Effects of drop and film viscosity on drop impacts onto thin films

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Abstract

While drop-film impacts have been studied extensively in the past, little thought has been given to separating the effects of the drop fluid properties and those of the film. Notably in the field of pool fire suppression, sprays impact pools consisting of different fluids, and both the spray properties and the pool properties will govern the resulting behavior [1, 2]. Distinguishing between the film and droplet's effects will also provide insight into behaviors observed on more common same-liquid drop-film impacts.

In this study, the central parameter examined is the fluid viscosity. Using various mixtures of water and glycerol, as well as FC-72, a range of kinematic viscosity covering 3 orders of magnitude (3.8E-7 to 1.1E-4 m^2/s) is examined, while the surface tensions cover a smaller range, from 0.01 to 0.07 N·m. A microliter valve creates mm-scale drops that freefall into the target film at velocities of 0.5 to 3.5 m/s, where a high speed video camera records the impact. The final parameter considered in this study is the ratio of pool depth to droplet diameter, which is examined in three regimes: 0.5 (shallow film), 1.0, and 3.0 (deep pool). This configuration covers Weber numbers from 20 – 3000 and Reynolds from 20 – 14000.

The impact outcomes characterized are coalescence, crown formation, jetting, and splashing of the crown and the jet. These regimes have been defined by past work, and for the same film-droplet liquids they have been mapped to ranges of dimensionless numbers, primarily the Weber number. These dimensionless ranges are examined for differing liquid impacts. To correct for differing drop and film properties, alternative dimensionless criteria are suggested. These criteria are proposed in light of substrate effects in the shallow film regime as well as in the deep pool regime where bottom effects are lessened.

Crown formation and subsequent crown splashing are shown to be governed by the viscosity and surface tension of the film, with minimal dependence on drop fluid properties. With a dimensionless pool depth (H* = pool depth/drop diameter) of 1, for every fluid examined, the critical Weber number for crown formation is on the order of 100 when pool density and surface tension are used. Applying the drop density and surface tension gives no apparent correlation between common dimensionless groups and observed behavior. In contrast, when characterizing the appearance of a post-impact Worthington jet, the drop's properties play a much larger role, with a critical minimum Weber number utilizing drop surface tension and density between 50 and 200 resulting in the appearance of a jet. The impact outcomes in other pool depth regimes are explored, as well.

Introduction

Drop impacts have been studied since the 19th Century, and drop impacts on to films of a different liquid were among the first experiments in this line of research [3]. In more recent times, the thrust of drop-film impact research has concerned same-liquid situations, with little focus on differing fluids [1]. Fedorchenko and Wang examined in detail the effects of viscosity on film and pool impact outcomes [2], but did not separate the effects of pool and droplet viscosity. Vander Wal, et al, explicitly state that their study is of drop impacts onto same-fluid films [4]. During that study, the effect of film thickness is investigated. Not since 1975 have the properties of the pool and of the drop been examined separately [5]. Tremendous advances in imaging and correspondingly in the field of drop impact study means the topic is due to be re-examined.

Sprays are prevalent means of fire suppression, and when solid material is burning a spray excels at extinguishing the fire. Pool fires are less simple to quench. An incorrectly applied fire retardant can induce pool splashing, spreading liquid and potentially worsening the fire. One solution is to use very fine sprays which rapidly evaporate and displaces the ambient oxygen combustion requires [6]. Direct (large drop) quenching of burning pools can extinguish the fire quickly, a must in kitchen and engine room fires, but the impact outcomes of the spray must be controlled to prevent splashing and subsequent additional damage. Since the extinguishing spray and the burning pool will never be the same liquid, an understanding of how the drop and pool properties individually control impact outcomes is critical to this application of sprays. An additional application of sprays where the target film and spray fluids differ are spray freeze drying, especially in the biomedical field, where a feed spray impinges on a cryogen liquid and freezes virtually instantly into useful solid particles [7].

