Experiments in Fluids (2006) 40: 23–32
DOI 10.1007/s00348-005-0043-3

ORIGINAL PAPER

Randy L. Vander Wal · Gordon M. Berger
Steven D. Mozes

The combined influence of a rough surface and thin fluid film upon the splashing threshold and splash dynamics of a droplet impacting onto them

Received: 25 February 2004 / Revised: 8 July 2005 / Accepted: 22 August 2005 / Published online: 11 October 2005

Abstract Surface roughness can have a critical effect upon the splashing threshold and dynamics of a drop impacting on either a dry or rough solid surface or one coated by a thin fluid film. As most coating applications and spray systems quickly evolve to a state where the droplets impinge upon fluid deposited by preceding droplets, the combined contributions of surface roughness and a pre-deposited thin liquid film of comparable thickness upon droplet impingement dynamics are examined. For comparison, we include results for droplets impacting on a smooth, dry surface and a smooth surface wetted by a thin fluid film. The inclusion of surface roughness considerably lowers the splashing threshold and alters the splashing dynamics such that differences in fluid surface tensions between 20.1 and 72.8 dynes/cm or viscosities between 0.4 and 3.3 cP have little effect.

1 Introduction

Splashing behavior is of considerable importance in a variety of applications ranging from spray coating to cooling. The splash/non-splash boundary is considerably influenced by the presence of a thin film and surface roughness. Surface roughness comes into play as many commercial products that are spray painted have an inherently non-smooth surface. Moreover, many consumer products are textured for practical or cosmetic appearance. Thin fluid films upon surfaces arise quite naturally as preceding droplets cover the dry surface during coating application (Yarin and Weiss 1995; Bohm et al. 2000; Sivakumar and Tropea 2002). Thus, these two factors are often found together.

Surprisingly, there are only a limited number of studies examining the effect of either feature upon the splash threshold and dynamics. For conciseness, we review only those studies conducted at ambient temperature as our experiments were. Early studies of droplets impacting upon dry surfaces include those of Engel (1955) and Levin and Hobbs (1971) who observed a strong correlation between increasing surface roughness and the tendency of droplets to splash and form a crown except for on very smooth surfaces. Stow and Hadfield (1981) examined the effect of a rough dry surface upon splashing using water as the fluid. They sorted their observations in terms of a splash/non-splash characterization using a power-law relation. Significantly, this relation was not universal, as different numerical constants were required for each particular surface roughness. Moreover, their studies were confined to water onto aluminum surfaces. Wu (1992) later sought to simplify the power-law relation of Stow and Hadfield for systems with small Ohnesorge numbers where the viscous effects could be neglected. Yet the two fitting parameters of the equation were based only on the data of Stow and Hadfield; their universality for other fluids and surfaces was untested. Mundo et al. (1995) noted that the effect of surface roughness was to alter the splashed droplet trajectories. For droplet impact upon spherical surfaces, Hardalupas et al. (1999) experimentally observed that surface roughness influenced both the crown formation process and its subsequent breakup. Crooks and Boger (2000) found that the splashing threshold for polymeric solutions could be accounted for by incorporating the non-dimensional surface roughness into Stow and Hadfield's formula. Using a three dimensional numerical code, Bussman et al. (2000) found that the effect of surface roughness was to initially decrease the number of fingers at early times, suggesting that the magnitude of the surface roughness is related to the strength of the perturbation of the advancing fluid.

R. L. Vander Wal (✉) · G. M. Berger · S. D. Mozes
NASA-Glenn, M.S. 110-3, 21000 Brookpark Rd,
Cleveland, OH 44135, USA
E-mail: randy@rvander.grc.nasa.gov
Tel.: +1-216-4339065
Fax: +1-216-4333793

The most thorough study to date, conducted by Range and Feuillebois (1998) ,examined the perturbations arising from drops impacting onto a variety of dry surface materials with different patternation. Their goal was to survey the number of perturbations on the rim of an outward spreading film for different rough surfaces and liquids in an effort to discern their origin. Using a series of glycerin–water mixtures for a particular surface roughness, the Weber number, which is independent of viscosity, was found to be critical for the onset of splashing. For some cases they found correlations between the critical Weber number at which splashing occurred and the non-dimensional surface roughness, using Wu's (1992) formula, but with different fitting parameters for each fluid.

A few of these studies have measured the surface roughness. Yarin and Weiss (1995) defined surface roughnesses of 1 and 16 μm, while Wang and Chen (2000) stated a measured value of 0.26 μm. Rioboo et al. (2003) assumed molecular scale roughness for the silicon wafer. In each of these studies, there is, however, a matter of scaling of roughness to drop size. Cossali et al. (1997) later recognized this and summarized the literature data of splashing upon rough surfaces by representing the splashing boundary as a power-law relation with the numerical constant defining the splash/non-splash boundary as a function of the non-dimensional surface roughness, for dry surfaces only. Notably, their own studies and splash deposition limit for droplets impacting upon fluid films were only developed for the case where the non-dimensional surface roughness was small relative to the non-dimensional fluid thickness and therefore negligible.

Among the studies of drop impact upon fluids, most of this literature deals with thick pools and the resulting bubble entrainment and/or subsequent jetting (Oguz and Prosperetti 1990; Pumphrey and Elmore 1990; Rein 1996). While a few studies have investigated thin fluid films, none of these appear to have characterized the surface finish (Yarin and Weiss 1995; Coghe et al. 1999; Wang and Chen 2000; Sivakumar and Tropea 2002; Rioboo et al. 2003), with the one recent exception (Cossali et al. 1997). Therein, it is generally assumed that the surface roughness is small relative to the film depth. To date, there appears to be no work studying the combined influence of surface roughness and a thin film, despite its common practical occurrence. Therein, the purpose of this study was to examine splashing thresholds and characteristics upon a wetted, rough surface as input for numerical modeling.

To decipher the combined influence of surface roughness and the thin film upon splashing dynamics, reference data was collected for a drop impinging upon both the dry rough surface and a thin film upon a mirror-finished aluminum surface for which the underlying surface finish would have negligible effect. The comparison of drop impingement dynamics in these systems with those observed for the combined systems of a thin film upon a rough surface permits resolution of their individual contributions.

