasets.

* Corresponding author, rajepse@sandia.gov

Methods

We focus in this work on a test series involving approximately 10 cm diameter drops of glycerin. These were done in conjunction with other water impacts as part of a larger test series. The tests have been described well in other conference papers [6,7], so a detailed description here is omitted. The tests discussed herein involved approximately 10 and 20 m/s impact speed on a smooth surface. Propelled by gravity drops in thin latex membranes, the membrane was severed and began retreating when the drop was about 10 cm above the surface, leaving a relatively smooth sphere of only fluid impacting the surface under ideal circumstances. Data were limited to only a few impact tests because of the scope of the project. Three glycerin impacts yielded acceptable results. These three form the context for the results and discussion.

High-speed Phantom cameras were used to record video evidence of the impacts from the side and from beneath. Measured quantities from the impact tests include spread distances of the impacting liquid and number of fingers, or instabilities present around the circumference of the impacting drop. Further, the mass remaining on the impact surface was recovered, from which we infer the splash mass by difference.

Comparisons are made to existing models for drop spread, fingers, and splash mass. Drop spread models have been reviewed by Healy et al. [8]. The dimensionless spread, β_{max}, is defined as the spread diameter divided by the drop diameter. Several more recent articles deal with the same issues [9-11]. These typically employ assumptions regarding the energy differential between the incoming drop and the final drop state to predict the final dimensionless spread diameter β. Herein, comparisons are made to four algebraic models. These models are as follows:

$$\frac{We}{2} = \frac{3}{2}\beta_{\max}^2\left[1+\frac{3We}{\mathrm{Re}}\left(\beta_{\max}^2\ln\beta_{\max}-\frac{\beta_{\max}^2-1}{2}\right)\left(\frac{\mu_{drop}}{\mu_{wall}}\right)^{0.14}\right]-6 \quad (1)$$

$$\frac{3We}{2\,\mathrm{Re}}\beta_{\max}^4+(1-\cos\theta)\beta_{\max}^2-\left(\frac{We}{3}+4\right)=0 \quad (2)$$

$$\beta_{\max}=\sqrt{\frac{We+12}{3(1-\cos\theta)+4\left(We/\sqrt{\mathrm{Re}}\right)}} \quad (3)$$

$$(We+12)\beta_{\max}=8+\beta_{\max}^3\left[3(1-\cos\theta)+4\frac{We}{\sqrt{\mathrm{Re}}}\right] \quad (4)$$

Sequentially, these are the Chandra-Avedesian model [12], the Kurabayashi-Yang model [13], the Pasandidah-Fard et al. model [14], and the Ukiwe-Kwok model [10]. Other more complex differential equation based models exist [8,11], but are not herein compared.

Drop finger models are recently reviewed [15]. Herein, comparisons are made to the Aziz and Chandra model [16], the Mehdizadeh et al. model [17] and the Yoon et al model [15] respectively:

$$N_f=\left(We\,\mathrm{Re}^{1/2}/48\right)^{1/2} \quad (5)$$

$$N_f=1.14We^{1/2} \quad (6)$$

$$N_f=57.0\log(We)-92.0 \quad (7)$$

Drop splash models that are most widely used predict the presence or absense of splash [14-15], with some modeling for the mass involved [6]. Little exists quantifying the mass of splash expected from a drop. In a recent conference paper, Brown et al. [6] presented a model for the mass ejected significantly away from the impact region:

$$\%Splash=\frac{100We}{We+10^6} \quad (8)$$

More well characterized models, however, exist for determining the splash inception threshold. Use of what is known as a K coefficient or K factor is commonplace to distinguish a drop that splashes and one that does not where K_{crit} is defined as the threshold of splash.

The Mundo et al. [17] and Cossali et al. [18] models follow in that order:

$$K \equiv Oh\,\mathrm{Re}^{1.25} = We^{0.50}\,\mathrm{Re}^{0.25} > K_{crit} = 57.7 \tag{9}$$

$$K \equiv Oh\,\mathrm{Re}^{-0.4} = We^{0.80}\,\mathrm{Re}^{0.40} > K_{crit} = 649 + \frac{3.76}{(R^*)^{0.63}} \tag{10}$$

Results

Figure 1 shows still photograph from high speed video for two of the impact tests. The 10 m/s nominal speed drop (Fig 1 A and B) did not splash except due to the retreating latex at the top of the drop, and no instabilities or fingers were found except for one clearly attributable to the retreating latex. The 20 m/s nominal speed drops (Fig 1 C and D) exhibited some splashing, and also resulted in fingers. Both of these tests were slightly affected by the retreating latex. This was because a portion of the latex was still in the process of retreating from around a part of the edge of the impacting drop. For finger counts, the unaffected portion was evaluated and assumed representative of the whole. Table 1 gives a summary of the relevant data extracted from these tests. Dimensionless parameters are calculated from nominal velocities and measured mass along with a density of 1260 kg/m^3, surface tension of 0.0633 Nm, and viscosity of 1.49 Pa-s.

