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EFFECTS OF DROP AND FILM VISCOSITY ON DROP IMPACTS ONTO THIN FILMS

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While drop–film impacts have been studied extensively in the past, little thought has been given towards separating the effects of the drop fluid properties from those of the film. Distinguishing between the behaviors resulting from characteristics of each independently could provide insight into the underlying physical phenomena with a clarity that is unavailable when the drop and the film consist of identical liquids. In this study, the viscosity is the central parameter varied in both drop and film liquid. Using water, aqueous glycerol mixtures, and Fluoroinert FC-72, a range of kinematic viscosity covering 3 orders of magnitude ($4 \times 10^{-7} - 6.5 \times 10^{-4}$ m^2/s*) is examined; a smaller range of surface tension (0.024–0.072 N/m) is covered, as well. Drop impacts occur over a range of Weber numbers from 20 to 3000 and Reynolds numbers from 20 to 14000. Impact outcomes categorized are both formation of a crown and splashing from the crown. Criteria for each impact outcome are presented in light of both film and drop properties; certain outcomes are found to depend more strongly on either the properties of the drop or the film individually. Crown formation appears to relate more strongly to the film's properties, whereas crown splashing has some dependence on the drop properties. Existing splashing correlations are examined in light of the separation of properties.*

KEY WORDS: *single drop impact, thin films, splashing*

1. INTRODUCTION

Liquid drop impacts have been studied since the advent of film photography in the nineteenth century, and drop impacts onto films of a different liquid were among the first experiments in this line of research (Worthington and Cole, 1897). In more recent times, the thrust of drop–film impact research has concerned same-liquid situations, with little focus on impacts of drops onto differing fluid films (Rein, 1993; Yarin, 2006). Fedorchenko and Wang examined in detail the effects of viscosity on film and film impact outcomes, but did not separate the effects of film and droplet viscosity (Fedorchenko and Wang, 2004). Vander Wal et al. explicitly state that their study is of drop impacts onto same-fluid films (Vander Wal et al., 2006). It seems that since 1975, little thought has

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NOMENCLATURE

d	diameter	μ	dynamic viscosity
h	thickness	Fr	$U/(gd)^{1/2}$, Froude number
U	impact velocity	Oh	$\mu/(\rho\sigma d)^{1/2}$, Ohnesorge number
σ	surface tension		
ρ	density	Re	Ud/ν, Reynolds number
ν	kinematic viscosity	We	$\rho U^2 d/\sigma$, Weber number

been given to separating the properties of the film and of the drop (Smith, 1975). With tremendous advances in imaging and correspondingly in the field of drop impact study, the topic is due for re-examination, especially given the numerous practical applications where drops impact on a different liquid film.

For example, sprays are prevalent means of fire suppression, and when solid material is burning a spray excels at extinguishing the fire. Film-fueled fires are less simple to quench. An incorrectly applied fire retardant can induce splashing, spread the burning liquid, and potentially worsen the fire. One solution is to use very fine sprays that evaporate rapidly and displace the ambient oxygen that combustion requires (Kim and Ryou, 2003). Direct quenching of burning pools can extinguish the fire quickly—imperative in kitchen and engine room fires—but the impact outcomes of the spray must be controlled to prevent splashing and subsequent additional damage. In either case of film-fueled fires, the extinguishing spray and the burning pool will never be the same liquid; thus, an understanding of how the drop and film properties individually control impact outcomes is critical in this application of sprays. Another application of dissimilar drop and film fluids is spray freeze drying, especially in the biomedical field, where a feed spray impinges on a cryogen liquid and freezes into useful solid particles (Eslamian and Ashgriz, 2011). On a cosmic scale, dissimilar "liquid" impacts are observed with meteor strikes: planetary crusts and atmospherically-superheated meteorites can behave analogously to viscous liquids at the velocity and energy scales observed in these events (Fink et al., 1984).

Rein defined four immediate outcomes after droplet impact in his review paper: floating, bouncing, coalescence, and splashing. He also defined subsequent outcomes happening after coalescence and splashing: vortex rings and jetting, respectively (Rein, 1993). Floating and bouncing rarely occurred in his work's scope of study; these behaviors are typically associated with extremely low impact velocities (Rein, 1993). This work instead focuses on the boundary between coalescence and splashing. The modified regimes examined in this study are therefore (1) coalescence, (2) crowning, and (3) crown splashing. In this study, these regimes are examined in light of varying the drop fluid and the pool fluid independently; drops of a range of fluids impact a corresponding range of films.

Fedorchenko and Wang's analysis of drop impacts on thin films went into significant detail concerning cavity formation and collapse and jet formation, and further proposed a model of crown formation. The maximum cavity depth and the length scales of the central jet are experimentally and analytically related to the Froude number as $\mathrm{Fr}^{1/4}$ (Fedorchenko and Wang, 2004). However, their analysis did not include the effects of surface tension. Vander Wal et al. noted that in fluids with increased surface tension, the occurrence of prompt splash was lessened, and also that increasing viscosity restricted splashing, both prompt and crown (Vander Wal et al., 2006). It is worth noting that Vander Wal et al. experimented with a range of viscosity covering one order of magnitude (Vander Wal et al., 2006), whereas this study covers three orders of magnitude in dynamic viscosity (Table 1). Both studies examine similar ranges of surface tension, however.

