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THE SPLASHING PHENOMENA OF A LIQUID DROPLET IMPACTING WITH A SESSILE DROPLET ON A DRY SURFACE

Mostafa Abouelsoud[1,2] *& BoFeng Bai*[1,*]

[1]*State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China*

[2]*Mechanical Engineering Department, Faculty of Engineering, South Valley University, Qena 83523, Egypt*

*Address all correspondence to: BoFeng Bai, State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China; Tel: +86 298 266 5316; Fax: +86 298 266 9033, E-mail: bfbai@mail.xjtu.edu.cn

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This paper presents the results of an experimental study on the collision of a liquid droplet with a sessile droplet on a solid surface. In particular, the splash morphology for deionized (DI) water, 30% glycerol water, and ethylene glycol with an impact velocity in the range of 2.7 to 3.81 m/s was investigated. For the DI water and 30% glycerol water droplets, three different volume ratios of the sessile droplet to the falling droplet (V_s/V_o), i.e., 2.22, 3.44, and 4.92 were used, while two values were used for the ethylene glycol droplet, i.e., 4.3 and 5.7. It was found that the three liquids have three different splashing patterns due to the effects of surface tension and liquid viscosity, i.e., prompt splashing for DI water, delayed splashing for 30% glycerol water, and crown wall breakup splashing for ethylene glycol, respectively. It was observed that lower viscosity led to prompt splashing while lower surface tension led to crown wall breakup splashing. The prompt splashing and crown wall breakup splashing produced smaller secondary droplets, while the velocity of the secondary droplets during crown wall breakup splashing was higher than that during prompt splashing. The crown shape was similar to the three different liquids, which was a bowl shape, and the value of the sessile droplet volume had a great effect on the crown shape. Also, an empirical equation to predict the value of the maximum height of the crown was constructed. It was found that the maximum height of the crown strongly depended on the Weber number and also on the value of the sessile droplet volume for the DI water, 30% glycerol water, and ethylene glycol droplets.

KEY WORDS: *droplet impact, crown shape, non-uniform film, Weber number*

1. INTRODUCTION

The collision of a falling droplet on a sessile droplet is a fundamental phenomenon in many industrial applications, such as internal combustion engines, ice accumulation on aircraft, spray coating, spray cooling, and soil erosion. Different phenomena of the droplet impact were found by changing the impact velocity of the falling droplet. Bouncing and coalescence occur at relatively low-impact velocity, while splashing phenomena only occur at relatively high-impact velocity. Splashing is related to secondary droplets generated at impact. Splashing morphology appears in different applications, some of which need to promote splashing such as internal combustion engines in order to obtain a good mixture between the air and fuel in the atomizing process. Other applications need to suppress splashing, such as spray cooling since it needs to increase the heat transfer between the surface and the droplets.

Many investigations have focused on the splashing pattern due to the impact of falling droplets on a solid surface and uniform film. Cossali et al. (1997) defined two splashing patterns: one is concerned with droplet ejection at

NOMENCLATURE

D	diameter (mm)
H	crown height (mm)
H^*	dimensionless crown height
h_s	maximum thickness of the sessile droplet (mm)
L_s	diameter of the sessile droplet (mm)
u	velocity (m/s)
V	liquid volume (μL)
We	Weber number

Greek Symbols

ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

$\max$	maximum
o	falling droplet
s	sessile droplet

the instant of impact, which is referred to as prompt splashing; the other one is delayed splash, which is related to breakup or ejected secondary droplets at the end of the crown expansion. Vander Wal et al. (2006) studied the effect of liquid properties and the thickness of the uniform film on the impact outcome. They found that high surface tension can suppress splashing from droplet impact on both dry surfaces and thin films. By conducting an experimental study, Kang (2016) investigated the outcome of the droplet impact on a thin liquid film; they observed that the impact velocity has a big effect on the crown height. Xu et al. (2007) and Xu (2007) discovered that decreasing the surrounding gas pressure can decrease the splashing onset. Wang and Chen (2000) showed that when the thickness of a film is very low there is no effect of the film thickness on the splashing threshold; their results were in qualitatively agreement with Rioboo et al. (2003). Yarin and Weiss (1995) suggested that the falling droplet size had no effect on the splashing threshold. Numerically, Liang et al. (2014); Asadi and Passandideh-Fard (2009); and Sang et al. (2011) used coupled level-set/volume-of-fluid, volume-of-fluid, and level-set methods, respectively, to study the crown behavior and splashing phenomena of a single droplet impact on a thin uniform film. Yarin (2006); Josserand and Thoroddsen (2016); and Liang and Mudawar (2016) presented review papers, which mentioned different studies on splashing patterns and crown behavior (Ma et al., 2012; Liang et al., 2013; Liu et al., 2015); the majority of these papers focused on the impact of a droplet on a solid surface or a uniform film. Fujimoto et al. (2002) and Nikolopoulos et al. (2010) carried out experimental studies of one-by-one droplet impact on a solid surface, in which they investigated the crown behavior.