A second purpose of the present study relates to the fact that of the few studies of droplet impacts upon dry rough surfaces, only two have examined the influence of fluid properties combined with surface finish upon the splashing dynamics. Stow and Hadfield (1981) examined roughness amplitude upon splash, for water. Range and Feuillebois (1998) presented data for water and ethanol impacting upon a variety of roughened surfaces. As expected, the critical Weber number for splashing decreased with an increase in surface roughness. Rioboo et al. (2001) examined combinations of roughness, fluid properties and impact conditions on dry surfaces upon various types of splashing. Though Hardalupas et al. (1999) noted that the effect of surface roughness was to introduce perturbations in the evolving crown, their splashing boundary for a wide range of fluid viscosities corresponding to a series of water–glycerol mixtures was for small spherical surfaces with negligible roughness. Thus, there is no test of the generality of the numerical relations defining the splashing boundary or splashing dynamics for drops of fluids with very different values of surface tension or viscosity impacting rough dry surfaces compared with those same surfaces covered by thin fluid films. Therein, our studies were performed using a variety of fluids to form a comparative basis for discerning the effects of viscosity and surface tension upon the splashing onset and ensuing dynamics. To best provide input for guiding and critical testing of theoretical models, we captured image sequences of the drop impact events.

As may be expected, effects vary with the scale of surface roughness and fluid film thickness. Where film thickness > > surface roughness, or surface roughness > > film thickness, the governing factor would be the larger geometric parameter with little-to-no contribution from the smaller factor. Maximum co-influence (and possible synergy) would be expected where each is comparable in geometric scale. Physically, this corresponds to the "film" filling in the hills and valleys characterizing the surface roughness. As many surfaces may be characterized by a roughness that is smaller than the drop diameter we considered the case where both RMS surface roughness and film thickness are small relative to the initial drop diameter, yet comparable to each other.

2 Experimental

The rough surface used here was a cross-cut, carbide–steel file. The diamond shaped surface islands were measured with a perthometer to have a surface roughness, *Ra*, of 200 μm. To separate the effects of the thin film from the surface roughness, experiments were also performed with drops impacting upon the same dry file, a dry diamond-lathed aluminum disk and a thin film upon this smooth surface. The mirror-finished Al surface was characterized with an RMS roughness of 2 nm as measured by a profilometer. Thin fluid films were formed upon the Al surface to a depth of approximately 200 μm. The film depth on the steel file (above the ridges) was maintained at approximately 100 ± 20 μm. Both materials were wetted by water, given their high surface energy. Therein, differences in underlying surface material may be neglected.

Drops were generated using a hand-held syringe to deliver 4.0 μl or 2.0 ± 0.06 mm in diameter to a needle attached to the end of an extended spring. This size was chosen to negate droplet oscillation that would cause uneven impact. Release of the latch holding the spring caused rapid retraction of the needle from the droplet, which then fell under the action of gravity onto the file, film or smooth surface. The fluids in this study and their relevant physical characteristics may be found in Table 1.

A Kodak EktaPro HG 2000 high-speed camera was then manually triggered and recorded the droplet impact at 2,000 frames/s for half of the imaging field. The exposure time was set at 28 μs while using a 105 mm Nikkor lens set at an aperture of 32 to minimize motion blurring and to provide a large depth of field. A halogen lamp illuminated the impact site through a single sheet of Roscoe 111 diffusion film to provide uniform high-intensity back-lighting.

Droplet velocities were increased or decreased by moving the release mechanism vertically and taking advantage of gravitational acceleration. All velocities were measured using XCAP 2.0, an image acquisition and analysis program from EPIX. Measured velocities have an error of ±0.15 m/s based on the pixel size and 0.5 ms image spacing. Table 2 summarizes the non-dimensional impact numbers; namely Reynolds, Weber and Ohnesorge.

3 Results and discussion

3.1 Dry and smooth surface

As illustrated in Fig. 1 and summarized in Table 3, drops of heptane, water and a 30% glycerol/water mixture merely spread and formed an outer, upraised rim upon the mirror-finished Al surface. Similar results have been repeatedly observed elsewhere (Chandra and Avedesian 1991; Pasandideh et al. 1996; Scheller and Bousfield 1995; Mao et al. 1997; Rioboo et al. 2001). Only ethanol, glycerol–water and hexadecane exhibited prompt splashing (though at different Weber numbers), a phenomenon attributed to a kinematic discontinuity between portions of the advancing wave front and ensuing instabilities as discussed previously (Allen 1975; Yarin and Weiss 1995; Thoroddsen and Sakakibara 1998; Rieber and Frohn 1999; Bussman et al. 2000; Kim et al. 2000; Trujillo and Lee 2001; Roisman and Tropea 2002; Rozhkov et al. 2002; Josserand and Zaleski 2003).

Table 1 Key physical properties of the fluids used

Fluid	Viscosity (centipoise)	Surface tension (dynes/cm)	Density (g/cm^3)
Heptane	0.409	20.1	0.684
Hexadecane	3.34	27.1	0.773
DI water	0.978	72.8	1.00
30% Glycerol/water	2.64	71.7	1.08
Ethanol	1.20	23.1	0.789

3.2 Dry and rough surface

In contrast to the impact upon a mirrored surface, a rough surface resulted in splashing at all impact velocities greater than 2.17 m/s, as summarized in Table 4. As Fig. 2 shows for all five fluids, there was neither recognizable spread nor rim formation. Instead, thin filaments were formed with axial distribution about the impact center and with generally more of them at higher velocities. For heptane and the glycerol–water mixture, with either low surface tension and viscosity or high surface tension and viscosity, respectively, minimal differences are observed. The slight variation in droplet size or number becomes indistinguishable. The thin liquid filaments of the splash are steeply curved upward from the drop surface. Their origin is not at the droplet impact center, but at a radial position somewhat larger than that of the initial drop. This indicates that the origin of the fluid is from the expanding liquid sheet and formed during droplet impact. The upward curvature may be attributed to a similar kinematic gradient that arises when a droplet impacts upon a thin liquid film (Yarin and Weiss 1995; Trujillo and Lee 2001; Roisman and Tropea 2002). In that instance, as modeled, a crown is formed consisting of a thin liquid sheet due to the kinematic discontinuity between the stationary film fluid and that of the advancing fluid front. In contrast, the rough dry surface leads only to widely separated, disconnected filaments.