A general correlation for splashing on a liquid film was proposed by Cossali et al. for the regime $H^* \equiv h_{\mathrm{film}}/d_{\mathrm{drop}} < 1$ as (Cossali et al., 1997):

$$\mathrm{We} * \mathrm{Oh}^{-0.4} \geq 2100 + 5880 {H^*}^{1.44} \tag{1}$$

Cossali et al. specify that this correlation works only for $\mathrm{Oh}_{\mathrm{drop}} > 7 \times 10^{-3}$, which excludes water and FC-72 drops observed in this study. This correlation is also found to be accurate for very shallow films ($H^* < 0.2$) for lower $\mathrm{Oh}_{\mathrm{drop}}$ numbers. Within that very thin film range of H^*, Vander Wal et al. found that surface roughness plays a significant role in the splashing behavior, with rougher surfaces increasing splashing tendencies (Vander Wal et al., 2005). That regime of H^* is outside of the range of this study, however. This study extends beyond the film thickness Cossali used, with $H^* = 1$.

On deeper films, Vander Wal et al. ultimately concluded that different splashing modes exist, relating to the film thickness and to fluid viscosity and surface tension, thus no single correlation is able to predict liquid film impact splashing universally (Vander Wal et al., 2006). Zhang et al. studied the formation of the crown in close detail, finding that splashing depends on the behavior of the immediate post-impact ejecta sheet and the somewhat delayed lamella formation (Zhang et al., 2011). Here, we focus on the behavior after impact more than the immediate lamella formation; and by separating

TABLE 1: Fluid properties

Fluid	**Density ($\mathrm{kg/m^3}$)**	**Viscosity ($\mathrm{m^2/s}$)**	**Surface tension (N/m)**	**Typical Ohnesorge**
FC-72	1680	4×10^{-7}	0.010	0.0035–0.0040
Water	998	1×10^{-6}	0.073	0.0021–0.0023
60% Glycerol	1148	9×10^{-6}	0.067	0.0200–0.0220
85% Glycerol	1222	9×10^{-5}	0.065	0.2000–0.2100
100% Glycerol	1260	6.5×10^{-4}	0.064	0.2700–0.2800

drop and film properties hope to determine in more detail why a universal correlation for splashing is not practical.

Figure 1 shows the progression of crown behavior studied in this paper, based on a regime map by Rein, in order of increasing Weber number (Rein, 1996). That study does not provide exact or even approximate values for the Weber number of transitions between the reported behaviors (crown formation, and crown splashing), but instead says that the transition Weber numbers depend on the Froude number; that is, the strength of inertial versus gravitational forces. Based on data from this study, the order of magnitude for the transition between each behavior is approximated in the figure.

In summary, this study seeks to fill in the gaps in the understanding of drop–film impact. A larger range of fluid viscosities is examined than has been used in any previous study, to the best of the authors' knowledge. Existing splashing correlations are found to be unable to address the full range of drops and films in this study, and new empirical correlations are proposed that predict crown formation and splashing based on the data from this study.

2. EXPERIMENTAL METHODS

Figure 2 depicts the experimental setup used in this study. Drops are produced by a microliter pneumatic valve (EFI, Inc., Model 740V-SS) fed from a pressurized reservoir; they separate based on surface tension and free-fall from a stainless steel nozzle of 1.65 mm outer diameter. By varying the height of the nozzle, the impact velocity can be adjusted from 0 to 3.5 m/s. A 12.7 cm diameter pool formed by a cast epoxy resin substrate and transparent acrylic tubing provides the impact target. The relatively large

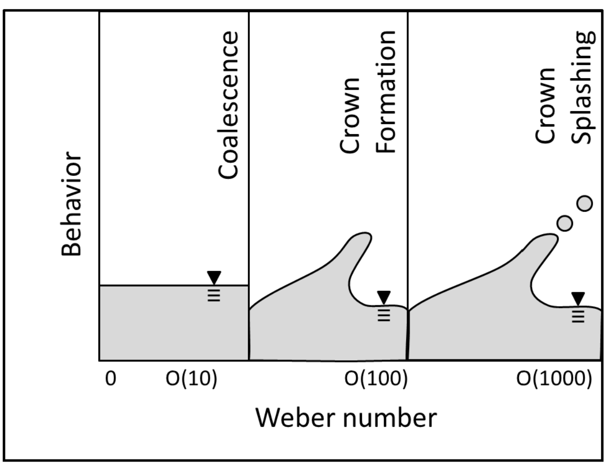

FIG. 1: Weber-based regime map for drop impact onto liquid pools, based on past observations (Rein, 1996), fitted to magnitudes found in this study. Diagram depicting the impact outcomes from a horizontal perspective.

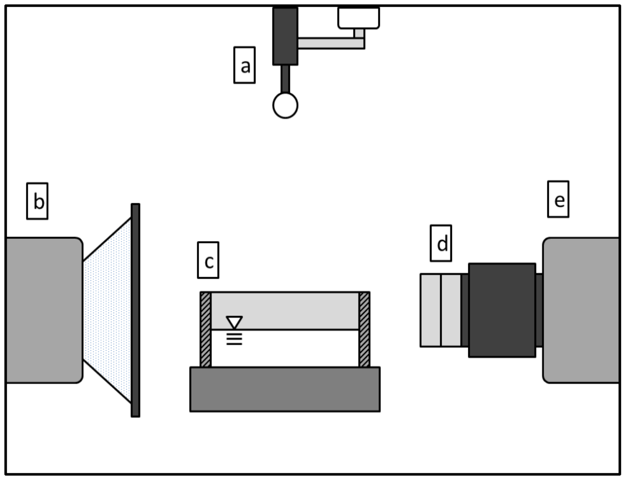

FIG. 2: Experimental setup for measuring film impacts. (a) Drop generator and fluid reservoir. (b) Backlight and diffuser. (c) Transparent-walled pool. (d) Magnification lenses. (e) Phantom v7.1 video camera.

diameter of the pool prevents the walls from affecting the impact behavior. A Phantom V7.1 video camera records the impacts at 512 $\times$ 256 pixels resolution at 9000 fps through a Nikon Micro-Nikkor 105 mm f/2.8 lens. The Phantom Camera Control (PCC 1.3, Vision Research, Inc.) software captures impact videos. Using this software to measure objects of known dimensions gives approximately 1% error in length measurements ($<\pm$0.05 mm); velocity measurement is expected to have a larger error due to slight blurring due to exposure time (10 μs) and was assumed accurate to within $\pm$0.1 m/s.