In this paper, we first focus on the splashing morphology and the crown behavior from the impact of a falling droplet and a sessile droplet with the same liquid on a solid surface. In addition, three types of splashing are defined: the first type is prompt splashing, the second type is delayed splashing, and the third type is splashing due to break up of the wall of the crown. Finally, the maximum heights of the crown for deionized (DI) water, 30% glycerol water droplets, and ethylene glycol droplets are compared.

2. EXPERIMENTAL TECHNIQUES

Figure 1 shows a schematic illustration of the experimental test rig. Two syringe pumps (22/2000, Harvard Apparatus, Holliston, MA, USA) were used, one for the impacting droplet and the other one for the sessile droplet. It should be noted that both the falling droplet and the sessile droplet had the same liquid. The impact outcome was captured by using a high-speed camera (Photron Fastcam, Tokyo, Japan) with a frame rate of 10,000 frames per second and shutter time of 1/81920. To decrease the effect of the surrounding air dynamics, a fabricated glass tube with a diameter of 50 mm was used. Three fluids, DI water, 30% glycerol water, and ethylene glycol were selected as the experimental liquids with static contact angles for the glass surface of 63.5°, 64°, and 57.01°, respectively. The droplet properties of the three liquids are given in Table 1.

To carry out the experiments, first a sessile droplet was produced by using a syringe pump with a flow rate of 0.01 ml·min^{-1} and pumping the liquid through a hole in the glass surface. As soon as the sessile droplet formed its

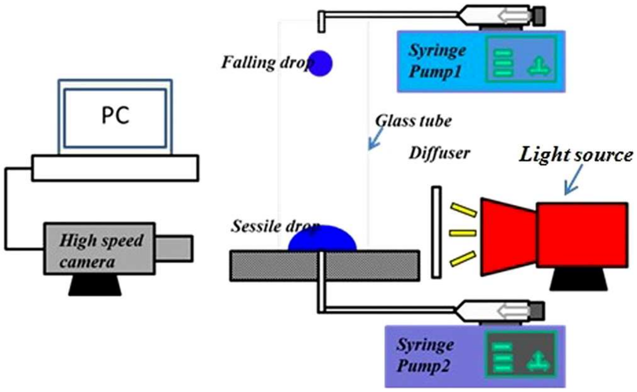


FIG. 1: Schematic diagram of the experiential test rig (not to scale)

TABLE 1: Experimental parameters

Fluid	μ [10^{-3} (Pa·s)]	σ [10^{-3} (J/m^2)]	ρ (kg/m^3)	θ	D_o (mm)	We	u (m/s)	V_s/V_o
DI Water	0.978	72.8	1000	63.4°	2.4	127–391	2.7–3.81	2.22, 3.44, and 4.92
30% Glycerol water	2.64	71.7	1080	64°	2.4	139–427	2.7–3.81	2.22, 3.44, and 4.92
Ethylene glycol	16.13	47	1109.7	57.01°	2.9	374–920	2.7–3.81	4.3 and 5.7

final shape, it was impacted by the falling droplet. The falling droplet was produced by pumping the liquid from the first syringe pump at a flow rate of 0.02 ml·min^{-1} through a tube to a flat-tip, stainless steel needle, where the droplet formed at the tip of the needle and then fell due to gravity. A code program was written in MATLAB for image processing and to determine the droplet diameter, impact velocity, and crown height. Figure 2 shows the impact parameters, which are summarized in Table 1. It is presumed that the sessile droplet has a spherical cap shape, thus Eq. (1) can be applied to calculate its volume. In addition, it is expected that the falling droplet has a spherical shape, thus Eq. (2) can be applied to calculate the volume of the falling droplet:

$$V_s = \pi h_s \left(\frac{L_s^2}{8} \frac{h_s^2}{6} \right) \tag{1}$$

$$V_o = \frac{4}{3}\pi \left(\frac{D_o}{2} \right)^3 \tag{2}$$

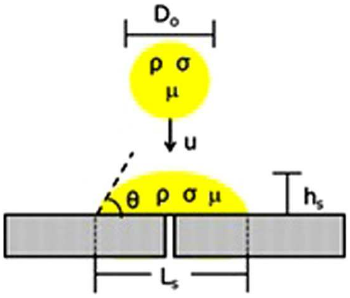


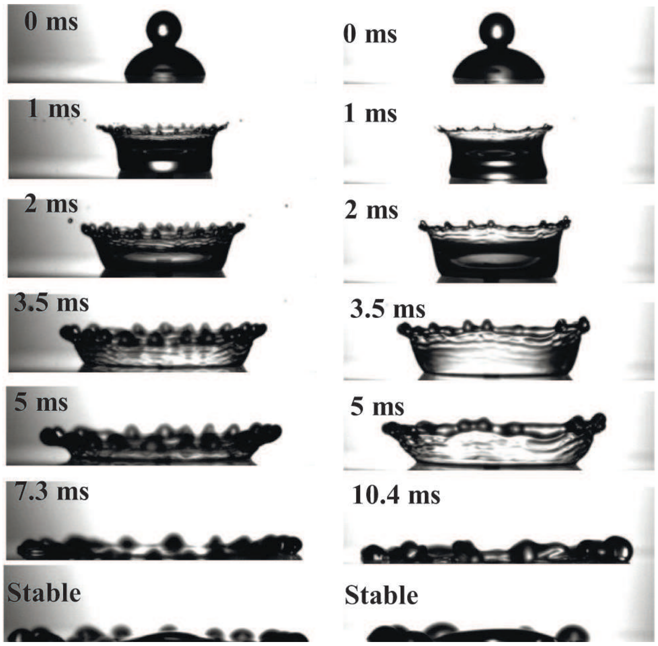
FIG. 2: Schematic illustration of a falling droplet impacting with a sessile droplet on a solid surface

Two main parameters were considered in this study: the Weber (We) number and the dimensionless sessile droplet volume (V_s/V_o). Since ethylene glycol has higher viscosity and lower surface tension than DI water and 30% glycerol water, it has a different contact angle and different dimensionless sessile droplet volume (V_s/V_o). Since the Weber number is given by We $= \rho u^2 D/\sigma$, where ρ, u, and σ are the liquid density, impact velocity, and surface tension, respectively, different velocities can be obtained by changing the heights of the falling droplet, which result in different Weber numbers (as shown in Table 1). For each volume of the sessile droplet, the Weber number of the falling droplet can be changed.