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Rein defined four immediate outcomes and two subsequent ones in his review paper: floating, bouncing, coalescence, and splashing all are immediate impact outcomes, with vortex rings happening sometimes after coalescence and jetting happening sometimes after splashing [1]. Floating and bouncing rarely occurred in this work's scope of study; these behaviors are typically associated with very low impact velocities [1]. Future work may address these phenomena as well. This work instead focuses on the coalescence versus splashing regime. Also, jetting behavior is disengaged from crown behavior in this study; Vander Wal, et al noted that jet formation can occur alongside both coalescence and crowning [4]. The modified regimes examined in this study are coalescence, crowning, and jetting, with splashing possible distinctly at impact (prompt), from the crown, and from the jet.

Fedorchenko and Wang's analysis of drop impacts on thin films went into significant detail concerning cavity formation and collapse and jet formation, as well as put forth 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 $Fr^{1/4}$ [2]. 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 [4]. It is worth noting that Vander Wal, et al experimented with a range of viscosity covering one order of magnitude [4], whereas this study covers three orders of magnitude in dynamic viscosity (Table 1). Both studies examine similar ranges of surface tension, however.

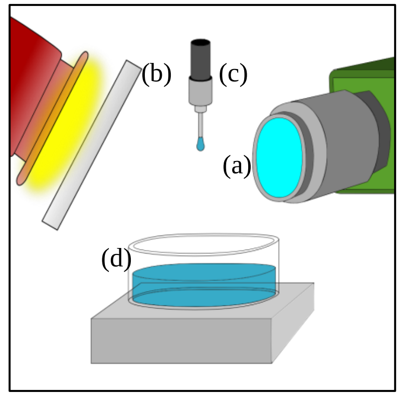

Figure 1. Experimental setup for measuring film impacts. (a) Phantom v7.1 video camera. (b) Backlight and diffuser. (c) Drop generator. (d) Acrylic walled-pool.

Experimental Methods

Figure 1 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 freefall 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 0.5 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. A Phantom V7.1 video camera records the impacts at 512 x 256 pixels resolution at 9000 fps through a Nikon Micro-Nikkor 105 mm f/2.8 lens. The Phantom Camera Control software is captures impact videos. Using the software to measure objects of known dimensions gives less than 1% error in length measurements by this method; velocity measurement is expected to have a larger error due to blurring.

Drop fluids used are water, 60% glycerol/40% water by weight mixture, 85% glycerol mixture, glycerol, and FC-72. Table 1 lists the relevant properties of each fluid. From the stainless nozzle, the water and glycerol mixtures have drop diameters of 3.3±0.2 mm. FC-72, due to a small surface tension, results in drop diameters of 1.7±0.1 mm. These fluids give a range of Weber number of 20-3,000 and Reynolds number from 20-14,000. Pool depth is the same as the drop diameter for each experiment, corresponding to the intermediate pool depth examined in [4]. Note, despite having much lower viscosity that water, FC-72 drops usually have a higher Ohnesorge number than water due to the smaller surface tension and related smaller average drop diameter.

Fluid	Density (g/cm^3)	Viscosity (cm^2/s)	Surface tension (dyne/cm)	Typical Ohnesorge value observed
FC-72	1.68	0.004	10.0	0.0035-0.0040
Water	1.00	0.01	72.8	0.0021-0.0023
60% Glycerol	1.15	0.09	66.9	0.0200-0.0220
85% Glycerol	1.22	0.89	65.1	0.2000-0.2100
100% Gylcerol	1.26	6.48	64.0	0.2700-0.2800

Table 1. Fluid properties.

Five impact behaviors are classified in this study. Coalescence, crown formation, crown splashing, jet formation, and jet splashing are observed, classified based on the observations from [1]. Coalescence is defined as the absence of a crown, capillary wave, or jet. We categorize crown formation to include the appearance of a capillary wave above the original surface level of the pool or a vertical crown thrown up from the cavity caused by the impact. Secondary droplets separating from the vertically-displaced crown is crown splashing. Jet formation describes a Worthington jet rising from the impact point, and jet splashing is when a secondary drop separates from that jet. Figure 2 depicts a representative photograph of each behavior.