Drop fluids used are water, 60% glycerol/40% water by weight mixture, 85% glycerol/15% water mixture, pure ($>$99.9%) glycerol, and Fluoroinert FC-72 (3M). Table 1 lists the relevant properties of each fluid. As the droplets of water, glycerol, and the mixtures form at the tip of the stainless steel nozzle, they have diameters of 3.3 $\pm$ 0.2 mm. FC-72 drops, however, have diameters of 1.7 $\pm$ 0.1 mm due to their low surface tension. These conditions give a range of Weber number of 20 to 3,000 and Reynolds number from 20 to 14,000. Film depth is the same as the drop diameter for each experiment, corresponding to the intermediate film depth examined by Vander Wal et al. (2006) and the maximum film depth of Cossali et al. (1997).

Three impact behaviors are classified in this study: (1) coalescence, (2) grown formation, and (3) crown splashing, in accordance with the observations classified by Rein (1993). Coalescence is defined as the absence of a crown or capillary wave. We categorize crown formation to include the appearance of a capillary wave above the original surface level of the film or an approximately vertical or outward-angled crown ejected from the cavity caused by the impact. Secondary droplets separating from the vertically-displaced crown is crown splashing. Figure 3 depicts a representative photograph from

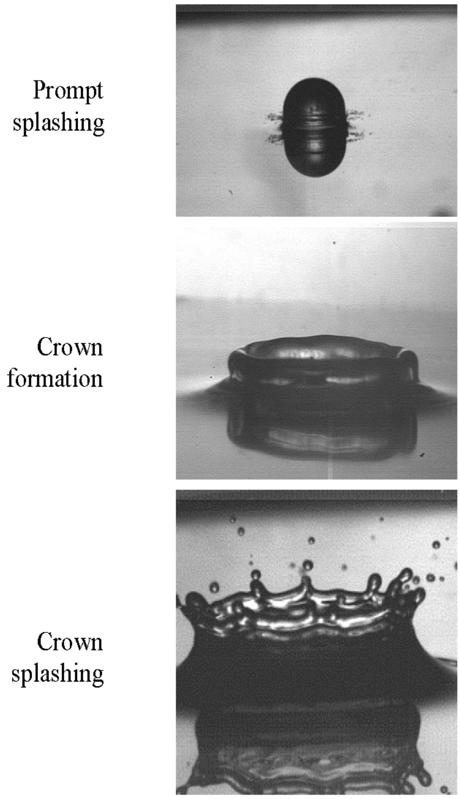

FIG. 3: Characteristics of observed impact phenomena.

videos taken for this study of each behavior, using the experimental setup described previously.

3. RESULTS AND DISCUSSION

Since Cossali's (Cossali et al., 1997) splashing correlation, as well as many other analyses of film-impact splashing, the Weber and Ohnesorge numbers are used initially as the relevant dimensionless groups to anticipate splashing, and the data for this study have been plotted on those axes as well. These axes distinguish the varying fluids from each other, as the Ohnesorge number is a characteristic of the fluid and a length scale. Each fluid in this study has a distinct range of Ohnesorge number, which is included in the Table 1. In order of increasing Oh, the fluids used in this study are water, FC-72, 60% glycerol, 85% glycerol, and pure glycerol. The use of film properties in characterizing liquid drop impact is, to the best of the authors' knowledge, novel; however, when examining the impact of a solid sphere onto a liquid surface, the film properties are always used in relevant dimensionless groups (Thoroddsen et al. 2004).

3.1 Crown Development and Splashing

Table 2 summarizes the findings for crown behavior for each film, in terms of the film Weber number thresholds (We_{film}) for crown formation and splashing. The table presents the transition regions for crown behaviors. Between the We_{film} values for the crown threshold and the lowest crown splashing, crown formation is observed without splashing. Between the lowest crown splashing and universal splashing values, crown formation occurs with as well as without splashing. Above the universal splashing We_{film}, crown splashing appears to occur with every impact. The requirements for crown formation are examined in detail in Fig. 4. Each depicted region marks the transition between

TABLE 2: Comparison of crown behavior Weber-based thresholds for several pools

Pool fluid	Crown Threshold	Lowest Splashing	Universal Splashing
FC-72	550	900	1100
Water	100	200	500
60% Glycerol	120	350	600
85% Glycerol	180	350	700