Table 2 Non-dimensional numbers of corresponding fluids and velocities

	Heptane	Hexadecane	DI water	30% Glycerol/water	Ethanol
2.17 m/s					
We	314.80	264.51	127.13	139.11	316.91
Re	7,136.80	988.21	4,365.83	1,743.02	3,811.23
3.15 m/s					
We	665.30	559.01	268.67	294.00	669.76
Re	10,375.16	1,436.63	6,346.85	2,533.92	5,540.60
4.22 m/s					
We	1,195.38	1,004.39	482.73	528.24	1,203.39
Re	13,907.13	1,925.68	8,507.48	3,396.54	7,426.76
Oh	1.83×10^{-3}	1.21×10^{-2}	1.90×10^{-3}	4.99×10^{-3}	4.67×10^{-3}

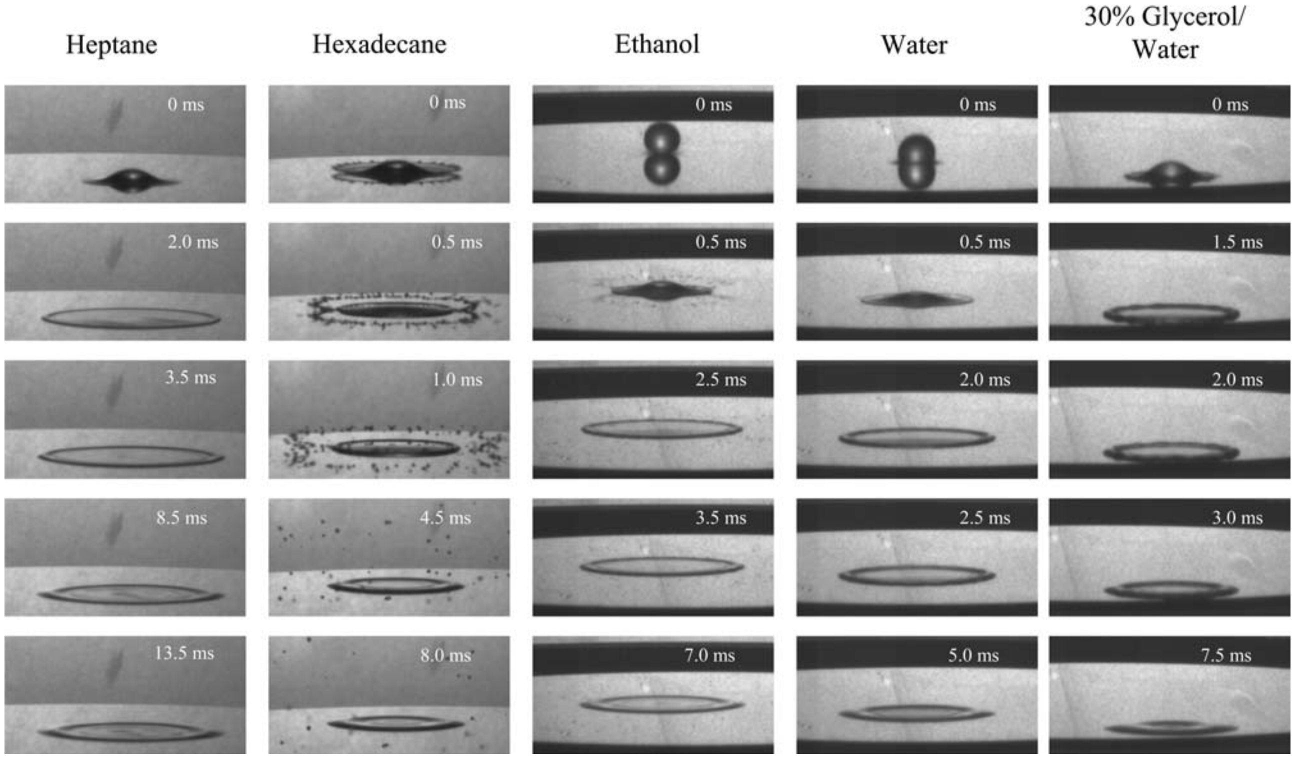

Fig. 1 A 2 mm droplet of the listed fluid dropped at 3.15 m/s onto a dry and smooth aluminum surface

It appears that the surface features disrupt the contact line of the advancing fluid. Local sections of the advancing fluid front move across alternating air pockets and solid surface features. The very different spread rates of adjacent fluid elements upon these two "materials" rapidly causes instability in the advancing fluid front and results in breakup. Differences in the fluid contact angle with air versus the solid surface further amplifies breakup of the advancing front. The result is shown by the formation of filaments, with high upward curvature. These filaments undergo breakup by capillary wave instability during their advancing elongation.

Observation of similar dynamics for each of the fluids studied here indicates that the surface roughness is their governing factor. The specific surface roughness and geometric patternation are likely to account for the

Table 3 Summary of the splash/non-splash behavior of a 2 mm droplet of the fluid onto a dry and smooth surface

Fluids	2.17 m/s	3.15 m/s	4.22 m/s
Impact event on a dry and smooth surface			
Heptane	No splash, widest spread, obvious non-wavy rim	No splash, widest spread, thin non-wavy rim	No splash, widest spread, thin non-wavy rim
Hexadecane	Prompt splash, less wide spread, thickest and wavy rim	Prompt splash, less wide spread, thin and non-wavy rim	Prompt splash, less wide spread, thin and non-wavy rim
DI water	No splash, least wide spread, thickest and least wavy rim	No splash, wider spread, obvious and non-wavy rim	No splash, widest spread, obvious and most wavy rim
30% Glycerol/water	No splash, least wide spread, thickest and non-wavy spread	No splash, less wide spread, obvious and wavy rim	Prompt splash, wider spread, thickest and wavy rim
Ethanol	Prompt splash, wider spread, obvious and least wavy rim	Prompt splash, wider spread, thin and non-wavy rim	prompt splash, widest spread, thin and least wavy rim