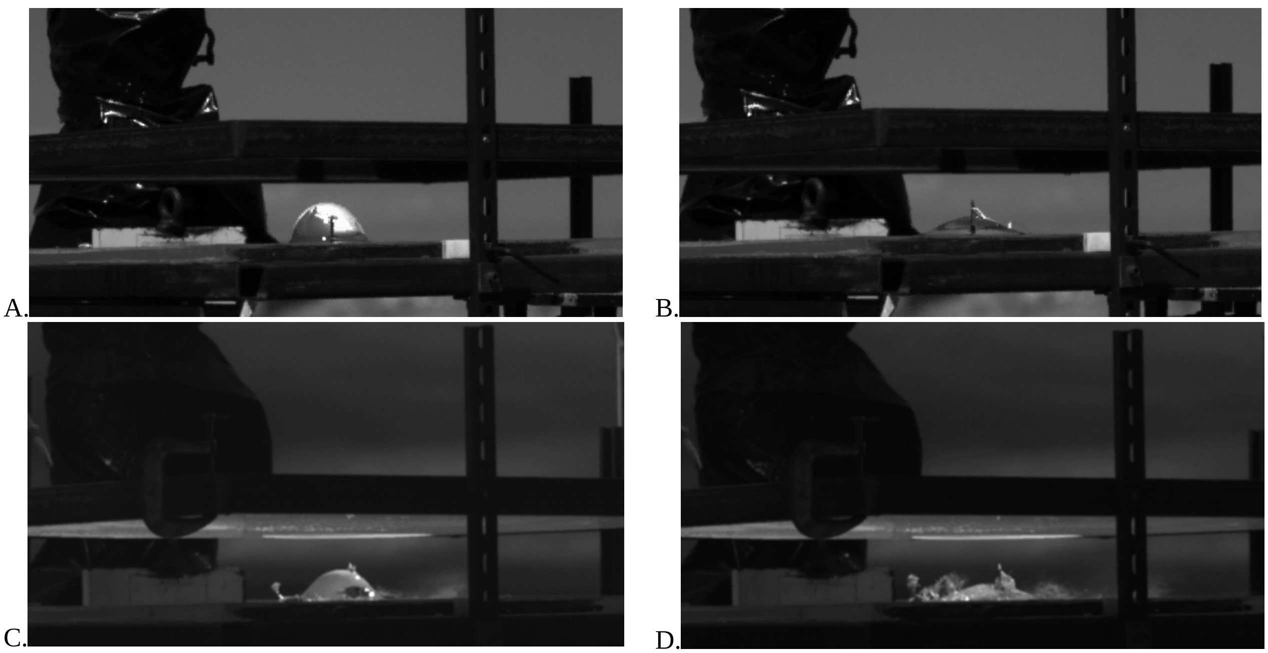

Figure 1. Stills from the high-speed photography of the Case 1 drop of glycerin with no splash or fingers (A,B), and the Case 2 drop with a small amount of splash (C,D) early in the impact (A,C) and later in the impact (B,D).

Table 1. A summary of the test data from the large-scale glycerin impacts.

Test Case	Nominal Velocity *m/s*	We	Re	Mass *Kg*	Fingers?	Splash?
1	10	2.48×10^5	1050	0.53	No	No
2	20	9.15×10^5	1935	0.48	Yes	Yes
3	20	9.89×10^5	2090	0.62	Yes	Yes

The spreading exceeded the range of vision of the camera, and is not quantified for the 20 m/s nominal speed impacts. The 10 m/s impact yielded measurable data for the spread distance on the surface of 23.5 cm. The spread distance and dimensionless spread distance, β, were measured in each quadrant and averaged. This also provides the only indicator of uncertainty since there were no repeats. Table 2 shows the predicted dimensionless spread distance of the impacting 10 m/s drop. An isothermal problem was assumed for the Kurabayashi-Yang model. Some models require a surface contact angle θ. Models were quite insensitive to this parameter for this scale of drop, and 45º was assumed for calculations.

