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Evaluation of some of the existing models for droplet and spray/wall interactions

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Abstract: In this study, a critical summary of existing spray/wall interaction models is given in synergy with a review of available experimental data. In particular, special attention is devoted to the limitations, difficulties and complexities of the most used approaches in the literatures. An attempt is also made to indicate the bottlenecks and criticalities which typically arise when investigators try to extend results obtained for isolated droplets to the more complex dynamics produced by spray impacts.

Keywords: Spray impact, empirical models, multiphase flow.

1 Introduction

Spray transport phenomena with wall interactions can be typically characterized by statistical quantities obtained from size and velocity measurements over many individual droplets. The most widely used quantities are size and velocity probability density distributions as well as droplet number and related fluxes of mass and momentum. From an experimental point of view, the phase Doppler instrument is the tool traditionally used for sprays in which the drop diameter is of the order of a few microns, see e.g., Bai and Gosman (1995); Kalantari and Tropea (2005); Marengo and Tropea (1999); Mundo, Sommerfeld, and Tropea (1995); Panao and Moreira (2005). An important prerequisite for using this instrument is that the droplets must be spherical, which is generally fulfilled for droplets experiencing low aerodynamic deformation forces.

In general, there are several additional pitfalls when using the phase Doppler instrument in a spray impinging on a wall, which must be considered in the optical setup and the data processing to avoid serious bias errors. On the other hand, it has become clear that the boundary conditions on the rigid wall, e.g., size of the target, or target position related to the nozzle exit have also a significant influence in the outcome of spray impact phenomena [Kalantari and Tropea (2007a,b)].

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For some very recent results on these subjects the reader may consider Sanada, Ando, and Colonius (2011); Rundqvist, Mark, Edelvik, and Carlsson (2011); Do-Quang, Carlson, and Amberg (2011); Planchette, Lorenceau, and Brenn (2011); Oukach, Hamdi, Ganaoui, and Pateyron (2012). Some exotic behaviors have been described by Monti, Savino, Lappa, and Tempesta (1998); Savino, Paterna, and Lappa (2003); Lappa (2005).

Much of the existing models on the topic of spray impact phenomena are restricted to the normal impact of single droplets onto a solid dry or wetted wall or sometimes onto a thin liquid film (see Table 1; Kalantari and Tropea (2007a)), where generally the impact conditions can be carefully controlled, see e.g. Bai and Gosman (1995); Marengo and Tropea (1999); Bai, Rusche, and Gosman (2002); Mundo, Sommerfeld, and Tropea (1998); Stanton and Rutland (1998); Wang and Watkins (1993), and ensuing results serve as a basis for model formulations. In this Table, four different liquid film regimes are classified on the basis of a threshold K-number (K_{th}) required for the onset of splashing ($K = We \cdot Oh^{-0.4}$; $Oh = \sqrt{We/Re}$, $We = \rho u^2 d/\sigma$; We is impact Weber number, u is the velocity component before impact, and σ is the surface tension, $Re = \rho u d/\mu$; Re is impact Reynolds number and μ is the fluid viscosity).

Table 1: Classification of film thickness formed on the wall due to spray impact (Kalantari and Tropea (2007a)).

Dimensionless film thickness ($\bar{h}^*$)	Wall film condition	Variation of K_{th}	K_{th} correlation (for 70% gly/water droplets)
$\bar{h}^* \leq 0.1$	wetted wall	Constant	~1770-1840
$0.1 < \bar{h}^* \leq 1$	thin liquid film	Increasing	$5032\bar{h}^* + 1304$
$1 < \bar{h}^* \leq 2$	shallow liquid film	Decreasing	$\sim 6100(\bar{h}^*)^{-0.54}$
$\bar{h}^* > 2$	deep liquid layer	Constant (asymptotic value)	~ 4050

In practice, to illustrate the drawbacks of the models based on the single drop impact, it is enough to mention that the splash created by a drop in a spray differs significantly from that of an isolated drop impact or from the impact of a train of drops on a stationary liquid film, see e.g. Kalantari and Tropea (2007a); Sivakumar and Tropea (2002). In a spray impact phenomena, splashing crowns are mostly non-symmetric and the main source for the non-symmetry of the splash is the impact of a neighbouring droplet during the splash [Kalantari and Tropea (2007a)].

In this paper, we try to summarize some of the existing models for spray impact and single drop impact and compare the outcomes of such models.

2 Results and Discussion

In the following section a summary of some previous theoretical/empirical models for spray impact and single drop impact is presented and the related predictions are compared with experimental data.

