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Comparison between splash of a droplet in isolation and in a spray impact

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Abstract

This study presents an experimental study of splashing droplets in spray impact phenomena. The obtained results indicate that the growth rates for crown base radius and crown height for a splashing droplet in a spray are significantly different than that of a single or train of single droplets impacting onto an undisturbed liquid layer. The dimensionless time required for development of the crown base radius takes about 70% longer in compare to the crown height development. Also results obtained in this study indicate that non-dimensional crown height increases linearly with Weber number before the impact.

Keywords

Splash, spray, spray impact, crown, Phase Doppler.

Introduction

In an overall effort to model the impact of liquid sprays onto rigid walls, the splashing phenomena plays an important role in determining the velocity and size distribution of ejected droplets from the wall as well as the ejected mass fraction, see e.g., Sivakumar and Tropea, 2002; Coghe et al., 1997; Cossali et al., 1997; Cossali et al., 2005.

In practice, increasing the number of splashing droplets in spray impact phenomena can decrease the quality of coated or painted surfaces. A large number of parameters and variables can influence the splashing phenomenon; physical properties of droplet fluid: viscosity, surface tension and density, impact parameters: impact velocity, flux density of impacting droplets, i.e. frequency of impacting droplets, and droplet trajectory, and target characteristics (rigid wall: dry or wetted wall (surface roughness, wall temperature), liquid layer (film thickness, surface roughness). From the mentioned parameters, two of them are very important in determining the onset of splashing: surface roughness and average depth of accumulated liquid film on the wall, e.g. splashing takes place faster for rough surfaces as postulated by Mundo et al., 1998 and Range and Feuillebois, 1998. Therefore, the ratio of average wall roughness to the average primary droplet size should be considered if rough or structured surfaces are used. Also the ratio of the average liquid film thickness accumulated on the wall to the average primary droplet size must be considered in the case of accumulated wall film,see e.g., Cossali et al., 1997; Kalantari and Tropea, 2007; Mundo et al., 1995; Rioboo et al., 2003.

Study of the splashing phenomenon for single drops and for drops in a spray can be very valuable for future modeling of single droplet and spray impact. The present work provides an experimental study for the maximum crown height and radius of splashing droplets in a real spray impact condition.

Material and methods

The water spray was created using two different hollow cone (pressure swirl) nozzles from Delevan and two different full cone nozzles from Spraying System Co., operated at pressures between 3 and 7 bars. To characterise the spray a dual-mode phase Doppler instrument from Dantec Dynamics was used, comprising a transmitting optics with a 400mm focal length, a receiving optics with a 310mm focal length, an “A” type mask and a 34° scattering angle.

The thickness of the liquid film created under spray impact has been estimated based on multiple images obtained by using a Sensicam CCD camera. Another high-speed camera with 32000 fps has been used to follow the splashing droplets from the wall.

Results and discussion

Our observations in this study and that of other investigations, e.g. Sivakumar and Tropea, 2002 indicate clearly that the splash created by a drop in a spray differs significantly from that of an isolated single drop impact or from the impact of a train of drops on a stationary liquid film, examined by Cossali et al., 1997, and Yarin and Weiss,

1995. These differences can be easily seen in Fig.1, indicating that splash of a droplet in spray impact is much more irregular and non-symmetric in comparison to the symmetric propagation of a crown in the case of an isolated single droplet impact onto an undisturbed liquid layer.

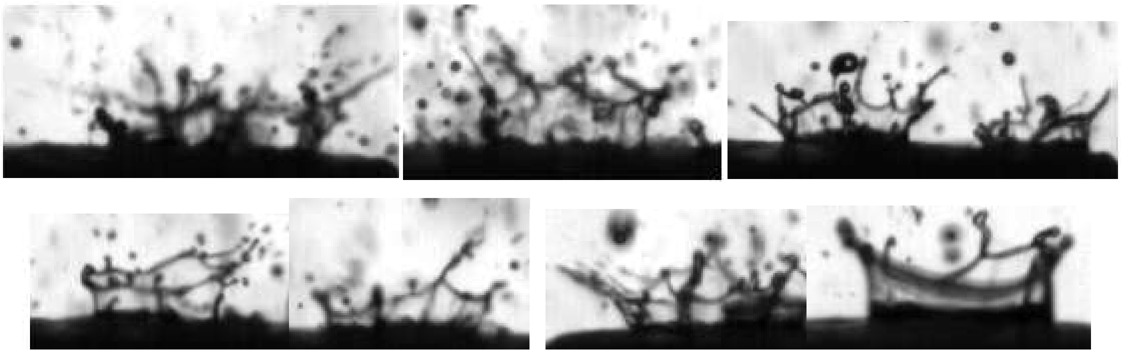


FIG. 1. Some exemplary splashing crowns in spray impacting onto a rigid wall (wall covered by a thin liquid film).