Provided descriptions are comparative summaries only; they are not complete

Table 4 Summary of the splash/non-splash behavior of a 2 mm droplet of the fluid onto a dry and rough surface

Fluids	2.17 m/s	3.15 m/s	4.22 m/s
Impact event on a dry and rough surface			
Heptane	Prompt and delayed splash, few fingers that are short and thin	Prompt and delayed splash, several fingers that are long and thin	Prompt and delayed splash, several fingers that are shortest and very thin
Hexadecane	Prompt and delayed splash, few fingers that are short and medium in width	Prompt and delayed splash, many fingers that are longest and medium in width	Prompt and delayed splash, many fingers that are longest and thin
DI water	Prompt and delayed splash, few fingers that are short and medium in width	Prompt and delayed splash, several fingers that are long and medium in width	Prompt and delayed splash, several fingers that are longest and medium in width
30% Glycerol/water	Prompt and delayed splash, several fingers that are short and thick	Prompt and delayed splash, several fingers that are longest and thick	Prompt and delayed splash, many fingers that are longest and medium in thickness
Ethanol	Prompt and delayed splash, several fingers that are short and medium in width	Prompt and delayed splash, several fingers that are long and thin	Prompt and delayed splash, several fingers that are longest and thin

Provided descriptions are comparative summaries only; they are not complete

number and angular variation of the filaments. The effect of larger impact energies is to amplify the splashing dynamics by the formation of more and longer filaments with more breakup occurring during their extension.

In contrast to the smooth surface, the effect of a rough surface upon the splash boundary is to dramatically lower the critical threshold for splash. This is summarized by the comparison of Tables 3 and 4. While this threshold is commonly expressed in terms of the impact Weber number, our recent work has found the Capillary number to more closely define a boundary between non-splashing and splashing droplet impacts with dry flat surfaces (Vander Wal et al. 2005a, 2005b).

The second effect of a rough surface upon drop impact is to equalize the drop impact dynamics relative to fluid property variations. Differences in surface tension and viscosity become far less significant in either

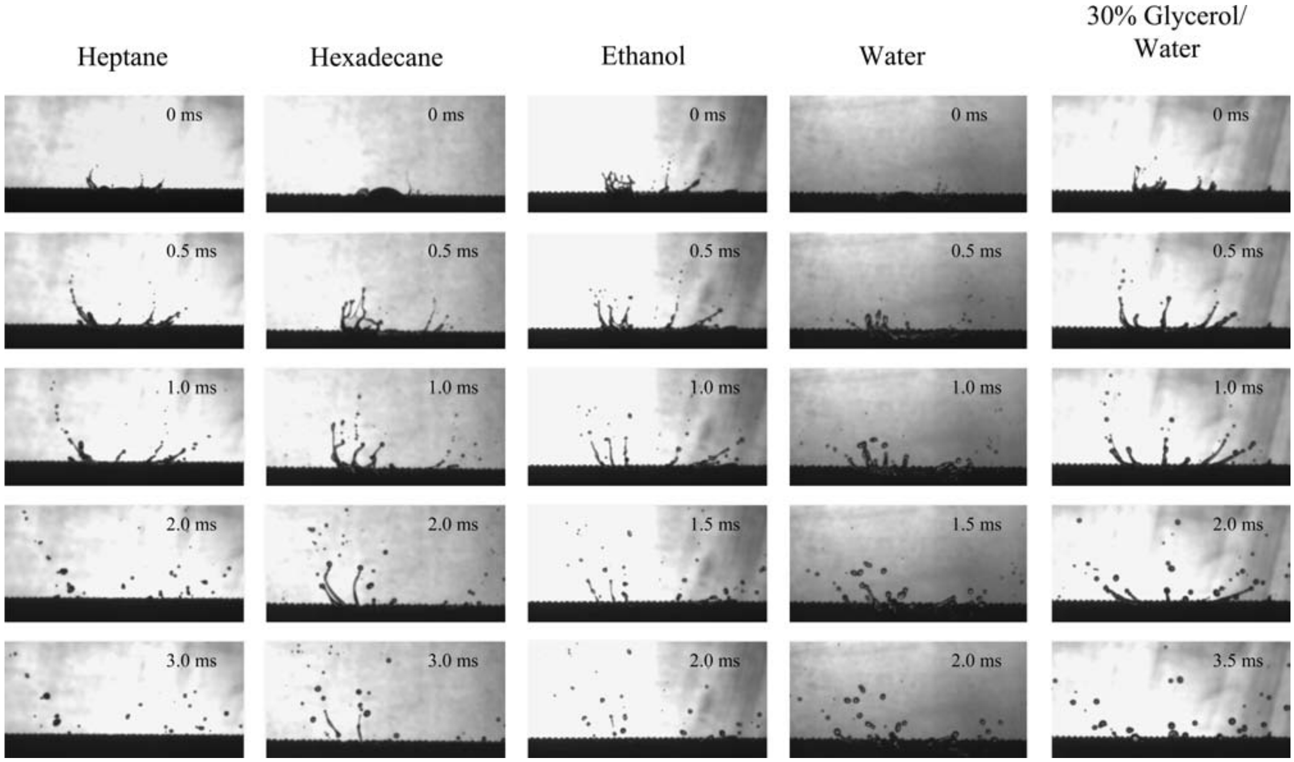

Fig. 2 A 2 mm droplet of the listed fluid dropped at 3.15 m/s onto a dry rough surface

Table 5 Summary of the splash/non-splash behavior of a 2 mm droplet of the fluid onto a thin film on a smooth surface