3. RESULTS AND DISCUSSION

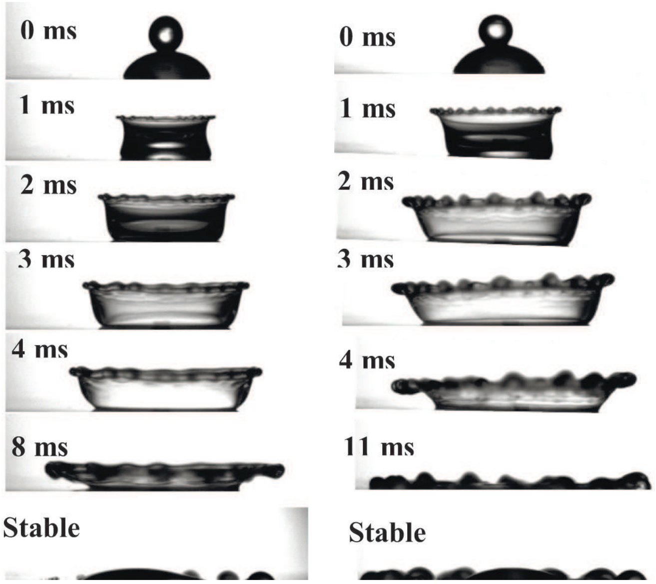
3.1 Impact Sequences

Figure 3 shows the outcome sequences of the impact for the DI water liquid at $u = 3.8$ m/s, and at two values of the dimensionless volume of the sessile droplet, $V_s/V_o = 3.44$ and 4.92. It was found that at high-impact velocity, the crown propagates quickly. In addition, it was observed that very tiny droplets were ejected from the crown rim at the instant of impact and during propagation of the crown; this type of splashing is called prompt splashing, as mentioned in Cossali et al. (2004). Qualitatively, this can be differentiated in Figs. 3(a) and 3(b) by the number of secondary droplets, which is greater in Fig. 3(a) at $V_s/V_o = 3.44$ than that in Fig. 3(b) at $V_s/V_o = 4.92$. The impact outcome of the 30% glycerol water droplet onto the sessile droplet is presented in Fig. 4. As the time increases, the crown propagates radially until it reaches the maximum crown diameter. It can be observed in Fig. 4 that fingers form at the top of the crown rim, after which the crown retracts and breakup occurs at the surface. This breakup at the end of the retraction process of the crown is called delayed or breakup splashing. Figure 5 specifies a series of images of the impact of the falling droplet on the sessile droplet for ethylene glycol at $u = 3.8$ m/s. It is clear that the initial behavior of the crown propagation from the impact is almost similar to the 30% glycerol water droplet until the wall of the crown starts breaking up. Since rupture of the crown wall starts in the bottom of the crown, it develops until



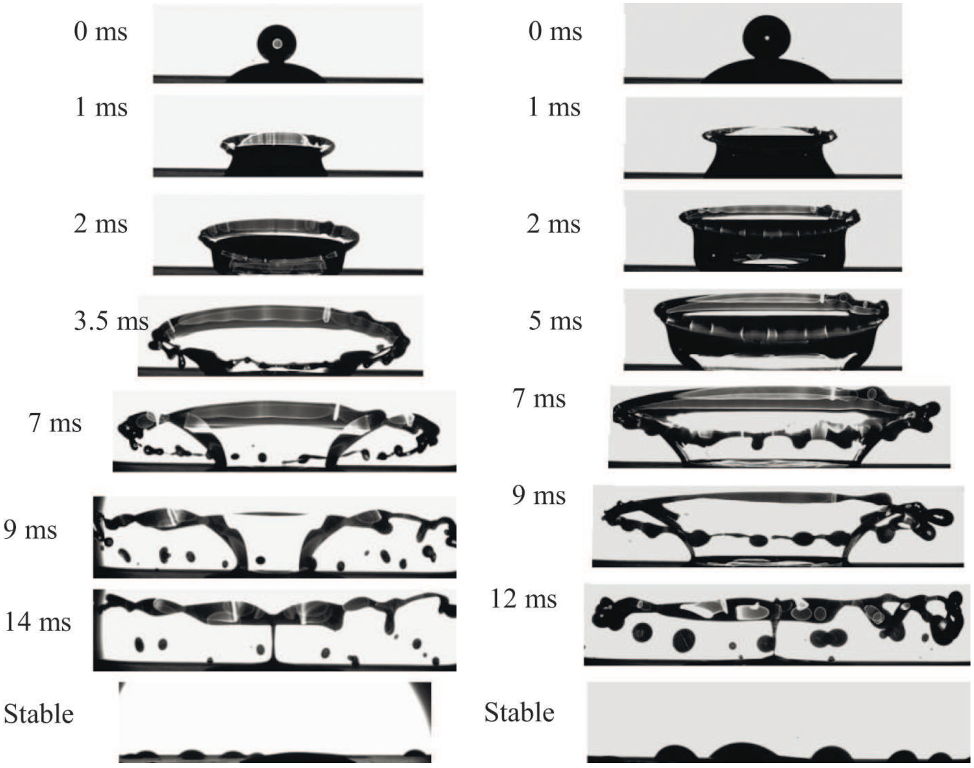
(a) (b)

FIG. 3: Effect of the dimensionless sessile droplet's volume of DI water on the shape of the crown and splash phenomena at different frames under $u = 3.8$ m/s: (a) $V_s/V_o = 3.44$; (b) $V_s/V_o = 4.92$



(a) (b)

FIG. 4: Effect of the dimensionless sessile droplet's volume of 30% glycerol water on the shape of the crown and splash phenomena at different frames under $u = 3.8$ m/s: (a) $V_s/V_o = 3.44$; (b) $V_s/V_o = 4.92$



(a) (b)

FIG. 5: Effect of the dimensionless sessile droplet's volume of ethylene glycol on the shape of the crown and splash phenomena at different frames under $u = 3.8$ m/s: (a) $V_s/V_o = 4.3$; (b) $V_s/V_o = 5.7$