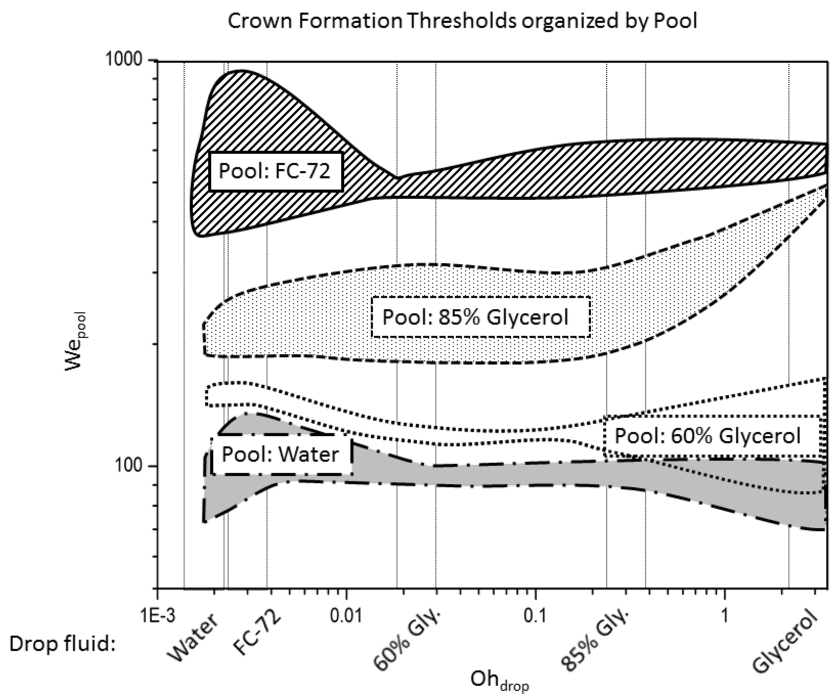

FIG. 4: Crown formation thresholds, organized by film. The regions represent the transition from no crown formation to consistent crown formation. The x-axis includes labels of each drop species with their respective Oh range represented by the vertical bars on the graph.

coalescence and crown formation for a film. A wider region means the transition is less clearly defined, with coalescence and crown formation both occurring within that range. For each film, the Weber range at which the transition occurs is approximately constant with regard to drop Oh ($\mathrm{Oh_{drop}}$) for $\mathrm{Oh_{drop}} < 1$, suggesting the drop's properties play a minimal role in crown formation. At the upper limits of $\mathrm{Oh_{drop}}$ tested in this study, there starts to be some deviation from the constant crown formation threshold, perhaps due to the highly viscous nature of the drops. In other words, at very high drop viscosity, the magnitude of that viscosity seems to restrict crown formation, while below $\mathrm{Oh_{drop}} \sim 1$, drop properties' effect on crown formation is minimal. In contrast, each film's near-constant transition $\mathrm{We_{film}}$ value is unique to that film. For water, 60% glycerol, and 85% glycerol, the transition value increases with film viscosity. Intuitively, this makes sense; a higher film viscosity ought to restrict highly dynamic behavior like crown formation. However, this trend does not hold for FC-72; as apparent in the figure, the FC-72 film requires a far higher Weber number than the other films for crown formation, despite having a two- to three-fold lower viscosity than water. In fact, FC-72 has the lowest viscosity and surface tension of the studied liquids, so in principle it should require the least amount of energy to form a crown. The other notable feature of the crown formation thresholds in Fig. 4 is the increase in the formation threshold for 85% glycerol for very high drop $\mathrm{Oh_{drop}}$. For $\mathrm{Oh_{drop}} > 1$ (pure glycerol, in this study), the 85% glycerol film takes a significantly increased $\mathrm{We_{film}}$ to form a crown. The very high viscosities involved in that film–drop pairing serve to severely restrict crown and crown splashing behavior.

Figure 5 shows the crown splashing threshold on each film. For the range of film viscosity covered in this study, crown splashing always occurs if $\mathrm{We_{film}}$ number is above 1000. Below this value, the onset of crown splashing follows roughly the same trend for all fluids. It starts at lower $\mathrm{We_{film}}$ for lower $\mathrm{Oh_{drop}}$ values and it reaches seemingly asymptotic values for $\mathrm{Oh_{drop}} > 0.04$, albeit a relatively wide spread of splashing threshold $\mathrm{We_{film}}$ for all film fluids. It seems that beyond that $\mathrm{Oh_{drop}}$, the effect of viscosity becomes constant regardless of the actual magnitude of viscosity. In contrast to the "crown formation" cases discussed above, the "crown splashing" behavior shows changing threshold values with varying drop fluids. Namely, the splashing threshold is reduced as drop viscosity decreases, suggesting that while the entirety of the corona splashing phenomenon cannot be attributed solely to film or drop viscosity and surface tension, the drop and film fluids' interaction that takes place during the impact that precedes splashing leads to a non-obvious role of dissipation (viscosity) and cohesive (surface tension) forces. As the film grows increasingly viscous, crown formation is inhibited, and therefore crown splashing is prevented.

Impacts onto pure glycerol films (viscosity $\sim$10 times that of 85% glycerol) resulted in no crown formation within the range of viscosities and surface tensions used in this study, with a single exception: An FC-72 droplet, with $\mathrm{We_{film}}$ = 97 and $\mathrm{Oh_{drop}}$ = 0.0038, appeared to crown and splash when it impinged upon the pure glycerol film. We suspect