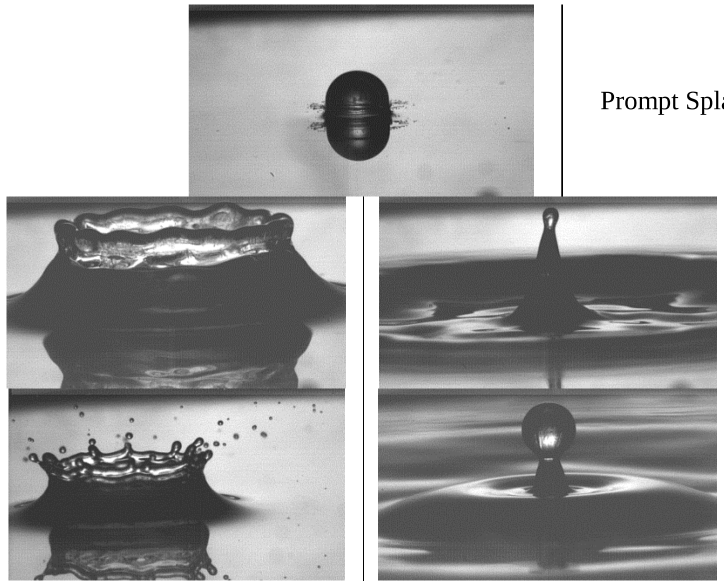

Figure 2. Characteristics of observed impact phenomena.

Results and Discussion

Results are divided into two categories: impact characteristics as scaled to the pool properties, and those scaled to the drop properties. The x-axis on all graphs is the Ohnesorge number (*Oh*) of the drop, as that is defined solely by the physical properties of each drop fluid. Using *Oh* allows easy recognition of each type of drop. The y-axis will vary based on the focus of the graph. When looking at crown behaviors, the Weber number based on the pool fluid is used, as past research [4] and the data agree that the Weber number is the clearest criterion for impact behaviors. Further, the range of Weber numbers across each pool fluid is relatively constant. For jet behaviors, the Weber number using the drop velocity and properties seems to best characterize the observed phenomena; the viscosity differences of the drop fluids already appear in the Ohnesorge number. Striped regions denoting the visually estimated regimes of different behaviors have been added to the graphs. When estimating the regions, it is assumed that increasing impact velocity from the initial appearance of splashing will continue to result in splashing, and decreasing velocity below the lowest observed velocity where a crown or jet appears will never lead to a crown or jet.

Selection of the axes of the graphs was by trial and error method. Potentially relevant dimensionless groups (Weber, Reynolds, Capillary, Ohnesorge; based on both pool and drop properties) were plotted against each other. The clearest behavior trends appeared on the We-Oh plots. It was We_{pool} that revealed the best arrangement of crown behavior, and We_{drop} that was best for jet behavior. In order from smallest to largest Ohnesorge number, and thus left to right data "columns" observed on the graphs, are water, FC-72, 60% glycerol mixture, 85% glycerol mixture, and glycerol (see Table 1). The use of pool properties in the characterization of 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 pool properties are virtually always used in the relevant dimensionless groups [8].

Crown Development and Splashing

Crown behaviors are studied relating to the pool fluid, in order of increasing viscosity of the pool fluid. First, an FC-72 pool is examined in Figure 3. The vertical line pattern indicates the region where capillary waves and non-splashing crowns are observed. A nearly-constant pool-based Weber value across a wide range of Ohnesorge numbers (0.0002-0.3) of approximately 500 marks the lower limit of this regime. The splashing threshold is the upper limit of this regime; as indicated by the horizontal line pattern, above a Weber number of 900 crown splashing always observed.

One step up in viscosity from FC-72 in the range of liquids examined is water. The crown behavior of water pool impacts is observed in Figure 4. Similar trends appear in the crown appearance and splashing thresholds, although the splashing threshold becomes more complex. The minimum Weber value for crown appearance appears to be 100- lower than the value for FC-72, suggesting (as intuitively expected) that pool viscosity plays a role in crown appearance. The constant Weber crown threshold across a range of droplet Ohnesorge numbers suggests that the crown is largely independent of droplet properties. The splashing threshold takes on a curved shape in this case, increasing as the droplet Ohnesorge number grows. This suggests higher droplet viscosity inhibits crown splashing. However, the value of the crown formation Weber number is an order of magnitude lower than that seen for the FC-72 pool, which means, against intuition, that the higher viscosity and higher surface tension pool produces a crown more easily than a the lower viscosity and surface tension liquid. This parallels the observations of Vu, et al, who noted for dry surface drop impacts that for extremely low viscosity droplets, splashing is inhibited [9]. The other interesting comparison with the FC-72 pool is the splashing criteria. For FC-72, the splashing criterion appears to be an approximately constant Weber number of 900. For the water pool, the same threshold is increasing towards that same value.