One exemplary sketch of a non-symmetric splash in a spray is illustrated in Fig.2. As shown in this sketch, the main source of this non-symmetric splash is the impact of a neighbouring droplet during the splash, Kalantari and Tropea, 2007a. If during the splash of a given droplet in a spray, other droplets impact close to the splashing droplet, then the higher hydrodynamic pressure exerted in the film near the base of the crown will feed fluid into the crown body on one side, yielding a non-symmetric splash. The thickness of the crown body and the crown height on this side will be larger than the other side, therefore secondary droplets ejected on this side will be larger due to the thicker rim bounding the crown, see Fig.2. Similar behaviour can also be observed due to oblique impact of a droplet in spray. Such examples of asymmetry splashing can be seen in Fig.1.

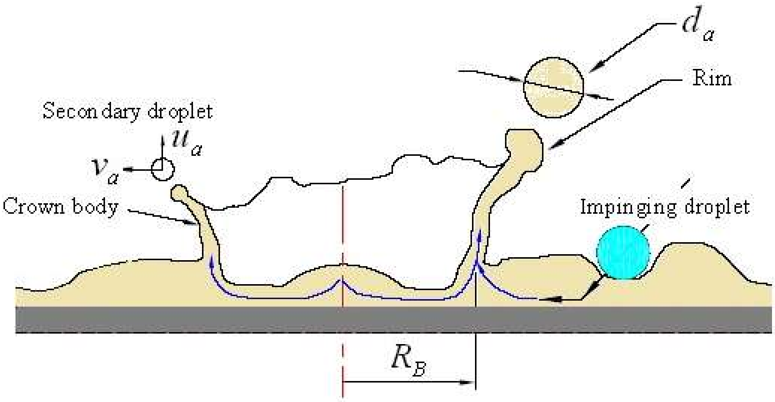
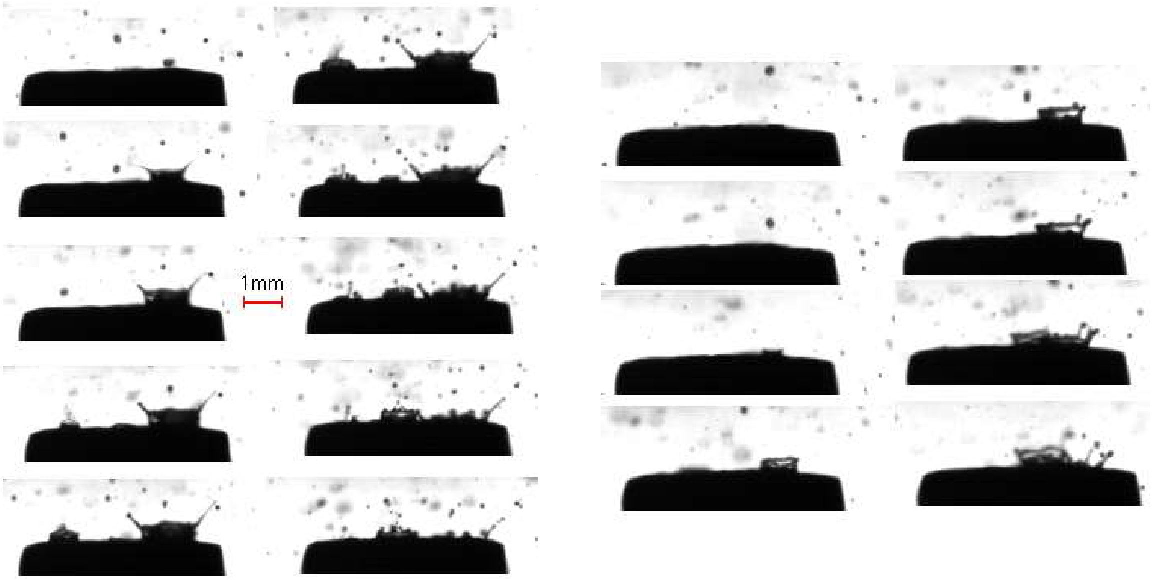


FIG. 2. Sketch of a non-symmetric splashing droplet in spray due to neighbourhood droplet(s) impact.