Fluids	2.17 nbsp;m/s	3.15 m/s	4.22 m/s
Impact event on a thin film on a smooth surface			
Heptane	Delayed splash, many fingers from a rough and low crown	Prompt and delayed splash, very many fingers from a smooth and average height crown	Prompt and delayed splash, very many fingers from a less smooth and average height crown
Hexadecane	No splash, no fingers from a very smooth and low crown	Delayed splash, very many fingers from a very smooth and high crown	Prompt and delayed splash, very many fingers from a very smooth and very high crown
DI water	No splash, no fingers from a rough and very low crown	Delayed splash, many fingers from a rough and low crown	Prompt and delayed splash, very many fingers from a smooth and average height crown
30% Glycerol/water	No splash, no fingers from a smooth and low crown	Delayed splash, very many fingers from a very smooth and low crown	Delayed splash, very many fingers from a very smooth and high crown
Ethanol	Delayed splash, few fingers from a smooth and low crown	Prompt and delayed splash, very many fingers from a very smooth and high crown	Prompt and delayed splash, very many fingers from a very smooth and very high crown

Provided descriptions are comparative summaries only; they are not complete

determining the splashing threshold or the subsequent dynamics which become very similar for all fluids. Differences in impact velocity merely alter the extension of the liquid filaments and the number of breakup products. Previously, we found a similar equalization effect for drops impinging upon thin liquid films, though differences in the splash threshold and dynamics were still manifest and interpretable in terms of surface tension and viscosity influences (Vander Wal et al. 2005a, 2005b).

3.3 Thin film on a smooth surface

Each of the five fluids presented here exhibited different splashing dynamics upon the thin film on the smooth

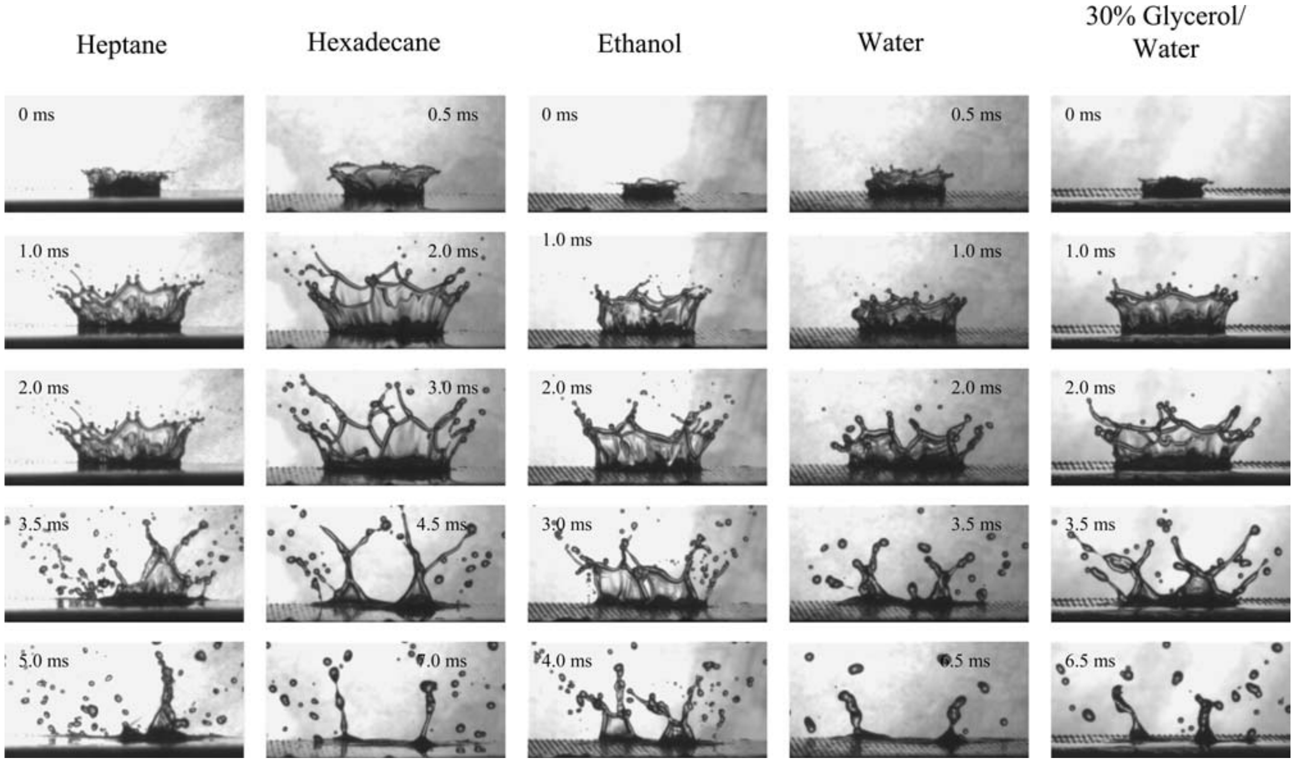

Fig. 3 A 2 mm droplet of the listed fluid dropped at 3.15 m/s onto a ~200 μm film of the same fluid on a smooth aluminum surface