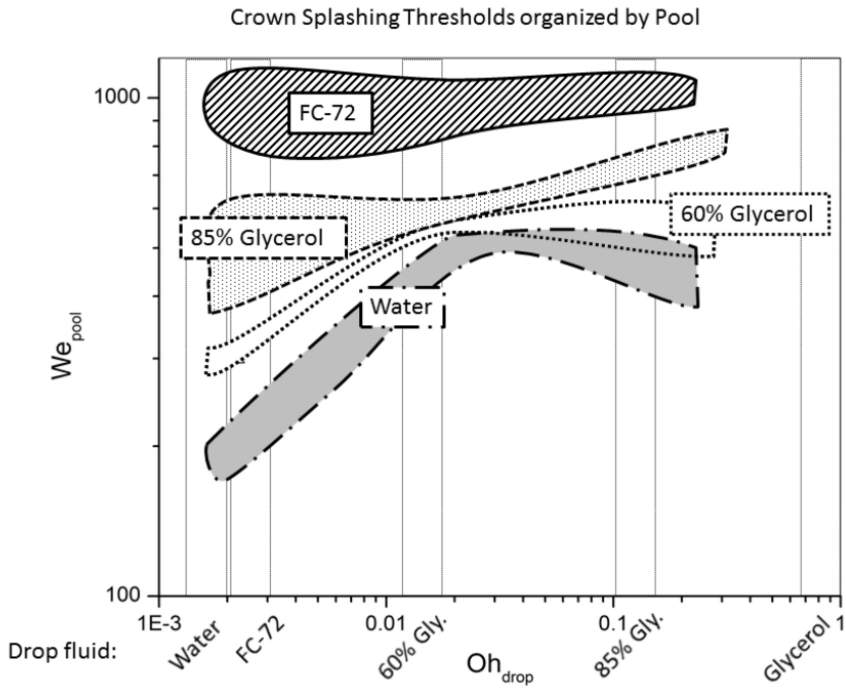

FIG. 5: Crown splashing behaviors, organized by film. The regions represent the observed transition from not splashing to consistently splashing. The *x*-axis includes labels of each drop species with their respective Oh range represented by the vertical bars on the graph.

that with such a difference in viscosity, a ratio of over 103, the glycerol film approximated a solid surface to that particular droplet. None of the other drops tested with that film appeared to crown or splash, having higher respective viscosities.

To better illustrate the complex role of viscosity in film impact splashing, crown behaviors are compared for a single type of drop across the range of films in this study in Fig. 6, organized onto $\mathrm{We}_{\mathrm{film}}/\mathrm{Oh}_{\mathrm{film}}$ axes. The film-based Ohnesorge number is used in this case to differentiate the film fluid. The splashing threshold spikes around $\mathrm{Oh}_{\mathrm{film}} \approx 0.003$, which corresponds to an FC-72 film; it then decreases as $\mathrm{Oh}_{\mathrm{film}}$ shifts. Figure 7 reorganizes the x-axis directly by film viscosity. The increased splashing threshold at the upper and lower viscous limits becomes obvious, with the lowest splashing threshold occurring on a water pool. Parallels to this intermediate range where splashing is most likely have appeared in dry surface impacts (Vu et al., 2011), and have been mentioned in other studies of liquid film impacts (Vander Wal et al., 2006); future work will expand the range of fluids and impact conditions studied to elaborate upon this phenomena. Specifically, the use of FC-72 to categorize viscosity is not ideal, as it has a significantly different surface tension than the other fluids used in this study. Unfortunately,

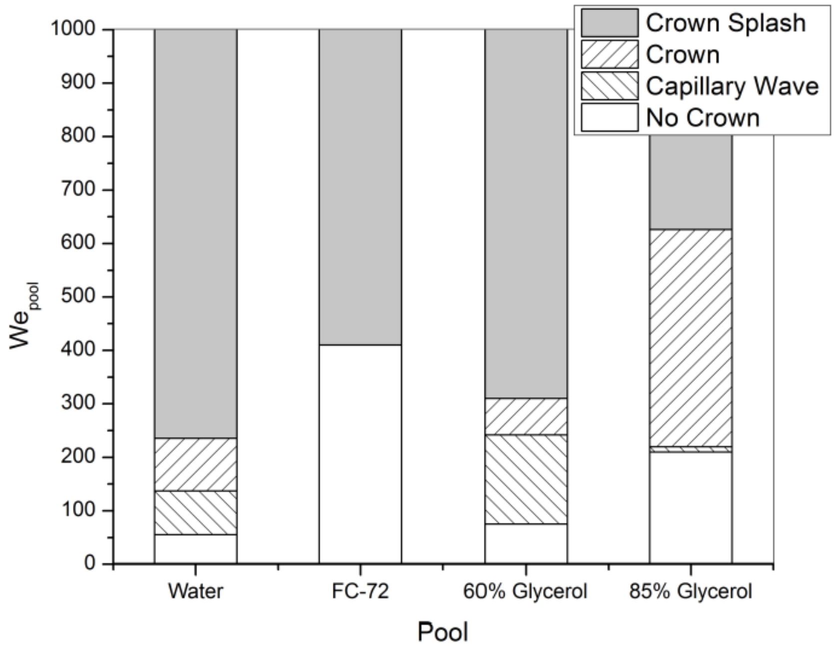

FIG. 6: Crown splashing behaviors of a water drop onto varying pools, organized by Oh_{pool}.

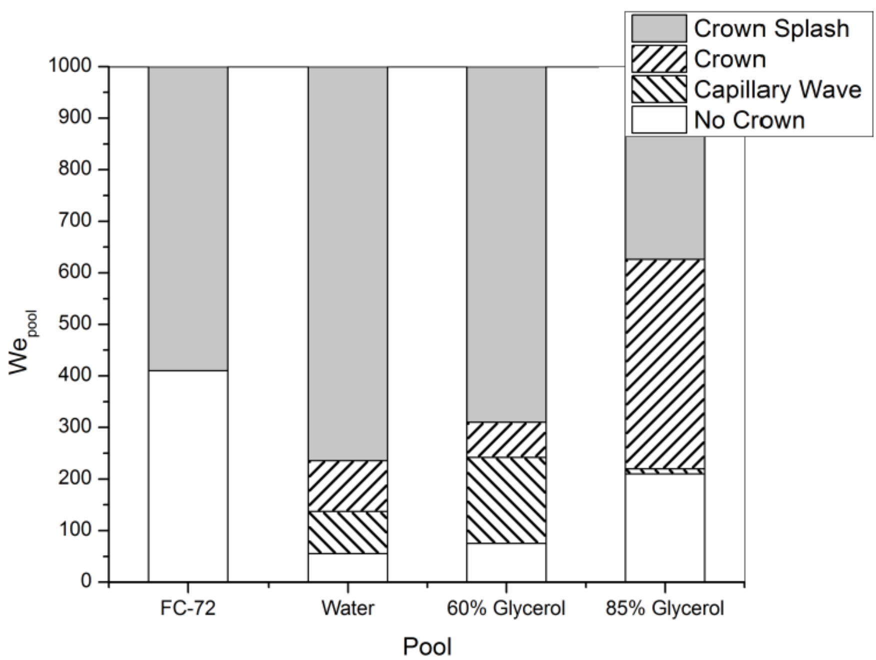

FIG. 7: Crown behavior observed when water drops impact varying pools, organized by pool viscosity.