Furthermore, it appears that the velocity fluctuations inside the accumulated wall film have a significant influence on the splashing phenomenon, Kalantari and Tropea, 2007. Meanwhile, in a spray the liquid film interface is irregular and non-steady; the curvature leads to local Laplace pressure fluctuations. Finally, the liquid film will exhibit high local pressure gradients due to the impacting drops. The overall behavior in a spray may involve a combination of effects.

Two exemplary sequential photographic image of a splashing droplet in a spray are presented in Figs.3a, and b. These sequential images were recorded by means of a high speed camera at 16 kfps. In this picture a liquid droplet with impact Weber number of a) 534 and b) 378 splashes on a rigid surface covered by a accumulated wall film due to spray impact.

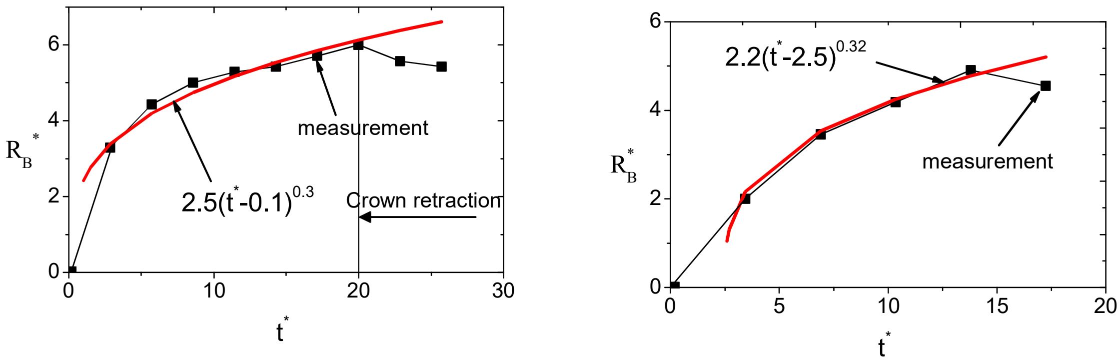


a

b

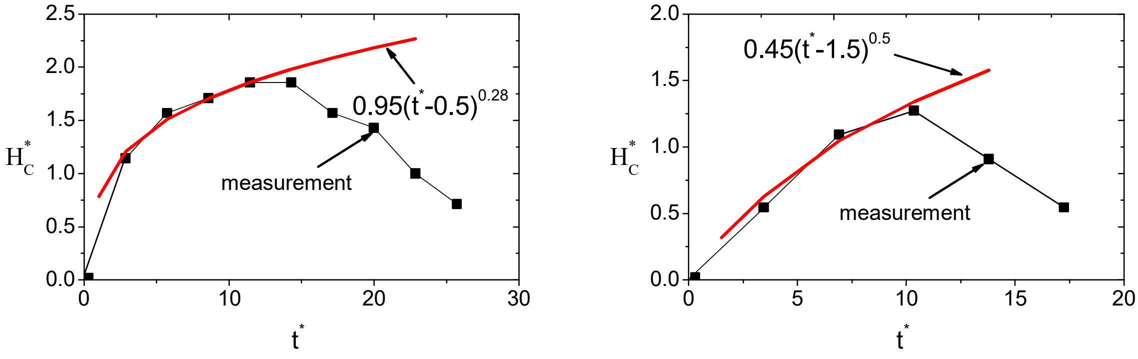
FIG. 3. . Photographic image sequence of a splashing droplet in a spray recorded with 16 kfps; a) $We_{nb}=¿$ 534 and $\acute{h}/d_b=¿$ 0.57, b) $We_{nb}=¿$ 378 and $\acute{h}/d_b=¿$ 0.71.