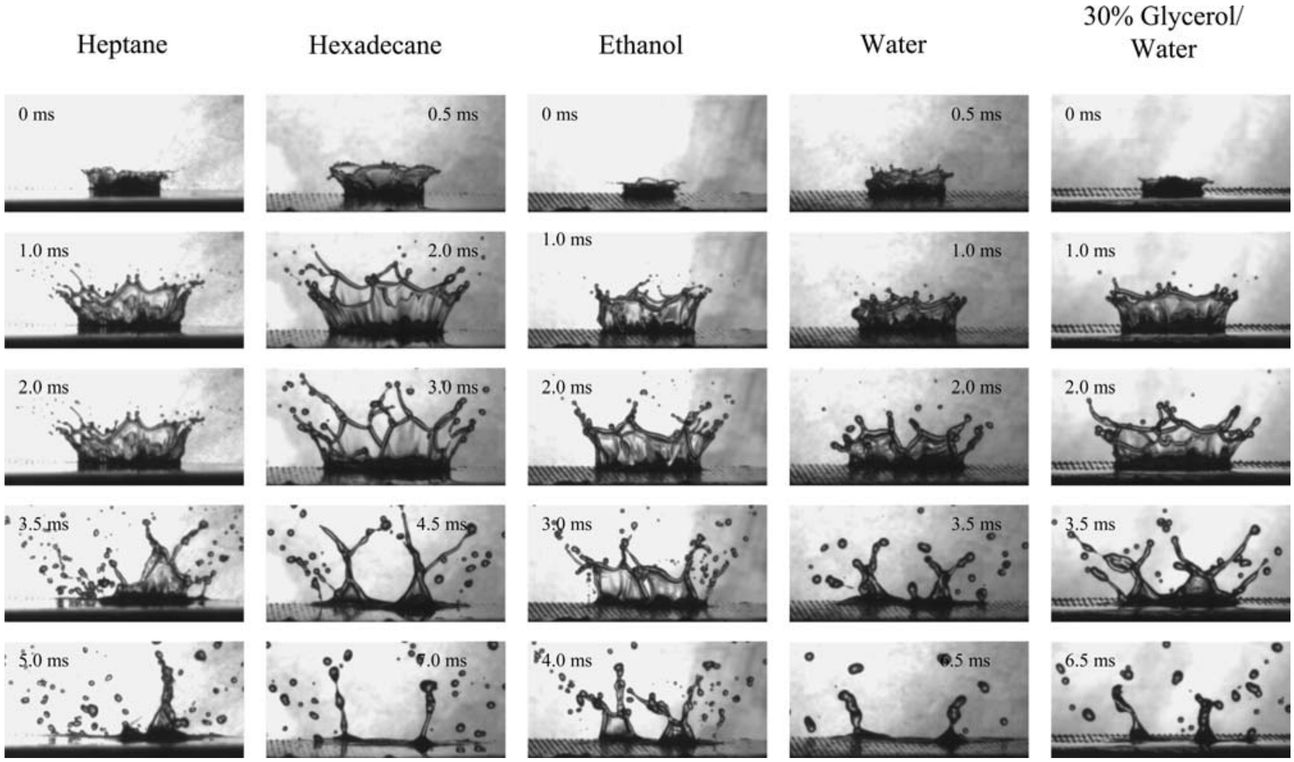

Fig. 4 A 2 mm droplet of the listed fluid dropped at 3.15 m/s onto a ~100 μm film of the same fluid on a rough surface

surface—this is summarized in Table 5. The production of the crown has been interpreted as arising through a kinematic discontinuity between the advancing drop fluid and the stationary fluid of the thin film (Yarin and Weiss 1995; Trujillo and Lee 2001; Roisman and Tropea 2002). While all fluids here, characterized by a variety of

Table 6 Summary of the splash/non-splash behavior of a 2 mm droplet of the fluid onto a film upon a rough surface

Fluids	2.17 m/s	3.15 m/s	4.22 m/s
Impact event on a thin film on a rough surface			
Heptane	Prompt and delayed splash, many fingers from a crown with very rough walls, medium delayed splash products	Prompt and delayed splash, most fingers from a crown with rough walls, medium delayed splash products	Prompt and delayed splash, most fingers from a crown with very rough walls, small delayed splash products
Hexadecane	Delayed splash, few fingers from a crown with very smooth walls, largest delayed splash products	Delayed splash, most fingers from a crown with smooth walls, large delayed splash products	Prompt and delayed splash, most fingers from a crown with smooth walls, medium delayed splash products
DI water	No splash, few fingers from a crown with rough walls	Prompt and delayed splash, many fingers from a crown with rough walls, largest delayed splash products	Prompt and delayed splash, most fingers from a crown with rough walls, large delayed splash products
30% Glycerol/water	No splash, many fingers from a crown with very smooth walls	Prompt and delayed splash, many fingers from a crown with smooth walls, large delayed splash products	Prompt and delayed splash, most fingers from a crown with smooth walls, medium delayed splash products
Ethanol	Delayed splash, many fingers from a crown with smooth walls, medium delayed splash ‘products	Prompt and delayed splash, most fingers from a crown with smooth walls, medium delayed splash products	Prompt and delayed splash, most fingers from a crown with smooth walls, small delayed splash products