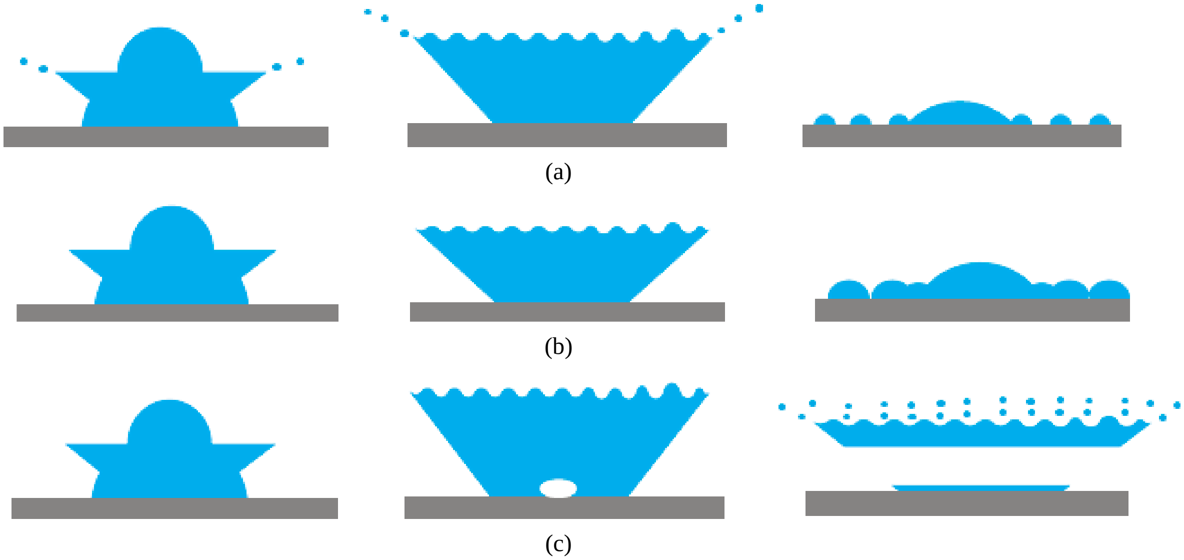
the entire crown's wall vanishes and small secondary droplets eject with high kinetic energy. We mentioned that this splash is referred to as crown wall breakup splashing (see Wang and Chen, 2000).

3.2 Splash Morphology

Based on the impact morphology results, it was found that there are three different types of splashing (as shown in Fig. 6): prompt splashing for the DI water droplet, delayed or breakup splashing at the end for the 30% glycerol water droplet, and crown wall breakup splashing for the ethylene glycol droplet. It was observed that the secondary droplet sizes for the prompt splashing and crown wall breakup splashing are smaller than the secondary droplets of the delayed splashing. In addition, the secondary droplets of the crown wall breakup splashing have higher velocity than the other types of splashing. It is obvious that as the liquid viscosity increases this suppresses the prompt splashing, thus in the current experiments only the behavior of DI water resulted in prompt splashing due to its low viscosity. This leads to an increase in the radial velocity of the crown, which affects the prompt splashing, as proven by Levin and Hobbs (1971). On the other hand, decreasing the liquid surface tension has a great effect on the rupture of the crown wall, which leads to breakup of the wall crown splashing, as happened with ethylene glycol. Generally, it was found that the liquid properties had no significant effect on the shape of the crown since it was almost a truncated cone shape, which mostly depends on the dimensionless value of the sessile droplet volume.

3.3 Maximum Crown Height

The maximum height of the crown is defined as the maximum distance between the crown base and the crown rim, as mentioned in Cossali et al. (2004) and clarified in Fig. 7. The maximum height of the crown occurs at the full extension of the crown. With the help of the MATLAB code, the maximum height of the crown can be measured. Figure 8 shows the effect of the Weber number on the non-dimensional maximum height of the crown (H_{max}/D_o) at different dimensionless values of the sessile droplet for the DI water, 30% glycerol water, and ethylene glycol


(a)

(b)

(c)

FIG. 6: Splashing patterns for different liquids: (a) prompt splashing for DI water; (b) delayed splashing for 30% glycerol water; (c) breakup of the wall crown splashing for ethylene glycol