In Fig.4, the non-dimensional crown base radius ($R_B^{¿}=R_B/d_b$) and crown height ($H_C^{¿}=H_C/d_b$) are presented as a function of dimensionless time ($t^{¿}=t\cdot u_b/d_b$) for the splashing droplet sequences illustrated in Figs.3a and b (ub and d_b are the normal velocity component and drop size before impact, respectively). These obtained growth rates for crown base radius and height for a splashing droplet in a spray are significantly different than that of a single or train of single droplets impacting onto an undisturbed liquid layer which are proportional to $t^{0.5}$, see Refs. Cossali et al., 1997; Cossali et al., 2004; Yarin and Weiss, 1995. In Fig. 4, "t*=0" corresponds to the time when initial droplet touch the film surface.



a

b



c **d**

FIG. 4. Instantaneous variation of: a, c) crown base radius and crown height with a, c) $We_{nb}=¿$ 534 and $\acute{h}/d_b=¿$ 0.57, and b, d) crown base radius and crown height with $We_{nb}=¿$ 378 and $\acute{h}/d_b=¿$ 0.71; dimensionless time ($t^{¿}=t\cdot u_b/d_b$).

Results presented in Fig. 4 indicate that development of crown base radius requires longer time in compare to the crown height development. As an example, in Fig. 4a crown base radius develops until t*=20, while crown height retracts after t*=14 for this splash, see Fig. 4c. The same qualitatively result can be observed in Figs. 4b and d.

In a single drop impact, experiments done by Cossali et., al, 1999 indicates that dimensionless times for the maximum crown height depends linearly on the impact Weber number, while our observations for the spray impact phenomena shows that dimensionless times for the maximum crown height is independent of the impact Weber number. Dimensionless times for the maximum crown height and maximum crown base radius in a spray impact is given in Eqs. 1 and 2.

Experimental data for the time ratio (the time at the instant of the maximum crown base radius-to-the time at the maximum crown height) are presented in Fig. 5. It is shown in this figure that the time ratio is distributed around the value 1.7 independent of the impact Weber number. This means that the dimensionless time required for development of the crown base radius takes about 70% longer in compare to the crown height development. The reason is that development of the crown base radius continues also after crown height retraction due to the downward flowing of liquid inside the crown body which feeds more liquid into the crown base under the influence of gravity.

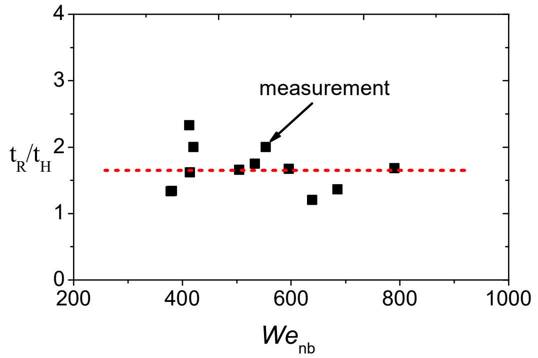


FIG. 5. Time ratio at the instant of the maximum crown height-to-the instant of the maximum crown base radius.

Observation of Sivakumar and Tropea, 2002 indicates that in a spray impact, the crown radius exhibits a growth rate proportional to $t^{0.2}$, whereas the crown heights development is proportional to $t^{0.5}$. Based on the conducted measurements in this study, non-dimensional crown height and crown base radius of a splashing droplet in a spray as a function of dimensionless time can be expressed in the following forms

$$H_C^* \propto (t^* - \tau_H)^{n_H} \qquad t^* \le 11 \pm 2 \quad ; \quad 0.5 \le \tau_H \le 3.5 \tag{1}$$

$$R_B^* \propto (t^* - \tau_R)^{n_R} \qquad t^* \le 19 \pm 3.7 \quad ; \quad 0.1 \le \tau_R \le 2.5 \tag{2}$$

where τ_R and τ_H are dimensionless constants (offset parameters) obtained from the experiments indicating the initial condition of the splashing phenomenon. The values n_R and n_H are presented in table 1 and compared with the previous observations.