2.1 Velocity of the ejected (secondary) droplets

Based on the work of Wang and Watkins (1993), for $We < 30$ only a rebounded droplet is observed. They also found that for $30 < We < 80$, the primary drop will break-up in two or three smaller drops rebounding from the wall. Based on their model, splash takes place for $We > 80$. This model for the normal and tangential velocity components of a rebounded droplet and its diameter (see Fig. 1) for $We < 80$ gives

$$u_a = -\kappa \cdot u_b; \tag{1a}$$

$$v_a = \kappa \cdot v_b \tag{1b}$$

where $\kappa = \sqrt{1 - 0.95 \cdot \sin^2 \theta_b}$, θ_b is being impact angle of the primary droplet, see Fig. 1. In their model $d_a = d_b$ and $N_a = 1$.

The empirical model of Bai and Gosman (1995) based on the results of single drop impact gives other expressions for the velocity of a rebounded droplet in the form of

$$u_a = -0.714 \cdot u_b; \tag{2a}$$

$$v_a = \xi \cdot v_b \tag{2b}$$

where $\xi = 0.993 - 1.7\theta_b + 1.56\theta_b^2 - 0.49\theta_b^3$; ($\theta_b$ in rad).

According to the model of Marengo and Tropea (1999), the normal and tangential velocity components of the secondary droplets generated due to single water droplets impacting onto a liquid film for the condition of $\theta_b < 10°$, $0.5 < \delta < 2$ and $K < 4000$ are (δ in this model represents the dimensionless film thickness $\delta = h_0/d_b$):

$$u_a^* = (0.056 + 0.057\delta) + 0.038 \times 10^{-3}(K - K_{C_r}), \tag{3}$$

$$v_a^* = (0.311 - 0.077\delta) - (0.009 + 0.024\delta) \times 10^{-3}(K - K_{C_r}), \tag{4}$$

where $u_a^* = u_a/u_b$, $v_a^* = v_a/u_b$ and $K = We \cdot Oh^{-0.4}$; $Oh = \sqrt{We/Re}$.

The model of Mundo, Sommerfeld, and Tropea (1995) gives the following expressions for the normal and tangential velocity components and diameter of the secondary droplets generated due to single droplets impacting onto a rigid wall. In

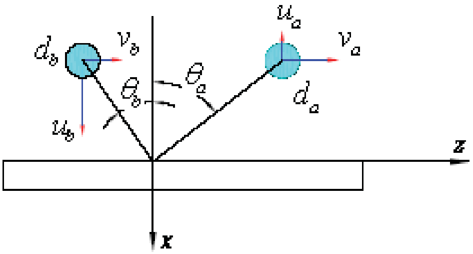

Figure 1: Nomenclature for impinging and ejecting droplets from wall; u_b and v_b are normal and tangential velocity components of the impacting droplet, respectively, θ_b is impact angle of the primary droplet. The subscript "a" stands for the ejecting droplet from the wall.

this study a rotating disk was used as a rigid wall in order to generate a tangential velocity component for a normal impacting droplet.

$$u_a = \left[1.337 - 1.318\left(\frac{d_a}{d_b}\right) + 2.339\left(\frac{d_a}{d_b}\right)^2\right] \cdot u_b \tag{5}$$

$$v_a = \left[-0.249 - 2.959\left(\frac{d_a}{d_b}\right) + 7.794\left(\frac{d_a}{d_b}\right)^2\right] \cdot v_b \tag{6}$$

where $d_a = \min[8.72\exp(-0.0281K), 1.0] \cdot d_b$; $K = Oh \cdot Re^{1.25}$. In their model splashing occurs for $K > 57.7$.

In Fig. 2 normal and tangential velocity components of the secondary droplets are plotted as a function of droplet size based on the model of Mundo, Sommerfeld, and Tropea (1995) for $d_a/d_b \leq 1$ (as considered in their model for estimating d_a). This model however overestimates the normal component of the after impact velocity, as the value of (u_a/u_b) always exceeds unity for all of the $0 \leq (d_a/d_b) \leq 1$, (Fig. 2). For $d_a/d_b \leq 0.45$, this model however gives a negative value for the ratio of tangential velocity component (v_a/v_b), see Fig. 2. The main source of this error could be the decision of neglecting the influence of the rotating disk in analyzing the experimental data. Note that the tangential velocity component before and after the impact should have the same directions, i.e., the ratio (v_a/v_b) always should be a positive value as shown schematically in Fig. 1.

Based on the results obtained by Kalantari and Tropea (2007a), the ejected magnitude of the tangential velocity component sometimes exceeds the impingement magnitude but the normal component of velocity for ejected droplets never exceeds the impingement values.