Table 2. A comparison of dimensionless spread factor for 10 m/s impact.

Source	Dimensionless Spread (βmax)	Equation	Reference
Chandra-Avedesian	3.31	1	12
Kurabayashi-Yang	3.88	2	13
Pasandidah-Fard et al.	2.82	3	14
Ukiwe-Kwok	2.82	4	10
Present Test	4.2 +/- 0.3		

Of the four models tested, the Kurabayashi-Yang performs the best, and is reasonably close to the actual test data. The others are not grossly different, unless one considers that a spread factor of 2.82 would over-predict the final thickness of the impact fluid as 7.8 mm compared to 3.5 mm assuming a cylindrical shape.

Table 3 shows a comparison between the finger models versus the test data from the three glycerin experiments. Although the number of tests is low, the measured finger counts are considered to have an uncertainty of +/- 20% based on experience with a previous test series [6]. Figure 2 shows the glycerin drop impact data from this series plotted versus water data from several sources. No existing models represent the glycerin data well, and most are off by at least an order of magnitude. In Figure 2.A, the number of glycerin fingers predicted by the Yoon et al. model is found with water to be incorrect by a few orders of magnitude in terms of number of fingers, or by several orders of magnitude in terms of the Weber number.

Table 3. A comparison of number of fingers.

Source	Number of Fingers Case 1 (10 m/s)	Number of Fingers Case 2 (20 m/s)	Number of Fingers Case 3 (20 m/s)	Equation	Reference
Aziz and Chandra	409	916	970	5	16
Mehizadeh et al.	568	1091	1133	6	17
Yoon et al.	216	248	250	7	15
Present Tests	0	48 +/- 20%	36 +/- 20%		

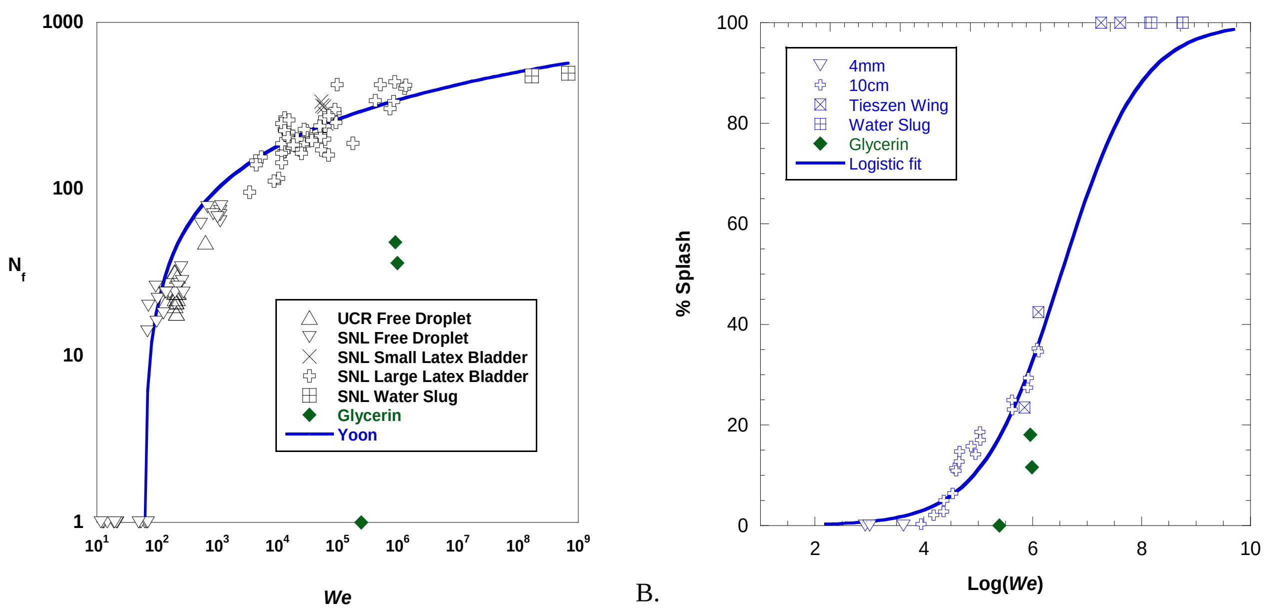

Figure 2. Glycerin drop impacts compared water for A. finger model and data, and B. splash percent model and data.