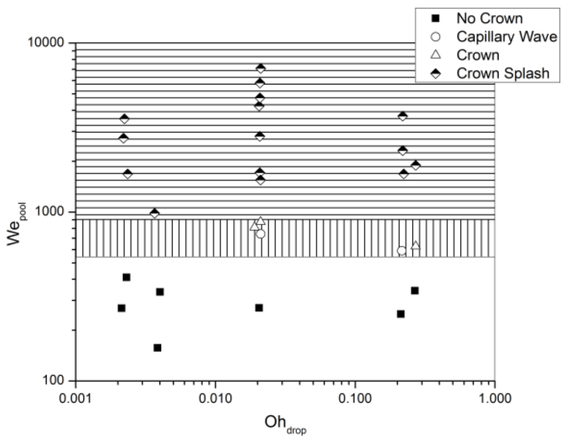

Figure 3. Crown behaviors observed on an FC-72 pool

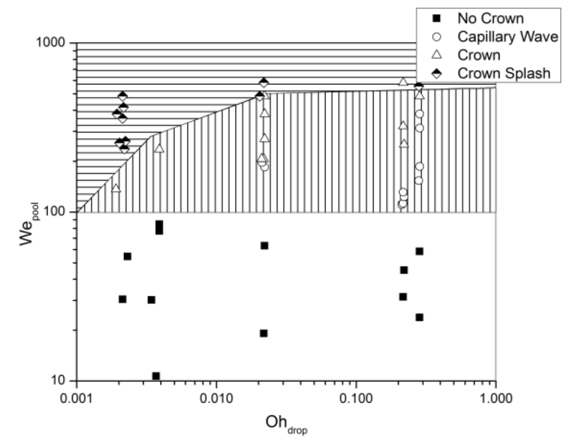

Figure 4. Crown behaviors observed on a water pool

60% aqueous glycerol has the next highest viscosity of the fluids in this study. Figure 5 shows the results of drop impacts onto a 60% glycerol pool. A single Weber number again marks the transition from no crown (coalescence) to crown appearance, and the value of approximately 110 is very close to the transition value seen for a water pool. The splashing threshold follows a similar pattern to the water pool, although it appears shifted upwards by approximately 25%- suggesting higher viscosity pools have inhibited splashing behavior. Now, the increase in pool viscosity appears to restrict crown formation and splashing, contrary to the FC-72 to water pool comparison. Again, however, the threshold for splashing seems to be increasing towards the constant value observed in the FC-72 pool, regardless of the viscosity changes of either the pool or the drop.

The last crown behavior graph is that of an 85% glycerol, 15% water pool (Figure 6). Similar trends occur; the lower limit for crown formation is less clearly defined but is in the range $100 < We < 200$. Again, at lower drop Ohnesorge numbers, the splashing limit is lessened to near the crown formation limit ($We \approx 150$), and as Oh increases, the splashing limit approaches $We \approx 900$.