Provided descriptions are comparative summaries only; they are not complete

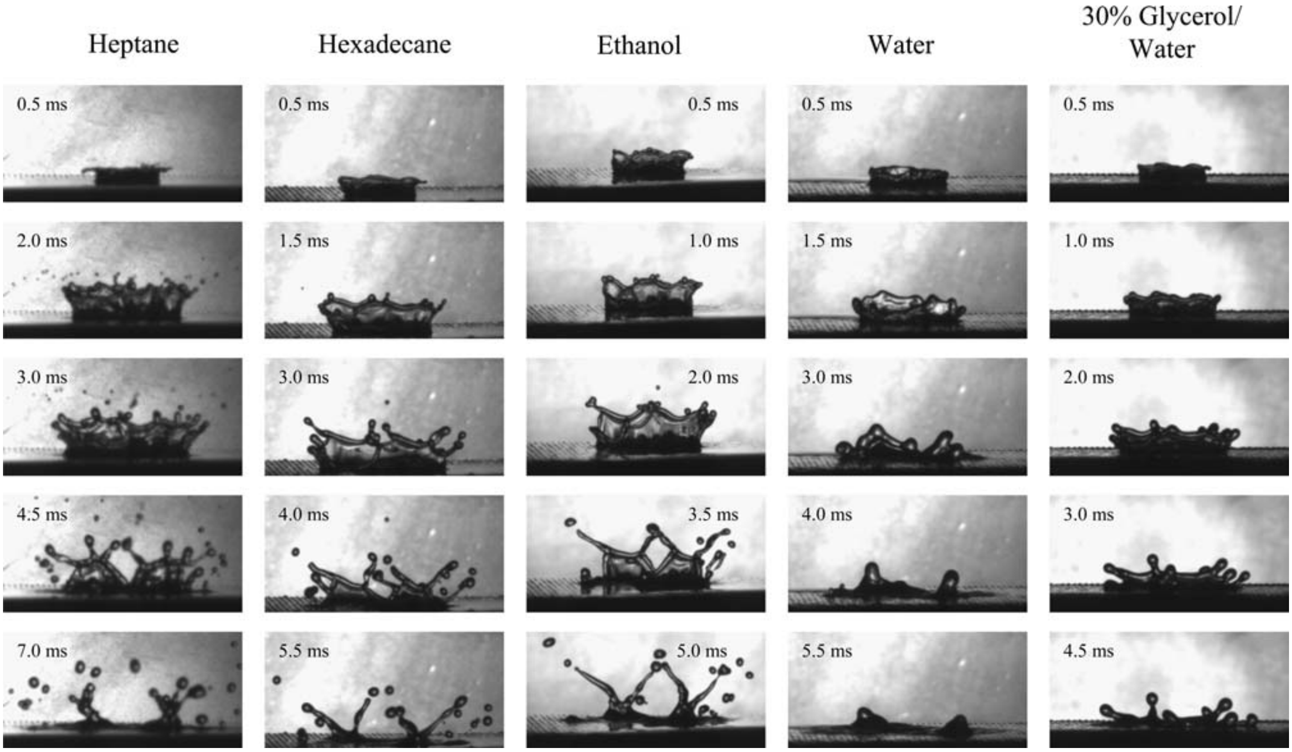

Fig. 5 A 2 mm droplet of the listed fluid dropped at 2.17 m/s onto a ~100 μm film of the same fluid on a rough surface

surface tensions and viscosities, form such a crown, the occurrence of prompt splash from the advancing crown and extent of delayed splash as the crown recedes and breaks up may be observed to depend upon fluid properties, as illustrated in Fig. 3. It is to be noted is that "delayed splash" refers to crown breakup during recession, not during advancement in the present discussion. These observations have been interpreted previously for dry surfaces (Allen 1975; Thoroddsen and Sakakibara 1998; Rieber and Frohn 1999; Bussman et al. 2000; Kim et al. 2000; Rioboo et al. 2001; Roisman et al. 2002) and on wetted surfaces (Yarin and Weiss 1995; Trujillo and Lee 2001; Roisman and Tropea 2002; Josserand and Zaleski 2003).

3.4 Thin film on a rough surface

As our previous group of experiments revealed, the effect of a thin film upon splashing dynamics was to create a thin axisymmetric crown. The height and breakup details depended primarily upon the impact energy and secondarily upon the fluid properties. In the case of a thin film upon the rough surface, we observe essentially a convolution of the influences imposed by a thin fluid film and the rough surface. As Table 6 summarizes and Fig. 4 shows, a crown is formed upon droplet impact. Unlike the crown formed upon thin films covering smooth surfaces, the effect of roughness becomes apparent in the circumferential periodic unevenness of the crown. The ribs of thicker fluid extending from the base to the rim of the crown strongly resemble those formed during impact upon the dry rough surface. Now, accompanying the crown, they appear to "support" the crown fluid film which seems to bridge these ribs. In other words, the disruption imposed by the rough surface appears in the presence of the film. Different from the dry surface is the opposite curvature of the filaments; similar is the delayed splashing mode via filament breakup. The added contribution of the film is the crown formation upon droplet impact.

In addition to the crown formation and structure, the droplet breakup dynamics also differs compared to those on a thin film atop a smooth surface. The filaments undergo a prompt breakup proceeding by drop evolution from their tips and delayed breakup during the later stages of crown evolution, both of which have a different physical origin. While the early process creates smaller droplets, the later process results in significantly larger drops created by Rayleigh instability. Further details may be seen by the comparison of Figs. 3 and 4. For example, prompt splash occurs even if it did not on the film covering the smooth surface, as for heptane, glycerol–water and water. Delayed splashing, associated with crown breakup occurs with high similarity for all the fluids studied here.

While water only exhibited prompt splashing on the thin film on a smooth surface at increased velocities, it did exhibit prompt and delayed splashing at lower velocities on the film over the rough surface. The only difference between water and the non-water based fluids was the creation of somewhat fewer splashed products. Despite the much higher viscosity of the glycerol–water mixture, the formation of filaments on top of the crown is very similar to that of water. The similarity of the splashing behavior of hexadecane to both water and the glycerol–water mixture further illustrates the minimal influence of surface tension upon the dynamics. By this comparison, surface tension also appears to have little influence other than to moderate the number of droplets released from the extended fluid filaments. This may be understood on the basis of Rayleigh instability causing the breakup of the fluid "cylinder" (Allen 1975; Thoroddsen and Sakakibara 1998; Rieber and Frohn 1999; Bussman et al. 2000; Kim et al. 2000; Rozhkov et al. 2002).

The formation of the crown has been observed before and interpreted on the basis of a radial kinematic discontinuity that develops between the initial and later stages of the advancing fluid or the advancing droplet and a static film (Yarin and Weiss 1995; Trujillo and Lee 2001; Roisman and Tropea 2002). As discussed previously for fluid impact upon the dry rough surface, its surface texture leads to non-axisymmetric kinematic discontinuities along the advancing fluid front, giving rise to the fluid filaments. As seen by the comparison of Figs. 2, 3, 4, the splashing dynamics upon the rough surface covered by a thin fluid film is a convolution of that which occurs on the dry rough surface and upon the thin film on a smooth surface. The elements of each parameter are evident in the type of crown formed and its subsequent breakup. As the velocity discontinuity along the fluid rim arises predominantly from the patternation of the rough surface, it is largely independent of fluid properties. This can be seen by comparing Fig. 4 with the images from a similar event at a smaller velocity in Fig. 5. Hence, the splashing threshold is primarily determined by the surface features and secondarily by the impact conditions or fluid properties. Thus, the main influence of fluid properties will be manifested in the breakup of the advancing fluid filaments.

4 Conclusions

Both a thin fluid film and a rough surface substantially alter the splashing threshold and subsequent splashing dynamics relative to a dry or smooth surface, respectively.

A rough surface dramatically lowers the critical threshold for splash that is observed for a smooth surface. Secondly, a rough surface largely equalizes the drop impact dynamics due to fluid property variations, particularly in the splashing regime. Differences in surface tension between 20.1 and 72.8 dynes/cm and viscosities between 0.4 and 3.3 cP become far less significant in either determining the splashing threshold or the subsequent dynamics which becomes very similar for all fluids where rough surfaces are involved. Differences in fluid properties alter the extension of the liquid filaments and hence the number of breakup products and to an extent the relative droplet sizes, as observed for the test conditions presented here.