Figure 2.B shows the percent of material splashed compared to the fit to a wide range of Weber number data from water tests. The low-speed (10 m/s) test did not produce splash, and is clearly not well described by the logistic fit. A comparison between test results and the two splash models is shown in Table 4. Neither model correctly predicts the 10 m/s nominal velocity test case results, and neither model is close to predicting the inception of splash

as is evidenced in the comparison between the critical and computed K values for Case 1. Critical values for the *K* coefficients differ from the *K* values by at least an order of magnitude. This suggests that the discrepancy is not simply a minor one occasioned by small uncertainties in the model coefficients. Dimensionless surface roughness (R^*) was taken to be 8×10^{-5}, as the surface roughness was less than 1×10^{-5} m. This is well outside the range of the dimensionless surface roughness that was employed in developing the model.

Table 4. A comparison of models for the inception of splash.

Source	Splash? Case 1	Splash? Case 2	Splash? Case 3	K Case 1	K_{crit} Case 1	Equation	Reference
Mundo et al.	Yes	Yes	Yes	2830	57.7	9	18
Cossali et al.	Yes	Yes	Yes	3.34×10^5	2081	10	19
Present Tests	No	Yes	Yes				

These results differ from previously obtained large-scale impacts primarily in the viscosity of the fluid. Glycerin properties are very similar to water and many fuels (surface tension and density), except that it has about 3 orders of magnitude higher viscosity. The scale of the impacts is also relatively unique, as impact testing is normally done for drops in the centimeter and smaller range.

Discussion

The drop spread models all under-predict the experimental spread for Case 1. They are comparatively close, with the worst being about 35% low. These are based primarily on energy balance assumptions regarding the arriving drops. We are unaware of any comparisons to tests with Weber numbers that are within a few orders of magnitude. The agreement is suggestive that the models, despite certain geometric assumptions, are reasonably able to predict final mass spread, and that the conditions of self-similarity are reasonably met.

Finger models and splash models were not close to correctly predicting the outcome of these tests. The finger models grossly over-predict the number of fingers. The splash percent model also significantly over-predicts the splash mass. Finger and splash models have evaluated impacts of the same length scale as these. Because surface tension for glycerin is relatively similar to that of water, this suggests the significance of the viscosity to the result. The models for predicting the inception of splash were derived from datasets containing glycerin and glycerin-water mixtures, but without the size of drops evaluated here. This may suggest that drop size is not correctly modeled, or as noted that the dimensionless roughness factor is not correctly modeled. But we found that a 10 m/s ~10 cm diameter drop did not splash. We have performed other small scale tests, and cannot achieve splash for glycerin. It may be that the previously reported data were analyzed without finding splash for any glycerin tests. Without having found the splash inception point, the binary nature of the splash inception probably masked the sensitivity of the outcome to the viscosity. For a binary result such as this, the transition point must be found before the data can be purported to be suggestive of results for a class of fluids.

Testing at this scale can be difficult and expensive and only a few experiments were done for glycerin. A potential criticism of the test series presented here is the lack of data quantity. However, we are reasonably confident in the result of our 10 m/s (Case 1) impact because virtually every experimental imperfection would tend to enhance the onset of instabilities and splashing rather than suppress it. Velocities have been verified with side camera analysis. Still, replication of these results will expectedly bring added confidence to their significance.

The outcome of these tests suggests the need for additional work on drop models that characterize splash. We infer from the tests that the viscosity is functionally related to the fingering and splash. Some of the models do not include viscosity in the model equations. Others that include viscosity do not appear to have fully captured the functional relationship between viscosity and splashing. In future model development, it is helpful to have data from widely varying conditions available to verify the similarity assumptions. These data are thought to be excellent for comparison and aid in verification that developed models have appropriately captured the physical behavior.

Nomenclature

		Greek		Subscripts	
K	Dimensionless Splash Criteria	β	Dimensionless Spread Factor	*crit*	critical
Nf	Number of Fingers	θ	Contact Angle	*drop*	At drop temperature
Oh	Ohneserge Number	μ.	Viscosity	*max*	maximum
R^*	Dimensionless Roughness			*wall*	At wall temperature
Re	Reynolds Number				
We	Weber Number				

Conclusions

The 10 cm diameter glycerin drop experiments yielded unexpected results that are not well described by any existing models. Algebraic drop spread models tend to under-predict the final spread by a small amount (5-35%) depending on the model. The models for number of fingers are incorrect by at least an order of magnitude. The splash percent model and the models that indicate a critical splash point also appear to be inadequate. These data suggest that additional work is necessary to develop an impact model that is broadly applicable to a wide range of fluid types and drop impacts. These are believed to be valuable data that provide information to future model development in test regimes that are well outside of typical test conditions found in the literature for impacting drops.