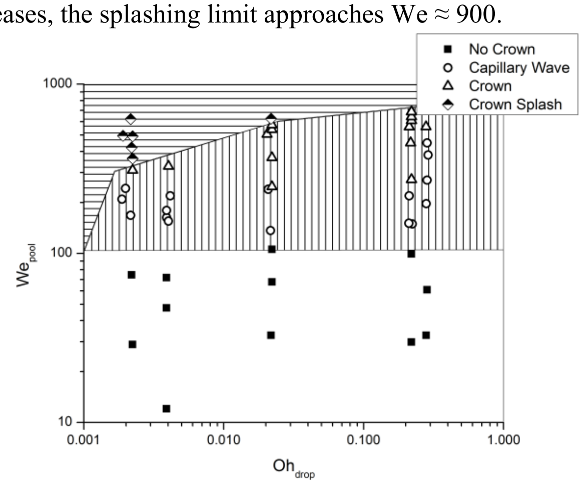

Figure 5. Crown behaviors of a 60% glycerol pool

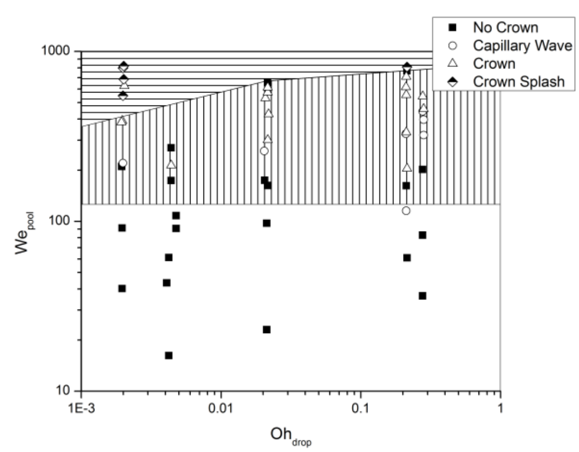

Figure 6. Crown behaviors of an 85% glycerol pool.

For the range of pool viscosity between that of FC-72 and 85% glycerol, crown splashing always occurs if the pool Weber number is above 900. As the Ohnesorge number (and thus, primarily, the viscosity) of the impacting drop decreases, crown splashing is observed at lower Weber numbers on water and 60% glycerol pools. The 900 Weber number criterion, regardless of pool fluid, suggests that at that point, the kinetic energy of the impact forces the pool fluid alone to splash. The decrease in this limit as drop viscosity decreases means the drop deformation plays a role in splashing- possibly, some drop fluid is ejected from the crown, with the pool fluid acting as a relatively solid "ramp". As the pool grows increasingly viscous, crown formation itself is inhibited, and therefore crown splashing is prevented. Impacts onto pure glycerol pools (kinematic viscosity approximately 10 times that of 85% glycerol) resulted in no crown formation within the range of Weber and Ohnesorge used in this study, with a single exception. An FC-72 droplet, $We_{pool} = 97$ and $Oh_{drop} = 0.0038$, appeared to crown and splash when it impinged upon the pure glycerol pool. We suspect that with such a difference in viscosity, over three orders of magnitude, the glycerol film approximated a solid surface to that droplet.

To better illustrate this splash-optimizing viscous intermediate range, Figure 7 shows the splashing behaviors of water drops impinging upon different pools. The increased splashing threshold (splashing designated by the cross-hatched region) at the upper and lower viscous limits is obvious. Also apparent is the restriction of simple crown formation on the FC-72 pool; if an impact forms a crown it is likely to cause that crown to splash as well. The other types of drops follow similar trends: the splashing threshold is lowest on the water pool, and it increases as viscosity grows *as well as* lessens. Crown formation without splashing occurs in a very narrow range of impact conditions on FC-72 pools, evidenced by Figure 3. Parallels to this optimally viscous splashing range have appeared in dry surface impacts, as well; 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 studied. Unfortunately, water and glycerol mixtures have unusually high surface tension, and few other useful fluids have significant differences in viscosity while having the same range of surface tension.

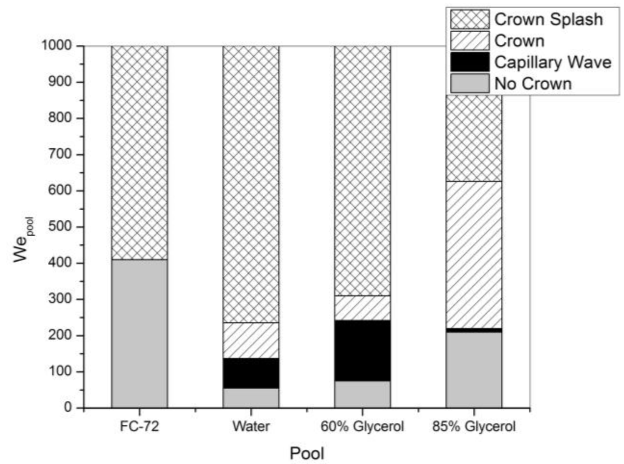

Figure 7. Crown behavior observed when water drops impact varying pools.