The splashing dynamics upon the rough surface covered by a thin fluid film is a convolution of those which occur on a dry rough surface and a thin film upon a smooth surface. The consequences of each factor are evident in the type of crown formed and its subsequent breakup. As the velocity discontinuity along the fluid rim arises predominantly from the patternation of the rough surface, it is largely independent of drop impact energy or fluid properties. Hence, the splashing threshold is primarily determined by surface features and secondarily by impact conditions and fluid properties. Thus, the main influence of fluid properties will be manifested in the breakup of the advancing fluid filaments.

Acknowledgements This work was supported by a NASA NRA 01-HEDs-03 Fluid Physics award (RVW) administered through NASA cooperative agreement NCC3-975 with The National Center for Microgravity Research on Fluids and Combustion (NCMR) at The NASA-Glenn Research Center. Disclaimer: Trade names or manufacturers' names are used for identification only. This usage does not constitute an official endorsement, either expressed or implied by either the National Aeronautics and Space Administration or The National Center for Microgravity Research.

Reference

Allen RF (1975) The role of surface tension in splashing. J Colloid Surface Sci 51:350–351

Bohm C, Weiss DA, Tropea C (2000) Multi-droplet impact onto solid walls: droplet-droplet interaction and collision of kinematic discontinuities. In: ILASS-Europe 2000, Sept. 11–13, pp VII7.1–7.6

Bussman M, Chandra S, Mostaghimi J (2000) Modeling the splash of a droplet impacting a solid surface. Phys Fluids 12:3121–3132

Chandra S, Avedisian CT (1991) On the collision of a droplet with a solid surface. Proc R Soc London Ser A432:13

Coghe A, Brunello G, Cossali GE Marengo M (1999) Single drop splash on thin film: measurements of crown characteristics. In: ILASS Europe 1999

Cossali GE, Coghe A, Marengo M (1997) The impact of a single drop on a wetted solid surface. Exp Fluids 22:463–372

Crooks R, Boger DV (2000) Influence of fluid elasticity on drops impacting on dry surfaces. J Rheol 4:973–996

Engel OG (1955) Waterdrop collisions with solid surfaces. J Res Natl Bur Stand 54:281

Hardalupas Y, Taylor AMKP, Wilkins JH (1999) Experimental investigation of sub-millimeter droplet impingement onto spherical surfaces. Int J Heat Fluid Flow 20:477–485

Josserand C, Zaleski S (2003) Droplet splashing on a thin liquid film. Phys Fluids 15:1650–1657

Kim H-Y, Feng ZC, Chun J-H (2000) Instability of a liquid jet emerging from a droplet upon collision with a solid surface. Phys Fluids 12:531–541

Levin Z, Hobbs PV (1971) Splashing of water drops on solid and wetted surfaces: Hydrodynamics and charge separation. Philos Trans R Soc London Ser A 269:555

Mao TM, Kuhn DCS, Tran H (1997) Spread and rebound of liquid droplets upon impact on flat surfaces. AIChE J 43:2169–2179

Mundo CHR, Sommerfeld M, Tropea C (1995) Droplet-wall collisions: experimental studies of the deformation and breakup process. Int J Multiphase Flow 21:151–173

Oguz HN, Prosperetti A (1990) Bubble entrainment by the impact of drops on liquid surfaces. J Fluid Mech 219:143–179

Pasandideh-Fard M, Qiao YM, Chandra S, Mostaghimi J (1996) Capillary effects during droplet impact on a solid surface. Phys Fluids 8:650–659

Pumphrey HC, Elmore PA (1990) The entrainment of bubbles by drop impacts. J Fluid Mech 220:539–567

Range K, Feuillebois F (1998) Influence of surface roughness on liquid drop impact. J Colloid Interface Sci 203:16–30

Rein M (1996) The translational regime between coalescing and splashing drops. J Fluid Mech 306:145–165

Rieber M, Frohn A (1999) A numerical study on the mechanism of splashing. Int J Heat Fluid Flow 20:455–461

Rioboo R, Bauthier C, Conti J, Voue M, De Connick J (2003) Experimental investigation of splash and crown formation during single drop impact upon wetted surfaces. Exp Fluids 32:1–8

Rioboo R, Tropea C, Marengo M (2001) Outcomes from a drop impact on solid surfaces. Atomization Spray 11:155–165

Roisman IV, Tropea C (2002) Impact of a drop onto a wetted wall: Description of crown formation and propagation. J Fluid Mech 472:373–397

Rozhkov A, Prunet-Foch B, Vignes-Adler M (2002) Impact of water drops on small targets. Phys Fluids 14:3485–3501

Scheller BL, Bousfield DW (1995) Newtonian drop impact with a solid surface. AIChE J 41:1357–1367

Sivakumar D, Tropea C (2002) Splashing impact of a spray onto a liquid film. Phys Fluids 14:L85–L88

Stow CD, Hadfield MG (1981) An experimental investigation of fluid flow resulting from the impact of a water drop with an unyielding dry surface. Proc Royal Soc Lond A373:419–441

Thoroddsen ST, Sakakibara J (1998) Evolution of the fingering pattern of an impacting drop. Phys Fluids 10:1359–1374

Trujillo MF, Lee CF (2001) Modeling crown formation due to the splashing of a droplet. Phys Fluids 13:2503–2516

Vander Wal RL, Berger GM, Mozes SD (2005a) Droplets splashing upon films of the same fluid of various depths

Vander Wal RL, Berger GM, Mozes, SD (2005b) The splash/non-splash boundary upon a dry surface and thin fluid film

Wang A-B, Chen C-C (2000) Splashing impact of a single drop onto very thin liquid films. Phys Fluids 12:2155–2158

Wu ZN (1992) Modelisation et calcul implicite multidomaine d'ecoulements diphasiques gaz-gouttelettes. PhD Thesis, Universite Pierre et Marie Curie, Paris

Yarin AL, Weiss D (1995) Impact of drops on solid surface: self-similar capillary waves and splashing as a new type of cinematic discontinuity. J Fluid Mech 283:141–173