water and glycerol mixtures have uncommonly high surface tension, and few other useful fluids have significant differences in viscosity while having the same range of surface tension. Also apparent is the narrow range of crown formation without splashing on the FC-72 film; if an impact forms a crown it is likely to cause that crown to splash as well. This is hypothesized to be related to the viscous splashing range and the lowered surface tension of FC-72. An impact that produces a crown on an FC-72 pool is likely to develop sufficient instability to break apart. A further possible explanation for FC-72's divergence from other fluids is one of miscibility: FC-72 does not mix with water or glycerol.

Drop viscosity does influence crown splashing, although it plays less of a role than the film properties. Increasing drop viscosity raises the splashing threshold. To further examine this trend, a solid sphere was used as "infinite-viscosity drop" analogue, and the corresponding splashing thresholds are found. A 4-mm diameter PVC sphere was dropped into a water film of the same depth. The film Weber number for crown splashing was found to be approximately 350; this number is slightly lower than the threshold found using an 85% glycerol drop. While the analogy may be imperfect, as the sphere does not deform at all whereas a liquid drop, even of extremely high viscosity, would deform over longer time scales (a fact which may change the impact outcome), it seems reasonable to believe that there is a limit to the effect of increasing drop viscosity, analogous to the "solid-surface" approximation observed for an FC-72 drop impinging on a highly viscous glycerol film. This limit is seen in Fig. 5, where each splashing threshold has a significant slope at lower $\mathrm{Oh}_{\mathrm{drop}}$ but levels off as $\mathrm{Oh}_{\mathrm{drop}}$ increases. The restrictive role of high viscosity in splashing has a maximum value: a counterpart to the intermediate viscous range where splashing is promoted.

The data gathered for crown splashing have been compared to the correlation by Cossali et al. (1997). That relation frequently underestimates the splashing thresholds we observed, since H^* in this study is outside the limit of accuracy for that relation. However, we note that with H^* being relatively large, the splashing threshold is increased from the Weber number range for splashing reported alongside that correlation (Cossali et al., 1997). Vander Wal et al. came to a similar conclusion, finding that in the neighborhood of $H^* = 1$, impact behavior undergoes a transition where the liquid film begins to restrict prompt and crown splashing (Vander Wal et al., 2006). Future work will address the effect of film depth on splashing. Further, by failing to make a distinction between drop and film viscosity, Cossali et al.'s and other correlations have a non-trivial weakness in addressing dissimilar film impacts.

3.2 New Correlation for Crown Behaviors

As existing correlations have been found to not adequately address crown behavior over the range of fluids used in this study, both by not adequately fitting the data and from the challenge presented by dissimilar fluids, it is necessary to develop a new correlation that can account for drop and film properties and fit the data of this study. From Fig. 4, it is evident that crown formation depends little on the drop properties ($\mathrm{Oh}_{\mathrm{drop}}$), but does depend on $\mathrm{We}_{\mathrm{film}}$. Figure 5 makes it clear that $\mathrm{Oh}_{\mathrm{drop}}$ does influence the splashing behavior of the crown.

The three dimensionless groups that seem to play a role in drop impact are the Weber, Reynolds, and Ohnesorge numbers. Further, each of these can be calculated based on the drop or film properties. Cossali's correlation is based on the Weber and Ohnesorge numbers, but does not distinguish the film or drop properties. Starting from the Weber number of the film and the Ohnesorge number of the drop, the data have been rescaled using combinations of the drop and film Weber, Reynolds, and Ohnesorge numbers until a criterion that unified the data was found. Using an exponential fit, the correlation can be written as

$$\frac{\mathrm{We}_{\mathrm{film}}}{\mathrm{Re}_{\mathrm{drop}}^{0.125}} \sim A \cdot \mathrm{Oh}_{\mathrm{drop}}^{B} \tag{2}$$

where A and B are the fitting constants. Using this grouping, with $\mathrm{Oh}_{\mathrm{drop}}$ on the x-axis and the $\mathrm{We}_{\mathrm{film}} - \mathrm{Re}_{\mathrm{drop}}$ grouping on the y-axis, the crown formation and crown splashing thresholds are plotted in Fig. 8 respectively.