Jet Development and Splashing

Jet behavior is distinctly separated from the crown behavior- a crown can often occur in drop impacts with no subsequent jet, although a jet usually does not occur without a crown. Our results suggest that the appearance and splashing criteria for the post-impact jet depend largely on the properties of the drop fluid, far more than they depend on the pool fluid, so the dimensionless groups used to characterize jet behavior use the physical properties of the drop. Again, the impact regimes are organized by the pool fluid, in order of increasing viscosity. Figure 8 shows the observations of jet behavior when drops strike an FC-72 pool. Jetting occurs in all but one case- it takes a very slow impact of an FC-72 drop to prevent jetting from happening. Jet splashing occurs for most drops above a Weber number of 300; for a highly viscous glycerol drop, jet splashing occurs for every tested impact.

Figure 8 shows the jet behaviors observed from a water pool. A criterion for the jet appearance appears to be near a drop Weber number of 40, regardless of the drop viscosity. Jet splashing is less simple to characterize across the full range of drop fluids examined. For all but the most viscous drops (FC-72, water, 60% glycerol, and 85% glycerol), up to an Ohnesorge number of approximately 0.2, jet splashing consistently appears above Weber = 300, with some splashing occurring down to Weber = 150. At the upper limits of the viscosity range examined, jets resulting from glycerol drops do not splash for any value of Weber number observed in this study. This disagrees with the findings seen in Figure 8, where the viscous glycerol drops induced jet splashing at Weber numbers lower than any other droplet could.

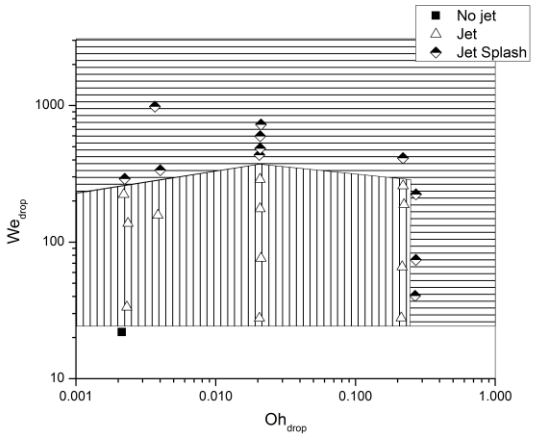

Figure 8. Jet behaviors of an FC-72 pool.

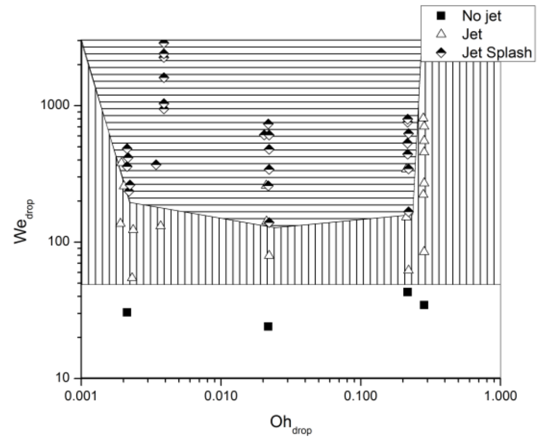

Figure 9. Jet behaviors of a water pool.

Jet behaviors observed from a 60% glycerol pool are seen in Figure 10. The jet appearance threshold appears to generally increase with increasing drop Ohnesorge, meaning a more viscous drop requires more energy to produce a jet. This suggests drop deformation after impact plays a role in governing jet formation. With less viscous drops, jets occur above the same We = 40 threshold as with the water pool. Splashing is less trivial to define than before- for 60% glycerol drops, splashing occurs as low as We = 100, while for water the minimum appears to be 200 and for FC-72 and 85% glycerol the threshold is bumped up to 500. Again, the pure glycerol drop does not splash within the range of Weber number studied. It appears that for an intermediate range of viscosity, jet splashing is most likely to occur. Moving out of that range to either more viscous drops (glycerol) or less viscous drops (FC-72) inhibits splashing. This parallels our findings about crown splashing- very low viscosity pools restrict crown splashing to higher Weber numbers, and very high viscosity pools do the same.