TABLE I. The values n_R and n_H for non-dimensional crown base radius and crown height of a splashing droplet in isolation and in a spray impact.

	n_H	n_R
Single or chain of drop impact, Cossali et al. 3, and Yarin and Weiss 13.	0.5	0.5
Spray impact, Sivakumar and Tropea1.	0.5	0.2
Spray impact, present study	$0.25 \le n_H \le 0.5$	$0.2 \le n_R \le 0.32$

Sivakumar and Tropea, 2002 postulated that in the case of spray impact, the non-dimensional crown height and radius does not exhibit a systematic dependence on the impact Weber number. Results obtained in this study indicate that the non-dimensional crown height in spray impact phenomena increases linearly with Weber number before the impact. A linear correlation for non-dimensional maximum crown height in the case of spray impact condition can be given as (see Fig.6).

$$H_C^* = 3.9 \times 10^{-3} We_{nb} - 3.54 \times 10^{-2} \tag{3}$$

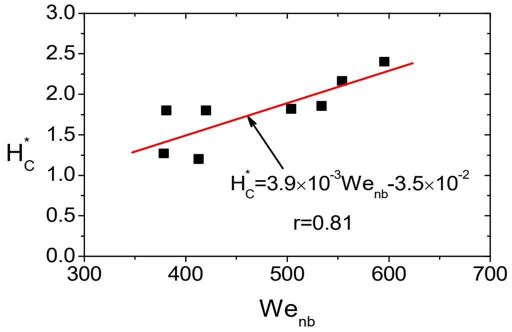


FIG. 6 : Maximum non-dimensional crown height as a function of impact Weber number before the impact in spray.

The obtained correlation (3) can be important for the measurement of spray impact phenomena with Phase-Doppler instrument. Since for capturing all the generated secondary droplets, the measurement volume must be placed above the maximum height of all possible crowns generated by splashing droplets.

For illustrating the influence of the wall film thickness on the mass ratio λ_m (the ejected-to-incident mass) in the case of constant impact Weber numbers, some exemplary results are presented in Fig. 7. It is shown in this figure that the average wall film thickness has non-predictable and complex influence on the mass ratio in the presence of a constant impact Weber number. The results presented in this figure indicate again the complexity of the spray impact phenomena. Physically increasing the average wall film thickness, yields a decrease in the number of splashed droplets (resulting in a decrease of the number of ejected droplets from splashed droplets), but yields also an increase of the number of secondary droplets generated from ejected wall films. Meanwhile several interaction sources must also be considered in generating the secondary droplets; interactions between two droplets (two ingoing drops, ingoing and ejecting drop or two secondary droplets), between an uprising jet and a drop and between a splashing droplet and other droplet (ingoing or ejecting droplet). Therefore all of these phenomena are involved in generating the secondary spray and this fact is reflected in the scatter of the data points in this figure. It is also shown in this figure that the impact Weber number has a strong influence on the total secondary-to-incident mass ratio in the case of a normal impact condition. As an example, decreasing the impact Weber number from 128 to 60 yields decreasing the mass ratio from 0.5 to 0.1.

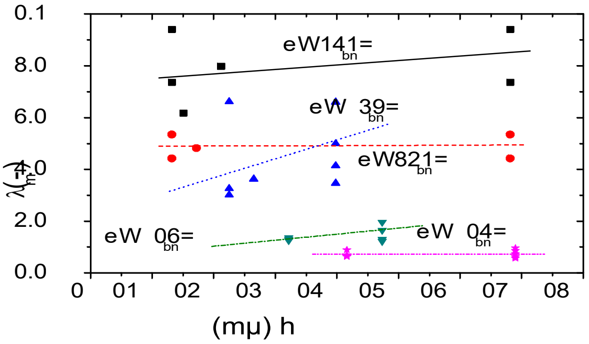


Fig. 7: Influence of the average film thickness on the total secondary-to-incident mass ratio for different constant impact Weber numbers.

Conclusions

From the conducted experiment in this study, the following final results can be concluded.

a) the splash created by a drop in a spray differs significantly from that of an isolated single drop impact or from the impact of a train of drops on a stationary liquid film; splash of a droplet in spray impact is much more irregular and non-symmetric,
b) development of crown base radius in spray impact phenomena requires longer time in compare to the crown height development,
c) the non-dimensional crown height in spray impact phenomena increases linearly with Weber number before the impact,
d) the dimensionless time required for development of the crown base radius takes about 70% longer in compare to the crown height development,
e) the impact Weber number has a strong influence on the total secondary-to-incident mass ratio in the case of a normal impact condition,
f) the average wall film thickness has non-predictable and complex influence on the total secondary-to-incident mass ratio.

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