In Fig. 8, the crown formation threshold is depicted, along with the curve fit in the form of Eq. (2). The constants for this fit are A = 152 and B = 0.0754, and the fit has an

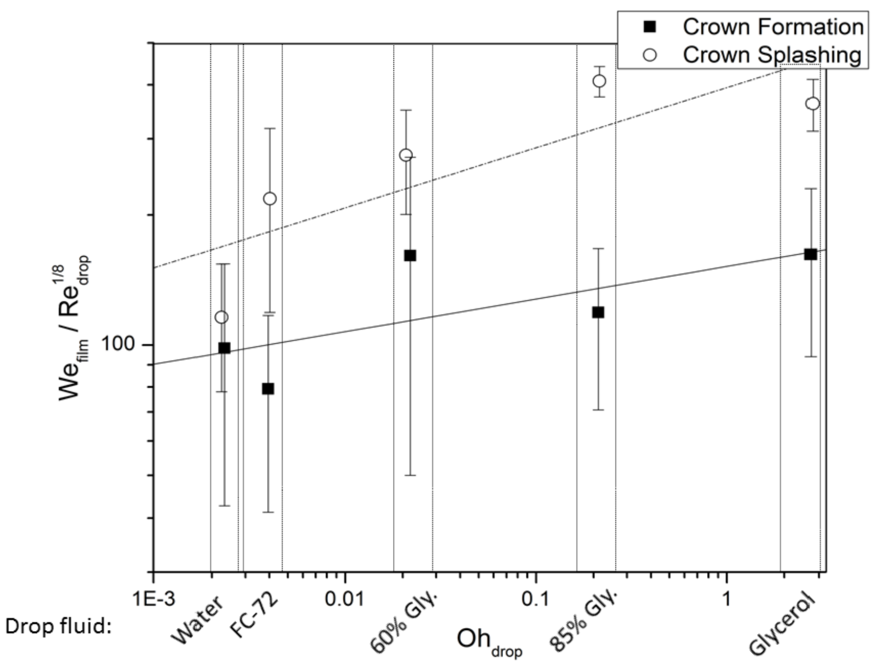

FIG. 8: Crown formation and splashing behavior in context of the proposed correlation. Error bars provide the spread of the transition regions.

R^2 value of 0.50. The crown splashing threshold and fit are also shown, with A = 394, B = 0.139, and an R^2 value of 0.68. The error bars at each point are used to depict the transition regions (the regimes where different behaviors overlap), i.e., the error bars for the splashing points are formed by the lowest observed (in terms of the $\mathrm{We}_{\mathrm{film}}/\mathrm{Re}_{\mathrm{drop}}^{1/8}$ grouping) splashing occurrence and the highest observed non-splashing occurrence. The data points presented in Fig. 8 are the arithmetic mean of the transition region.

This empirical correlation can be explained from the previous discussion on crown behaviors. The drop Reynolds number is taken to a relatively low exponent, reflecting the small but non-negligible effect of increasing drop viscosity observed in Fig. 5. The $\mathrm{We}_{\mathrm{film}}$ and $\mathrm{Oh}_{\mathrm{drop}}$ effects are from the original correlation (Cossali et al., 1997). In essence, the existing crown–splashing correlation has been adapted by including the drop properties. While this new correlation is not an extremely close fit to the data, the range of fluids it covers is unprecedented, and it predicts both crown formation and crown splashing with reasonable accuracy; existing correlations usually predict only splashing.

This correlation has been found using only $H^* = 1$ and for a range of drop and film Ohnesorge numbers $0.002 > \mathrm{Oh} > 3$. It does not account for mixing nor has it been tested over a range of surface tension.

3.3 Distinction between Film and Drop Properties

Figure 9 shows crown behavior based on $\mathrm{We}_{\mathrm{drop}}$ for a range of drop fluids impacting on a water film, in contrast to Fig. 5 where $\mathrm{We}_{\mathrm{film}}$ is used. Generally, the data are not significantly different from those observed in Fig. 5. For the water and glycerol mixture drops, the increase in drop Oh leads to increasing splashing thresholds. The exception is FC-72 drops, with its low viscosity and surface tension, which requires unusually high $\mathrm{We}_{\mathrm{drop}}$ to even produce a crown. Using the film We makes the outcomes for FC-72 impacts fit the trends established with other drops, as seen in Fig. 5. Similar aberrations appear when crown splashing on other films is presented using the drop-based Weber number.

As crown behavior is mostly decoupled from drop properties, a future thrust of this study would more thoroughly examine crown behavior when a solid sphere strikes a liquid film. Past studies have examined solid sphere impact, but addressed the interior cavity behavior (Marston et al., 2011) or crown behavior at velocities beyond the range of this study (Thoroddsen et al., 2004).

Data from FC-72 droplets often diverges from the trends observed for other droplets. Intuitively, FC-72 should splash more easily than the other liquids, given its lower viscosity (1/2 that of water) and lower surface tension (1/7 that of water). However, for crown splashing in an FC-72 film (Fig. 5) the splashing threshold is almost always higher than for other liquids. In dry surface drop impacts, viscosity has been observed to have two roles in splashing. First, viscosity induces velocity gradients within the spreading

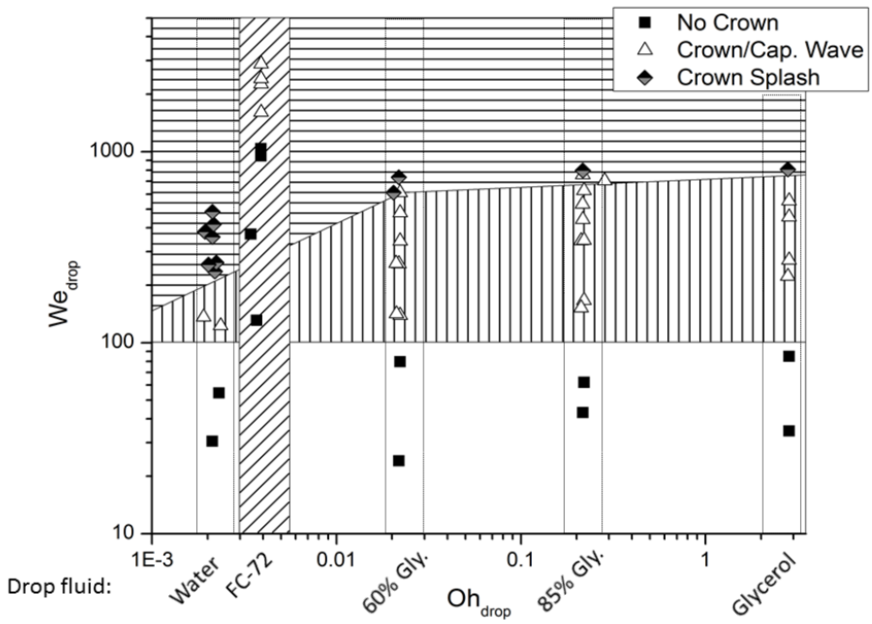

FIG. 9: Crown behavior with drop-based Weber number for each drop fluid onto a water pool.