An 85% glycerol pool starts to noticeably inhibit jet formation and splashing (Figure 11). The minimum threshold for jet formation for any type of drop is Weber number of over 100, with splashing only occurring rarely even as Weber increases to 1,000. High viscosity inhibition of jetting is intuitive- jetting requires enough kinetic energy for the drop to create a cavity on impact and subsequently rebound; as the pool gets increasingly viscous the kinetic energy of the drop goes more towards fighting the resistance of the pool. A pure glycerol pool resulted in no jetting at any impact condition studied; due to height restrictions of the drop freefall setup, we could not produce a high enough Weber number drop to cause a jet. This strong inhibition of jet formation parallels crown formation restriction on highly viscous pools- it seems that at around the viscosity of pure glycerol, the impact energy of a droplet must be greatly increased to have any effect on the pool.

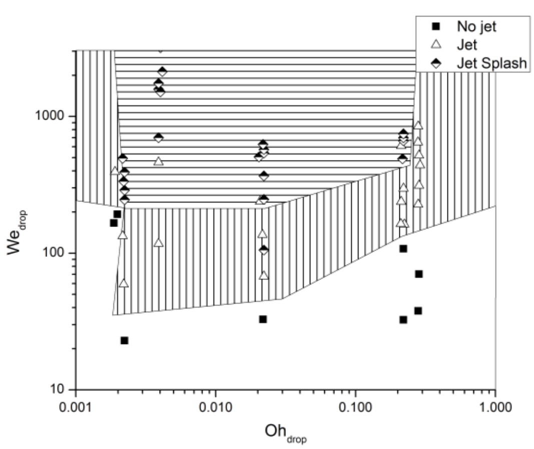

Figure 10. Jet behaviors of a 60% glycerol pool

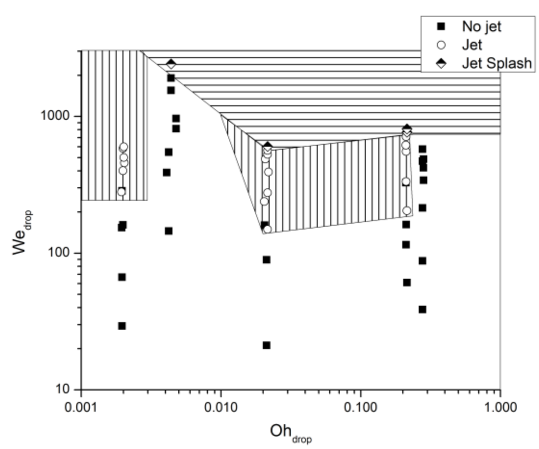

Figure 11. Jet behaviors of an 85% glycerol pool.

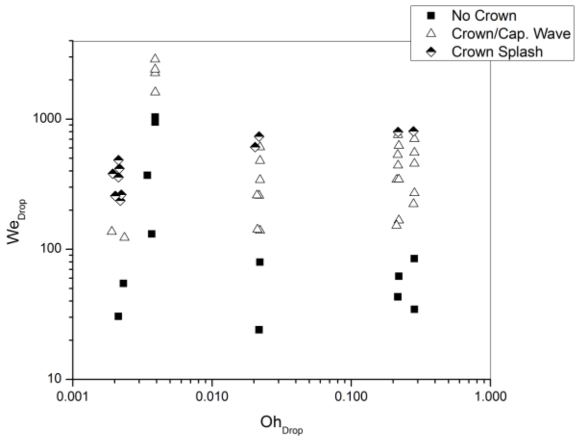

Figure 12. Crown behavior with drop *We*. Water pool.