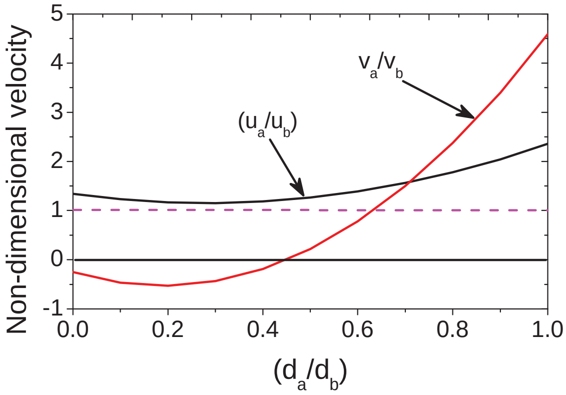

Figure 2: Normal and tangential velocity components of secondary droplets as a function of droplet size based on the model of Mundo, Sommerfeld, and Tropea (1995).

The model of Kalantari and Tropea (2007a,b) shows that the ratio of the normal component of velocity $(u_a/u_b$ decreases with increasing the Weber number (We_{nb}) based on the normal component of velocity before the impact, but the ratio of tangential component of velocity (v_a/v_b) is independent of the impact Weber number. In their model, the ratio (u_a/u_b) falls in the range $0.15 < u_a/u_b < 0.5$ for $10 < We_{nb} < 160$. This model gives a general correlation for normal component of velocity as

$$u_a/u_b = -1.1 \cdot (We_{nb})^{-0.36} \tag{7}$$

Their model gives a linear correlation between the tangential component of velocities before and after impact in the form of

$$v_a = 0.862 \cdot v_b - 0.094 \tag{8}$$

In Fig. 3 the velocity of ejected droplets for each of the normal and tangential components are compared with the experimental data based on the model of Kalantari and Tropea (2007a); Bai and Gosman (1995); Wang and Watkins (1993) for some specific spray condition, i.e., $10 < We_b < 160$ and negligible surface roughness, albeit very representative of other operational conditions. Results presented in Fig. 3a, and b indicate that the model of Wang and Watkins (1993) has a good prediction for the tangential velocity component of the secondary spray, but in contrast it gives a poor estimation of the normal velocity component. The model by Bai and Gosman (1995) gives an acceptable prediction only for the tangential velocity component, whereas the model by Kalantari and Tropea (2007a) gives a good estimation for both normal and tangential velocity components of the secondary spray. The last model has been formulated on the basis of average quantities before and after impact, i.e. results from single drop impacts are not used as a basis for the model formulation, as has been done in many previous modelling efforts. The model of Mundo, Sommerfeld, and Tropea (1995) give unrealistic estimation for both components of the velocity as explained above and illustrated in Fig. 2.

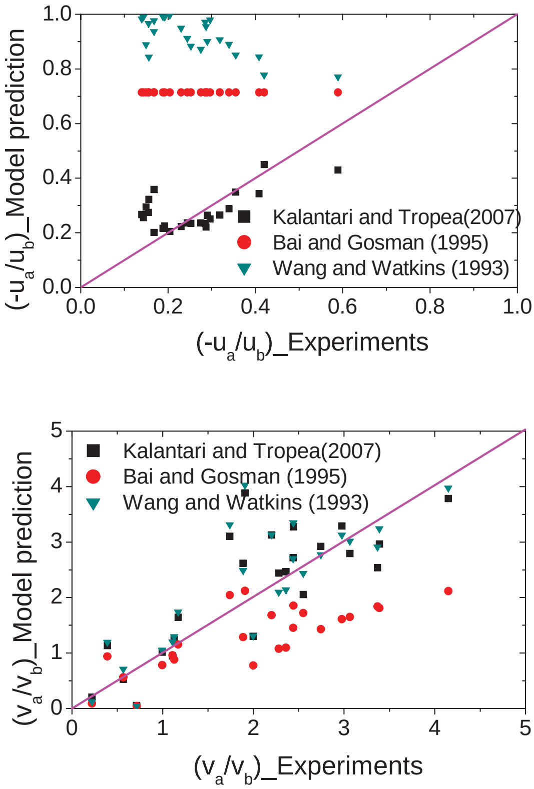

Figure 3: Comparison between the empirical models for velocity of the secondary droplets with the experimental results; a) normal component, and b) tangential component.