lamella, facilitating the growth of instability. Very low viscosity minimizes velocity gradients, preventing instability development. Further, viscosity thickens the drop lamella so the drop rim has enough inertia to splash. A drop of lower viscosity has a thinner lamella, so there is less inertia to overcome surface tension (Vu et al., 2011). Similar explanations for the restricted crown splashing may be possible. The crown from an FC-72 film may be sufficiently thin that surface tension can hold it together.

4. CONCLUSIONS

Few studies in the past have disengaged the film properties from those of the impinging drop. The findings in this paper highlight that these distinctions have potential to transform how drop–film impact phenomena are studied.

Due to the vast range of conditions and complex phenomena associated with drop impingement splashing, it is unusual to find simple criteria such as the observed film-based Weber number = 1000 for crown splashing. While extremely high viscosity is a limit of this criterion, it does apply for over three orders of magnitude of film viscosity. Low viscosity drops can splash at lower We, but all drops examined splashed above the critical value. This study covered only a single film thickness, where the film is approximately the same as the drop diameter. Future work of crown splash criterion would require investigation of the effects of varying film thickness; we suspect it will at least shift the criterion We value. In addition, film viscosity is likely to influence the effect of film thickness, as well; a possible explanation for the lack of crown formation on a glycerol film.

Ongoing work includes exploring the effects of film depth, varying surface tension and miscibility, and refining the new correlation to account for those factors. Further, exploring the dual role of viscosity in all drop impacts, as both an inhibitor and promoter of splashing at different values, could illuminate the underlying physics that make drop impact such a complex phenomenon that has yet to be solved.

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REFERENCES

Cossali, G., Coghe, A., and Marengo, M., The impact of a single drop on a wetted solid surface, *Exp. Fluids*, vol. **22**, pp. 463–472, 1997.

Eslamian, M. and Ashgriz, N., Spray drying, spray pyrolysis and spray freeze drying, *Handbook of Atomization and Sprays*, Ashgriz, N. (ed.), New York: Springer, pp. 849–860, 2011.

Fedorchenko, A. I. and Wang, A.-B., On some common features of drop impact on liquid surfaces, *Phys. Fluids*, vol. **16**, no. 5, pp. 1349–1365, 2004.

Fink, J., Gault, D., and Greeley, R., The effect of viscosity on impact cratering and possible application to the icy satellites of Saturn and Jupiter, *J. Geophys. Res.*, vol. **89**, no. B1, pp. 417–423, 1984.

Kim, S. C. and Ryou, H. S., An experimental and numerical study on fire suppression using a water mist in an enclosure, *Buil. Env.*, vol. **38**, no. 11, pp. 1309–1316, 2003.

Marston, J. O., Vakarelski, I. U., and Thoroddsen, S. T., Bubble entrapment during sphere impact onto quiescent liquid surfaces, *J. Fluid Mech.*, vol. **680**, pp. 660–670, 2011.

Rein, M., Phenomena of liquid drop impact on solid and liquid surfaces, *Fluid Dyn. Res.*, vol. **12**, pp. 61–93, 1993.

Rein, M., The transitional regime between coalescing and splashing drops, *J. Fluid Mech.*, vol. **306**, no. 1, pp. 145–165, 1996.

Smith, H. J., *The Hydrodynamic and Physico-Chemical Basis of the Drop Picture Method*, Gottingen: Max Planck Institut für Strömungsforschung, Bericht Nr. 8, 1975.

Thoroddsen, S. T., Etoh, T. G., Takehara, K., and Takano, Y., Impact jetting by a solid sphere, *J. Fluid Mech.*, vol. **499**, pp. 139–148, 2004.

Vander Wal, R., Berger, G., and Mozes, S., Droplets splashing upon films of the same fluid of various depths, *Exp. Fluids*, vol. **40**, no. 1, pp. 33–52, 2006.

Vander Wal, R. L., Berger, G. M., and Mozes, S. D., The combined influence of a rough surface and thin fluid film upon the splashing threshold and splash dynamics of a droplet impacting onto them, *Exp. Fluids*, vol. **40**, no. 1, pp. 23–32, 2005.

Vu, H., Banks, D., and Aguilar, G., Examining viscosity and surface wettability in lamella lift dynamics and droplet splashing, *Atomization Sprays*, vol. **21**, no. 4, pp. 303–315, 2011.

Worthington, A. M. and Cole, R. S., Impact with a liquid surface, studied by the aid of instantaneous photography, *Philosoph. Trans. Royal Soc. London, Ser. A*, vol. **189**, pp. 37–148, 1897.

Yarin, A. L., Drop impact dynamics: Splashing, spreading, receding, bouncing ..., *Ann. Rev. Fluid Mech.*, vol. **38**, pp. 159–192, 2006.

Zhang, L. V., Toole, J., Fezzaa, K, and Deegan, R. D., Evolution of the ejecta sheet from the impact of a drop with a deep pool, *J. Fluid Mech.*, vol. **690**, pp. 5–15, 2011.