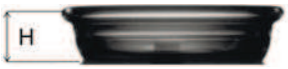


FIG. 7: Crown morphology: H denotes crown height

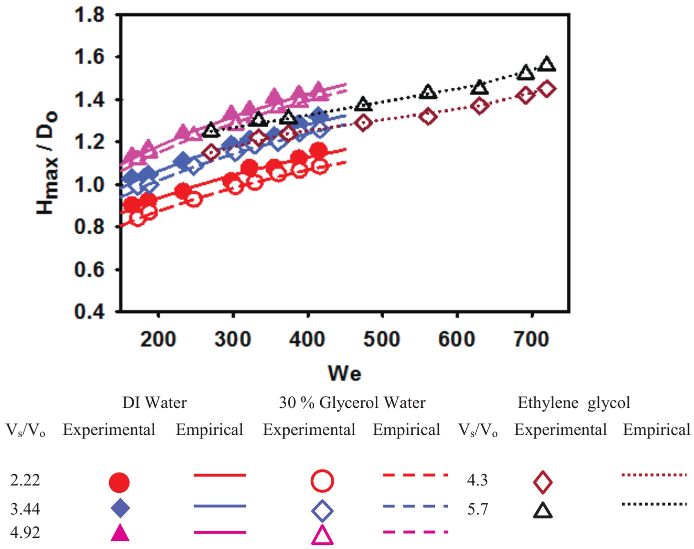


FIG. 8: Effect of the sessile droplet's volume on the maximum crown height

droplets. Each symbol shape corresponds to the liquids and V_s/V_o values shown in Fig. 8. It can be observed that the droplets for the three liquids have the same curve trend. As the Weber number increases the non-dimensional maximum height of the crown increases. This means that the falling droplet has relatively high kinetic energy, which leads to rapid crown propagation and increases the crown's height. It can also be observed that as the ratio of the sessile droplet volume to the falling droplet volume increases the non-dimensional maximum height of the crown increases. Although the behavior of the maximum height of the crown for the DI water droplet and the 30% glycerol water droplet are very close, it can be noticed that the non-dimensional maximum height of the crown for DI water droplet is slightly higher than for 30% glycerol water droplet. This is attributed to the higher viscosity of the 30% glycerol water droplet, which decelerates the crown propagation during the impact of the droplets. Since ethylene glycol droplet has lower surface tension it has a higher Weber number.

In summary, it should be noted that the Weber number has a great effect on the maximum height of the crown. By curve fitting, an empirical equation can be constructed, which verifies the best fit for the maximum height of the crown as follows:

$$\frac{H_{\max}}{D_o} = a\left(\frac{V_s}{V}\right)^b (\mathrm{We})^c \tag{3}$$

where a, b, and c are constants for the same liquid. The values for the three liquids are given in Table 2, which also shows the deviation of the correlation. The deviation is a relative error and the maximum and minimum values of this error can be calculated as follows:

$$\varepsilon = \frac{(y_i - f_i)^2}{y_i^2} \tag{4}$$

where ε is the relative error, y_i is the measured maximum height of the crown, and f_i is the predicted maximum height of the crown.

TABLE 2: The values of the correlation constants

Liquid	a	b	c	Deviation of the Correlation	Confidence Level
DI water	0.178	0.290	0.270	± 4.0%	88%
30% Glycerol water	0.137	0.416	0.282	± 5.0%	86%
Ethylene glycol	0.2004	0.336	0.222	± 6.5%	85%

4. CONCLUSIONS

In this work, experimental studies have been carried out on the collision of an impacting droplet with a sessile droplet on a glass surface. Three different types of splashing have been identified: (1) prompt splashing, which is related to very tiny droplets ejected at the instant of the impact; (2) delayed splash, which is related to the breakup or ejected secondary droplets at the end of the crown expansion; and (3) crown wall breakup splashing, which is concerned with small droplet ejection after the crown wall has ruptured. At low viscosity, we can observe prompt splashing, which occurred for the DI water droplet. Low surface tension led to crown wall breakup splashing, which occurred for the ethylene glycol droplet; consequently, for high viscosity and high surface tension delayed splashing can be seen as for the 30% glycerol water droplet. The shape of the crown was similar in the liquids, and was only affected by the value of the sessile droplet's volume. It was noticed that the Weber number has a strong effect on the maximum crown height. Although the behavior of the maximum height of the crown for the DI water droplet and the 30% glycerol water droplet was very close, it was noticed that the non-dimensional maximum height of the crown for the DI water droplet was slightly higher than the 30% glycerol water droplet. This was attributed to the higher viscosity of the 30% glycerol water droplet, which decelerates the crown propagation during the impacting of the droplets. Based on the current experimental results, an empirical correlation for the maximum height of the crown was proposed, which showed good results.

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