Acknowledgements

The authors appreciate the work of Luis Abeyta who led much of the experimental set-up and testing. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract No. DE-AC04-94AL85000.

References

1. Tieszen, S.R., “Fuel Dispersal Modeling for Aircraft-Runway Impact Scenarios,” SAND95-2529 (1995).
2. Jepsen, R.A., T. O’Hern, B. Demosthenous, E. Bystrom, M. Nissen, E. Romero, and S. S. Yoon, “Diagnostics for liquid dispersion due to a high-speed impact with accident or vulnerablility assessment application,” Measurement Science and Technology, 20, 2, 025401, pp. 12, (2009).
3. Mlakar, P.F., D.O. Dusenberry, J.R. Harris, G. Haynes, L.T. Phan, and M.A. Sozen, “The Pentagon Building Performance Report,” ASCE, Reston, VA USA, January 2003.
4. McAllister, T., Editor, “World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations,” FEMA 403, New York, NY USA, May, 2002.
5. Gann, R.G., Editor, “Final Report on the Collapse of the World Trade Center Towers, NIST NCSTAR 1, Washington, D.C. USA, September 2005.
6. Brown, A.L., Jepsen, R.A., and Yoon, S.S., “Modeling Large-scale Drop Impact: Splash Criteria and Droplet Distribution,” ILASS *Americas*, *21st Annual conference on Liquid Atomization and Spray Systems*, Orlando, FL, May 18-21, 2008.
7. Jepsen, R.A., and Brown, A.L., “Drop Fingering on Oblique Impact: Part 1—Experimental Data,” Submitted to the 11th ICLASS, Vail, CO USA, July 26-30, 2009.
8. Healy, W.M., J.G. Hartley, and S.I. Abdel-Khalik, “Comparison between theoretical models and experimental data for the spreading of liquid droplets impacting a solid surface,” *Int. J. Heat Mass Transfer*, 39, 14, 3079-3082, (1996).
9. Healy, W.M., J.G. Hartley, and S.I. Abdel-Khalik, “Surface wetting effects on the spreading of liquid droplets impacting a solid surface at low Weber numbers,” *Int. J. Heat Mass Transfer*, 44:235-240, (2001).
10. Ukiwe, C., and D.Y. Kwok, “On the Maximum Spreading Diameter of Impacting Droplets on Well-Prepared Solid Surfaces,” *Langmuir*, 21, 666-673, (2005).
11. Attané, P., F. Girad, and V. Morin, “An energy balance approach of the dynamics of drop impact on a solid surface,” *Physics of Fluids*, 19, 012101, (2007).
12. Chandra, S., and C.T. Avedisian, “On the collision of a droplet with a solid surface,” *Proc. R. Soc. Lond. A* 432:13-41, (1991).
13. Yang, W.J., “Theory on vaporization and combustion of liquid drops of pure substances and binary mixtures on heated surfaces,” 535, Institute of Space and Aeronautical Science, University of Tokyo, Tokyo 1975.
14. Pasandideh-Fard, M., S.D. Aziz, S. Chandra, and J. Mostaghimi, “Surface cooling by an impinging water drop,” Presented at the *33rd National Heat Transfer Conference*, Albuquerque, NM, August 1999.
15. Yoon, S.S., Jepsen, R.A., Nissen, M.R., O’Hern, T.J., “Experimental investigation on splashing and nonlinear fingerlike instability of large water drops,” *Journal of Fluids and Structures*, 23:101-115 (2007).
16. Aziz, S.D., and Chandra, S., “Impact, recoil, and splashing of molten metal droplets,” *International Journal of Heat and Mass Transfer*, 43:2841-2857 (2000).
17. Mehdizadeh, N.Z., Chandra, S., and Mostaghimi, J., “Formation of fingers around the edges of a drop hitting a metal plate with high velocity,” *Journal of Fluid Mechanics*, 510:353-373 (2004).
18. Mundo, C., Sommerfeld, M., and Tropea, C., “Droplet-wall Collisions: Experimental Studies of the Deformation and Breakup Process,” *Int. J. Multiphase Flow*, 21:2:151-173 (1995).
19. Cossali, G.E., Coghe, A., Marengo, M., “The Impact of a Single Drop on a Wetted Solid Sur-face,” *Experiments in Fluids*, 22:463-472 (1997).