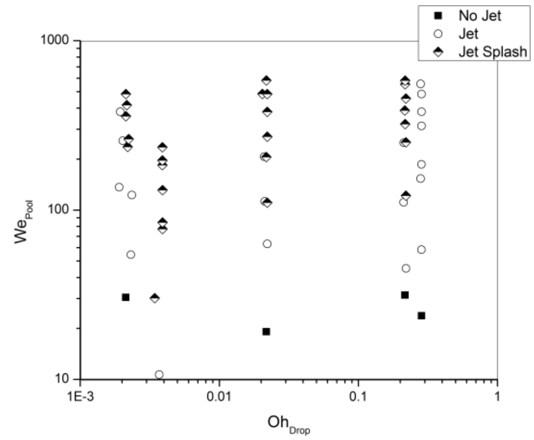

Figure 13. Jet behavior based on pool *We*. Water pool.

Figure 12 shows crown behavior based on drop *We* on a water pool. Similar trends generally appear as when the pool *We* is used, except for the second grouping of data from the left. That data is FC-72, with its low viscosity and surface tension, which requires unusually high drop *We* to even produce a crown. Using the pool *We* makes the outcomes for FC-72 impacts fit the trends established with other drops, as seen in Figure 4. Jet behavior plotted with the Weber number of the pool is seen in Figure 13, where it is observed that FC-72 droplets result in jets and jet splashing at far lower pool Weber numbers than other drops. Figure 9 shows a more organized pattern, where outside ranges of drop Ohnesorge have restricted splashing, instead of the discontinuous jump seen in Figure 13.

Crown behavior seems to fit into simpler conditions than jet behavior. Whereas crown formation begins immediately after impact, precluding significant mixing and often drop viscous effects, jet formation is delayed, leading to more complex interplay between pool and drop. It primarily seems to be droplet properties governing the jet, but the pool does make a difference- Figure 8 shows that an FC-72 pool shows different splashing characteristics than any other pool, especially with very high and very low viscosity droplets.

One other factor that will affect jetting is the pool thickness. While this factor is unexplored in this study, other studies have found that impact behaviors can be significantly influenced by film thickness- with thinner films, the solid substrate below the liquid interferes. It seems reasonable to expect that an impact onto a less-viscous film will lead to more substrate influence than a highly viscous pool. The interplay between pool viscosity, thickness, and the substrate could account for FC-72's divergent behavior from other liquids. Future work will address this.

As crown behavior is mostly decoupled from drop properties, a future thrust of this study would examine crown behavior when a solid sphere strikes a liquid film. Past studies have examined solid sphere impact, but address the interior cavity behavior [10] or crown behavior at velocities beyond the range of this study [8]. In shallow film solid sphere impacts, jetting behavior is inhibited, as the sphere prevents the cavity collapse from throwing up a jet.

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 both crown splashing in an FC-72 pool (Figure 3) and jet splashing with an FC-72 drop, 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 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 [9]. Similar explanations for the restricted jet and crown splashing may be possible. The crown from an FC-72 pool may be sufficiently thin that surface tension can hold it together. Upon impact, an FC-72 drop deforms more easily than other drops, leading to a narrower jet that needs higher velocity to break apart.

Conclusions

Few studies in the past have disengaged the pool properties from those of the impinging drop; similarly, crown behavior has rarely been separated from jet behavior. 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 such simple criteria as the observed pool-based Weber = 900 for crown splashing. While extremely high viscosity is a limit of this criterion, it does apply for over three orders of magnitude of pool viscosity. Low viscosity drops tend splash at lower *We*, but all examined splashed above the critical value. This study only covered a single film thickness- where the film is approximately the same as the drop diameter. Future investigation 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 pool.

While jet behavior is less easily characterized by simple dimensionless groups than crown phenomena, examining it has illuminated an interesting dual viscous effect on impingement behavior: restriction of splashing at both low and high viscosity, with a “splashing-optimal” intermediate range of viscosity seemingly centered near that of water. This split range splashing inhibition has been noticed in dry surface drop impingements and in like-fluid impingements, as well. Research clarifying more precisely the role of viscosity in drop impingement splashing, especially in relation to instability development and crown/lamella flows is ongoing.

Acknowlegements

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Nomenclature

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

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