Examination the model of Marengo and Tropea (1999) was not possible, since the average $K-$values in this study ($K = We \cdot Oh^{-0.4}$) were less than the minimum K-values necessary to operate their model. The reason is that the micron-size droplets existing in a spray impact have very large Oh-numbers in comparison to the millimeteric droplets which were used in their experiments to derive the model; as an example a $30\mu m$ droplet has 10 times larger Oh-number in comparison to a 3 mm droplet for the same liquid. In the model of Marengo and Tropea (1999), Oh-number exists in the structure of K-value. However this model can be examined for micron-size droplets with very high impact velocities.

2.2 Ejection angle of the secondary droplets

The properties of secondary splashed droplets appear to depend strongly on the ejection time. For early ejected droplets, the ejection velocity and angle are larger. Meanwhile, the size of the ejected secondary droplets from a splashing crown increases from a minimum value to the maximum during the ejection phenomena Cossali, Marengo, Coghe, and Zhdanov (2004). The txperimental investigation by Kalantari and Tropea (2007a) indicates that ejection angle of the secondary droplets depends strongly on the impingement angle. Some of the existing models for ejection angle of the secondary droplets are given below.

Stanton and Rutland (1996)

$$\theta_a = 0.266\theta_b + 65.4^\circ \tag{9}$$

Mundo, Sommerfeld, and Tropea (1995)

$$\theta_a = 0.316\theta_b + 62.24^\circ \tag{10}$$

Kalantari and Tropea (2007a)

$$\theta_a = 0.623 \cdot \theta_b + 41^\circ \tag{11}$$

Results of these models are compared with the experimental data for spray impact and shown in Fig. 4.

2.3 Total splashing-to-incident mass and number ratio ($\lambda_m = m_a/m_b, \lambda_N = N_a/N_b$)

Total splashing-to-incident mass ratio is a complex function of several parameters such as: droplet Weber number, droplet Reynolds number, wall roughness, wall film thickness, velocity fluctuations inside the accumulated wall film, interaction between uprising jets or crowns with impacting drops or other splashing droplets and many other interactions . Based on experimental observation for single drop impact, λ_m takes a random value in the range $[0.2, 0.8]$ for a dry wall and $[0.2, 1.1]$

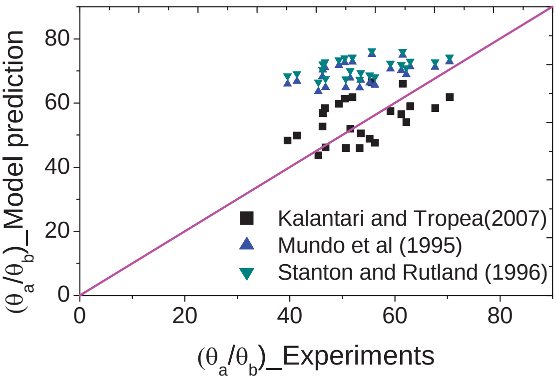

Figure 4: Comparison between the empirical models for the ejection angle of the secondary droplets with the experimental results.

for a wetted wall, Bai and Gosman (1995). According to previous work, no general correlation is available for the total splashing-to-incident mass and number ratio. This result can be written in the form of (model of Bai and Gosman (1995))

$$\lambda_m = 0.2 + 0.6rnd(1) \quad \text{for a dry wall} \tag{12}$$

$$\lambda_m = 0.2 + 0.9rnd(1) \quad \text{for a wetted wall} \tag{13}$$

where $rnd(1)$ is a random number fall in the range $(0,1)$.

Based on work done by Bai and Gosman (1995), the quantity of secondary droplets per splash can be written as

$$N_a = 5 \cdot \left(\frac{We}{We_{C_r}} - 1 \right) \tag{14}$$

where We_{C_r} is the critical Weber number for the onset of splash assumed to be $We_{C_r} = 80$.

Based on the model of Marengo and Tropea (1999), the mass of secondary droplets generated from single water drops impacting onto a moving liquid film can be written as

$$(m_a/m_b) \cong (0.36 + 0.24\delta)[(K - K_{C_r})10^{-3}]^{(2.93-1.52\delta)} \tag{15}$$

Number of secondary droplets due to a single water droplet impacting onto a moving liquid film was driven by Marengo and Tropea (1999) as

$$N_a = \max\left(0, 1 + 0.363 \cdot 2^{\beta} \cdot \left(1 + 10^{-3} \cdot \frac{K - K_{C_r}}{1 - e^{K - K_{C_r}}}\right)\right) \cdot K \cdot 10^{-3} \cdot N_b \tag{16}$$

where β defines by $\beta = (0.242 + 2.928 \cdot \delta) \cdot (K - K_{C_r})$.

Correlations obtained by Roisman, Araneo, Mareng, and Tropea (1999); Tropea and Roisman (2000) indicate that the secondary-to-incident mass flux and number flux ratios correlate with the average impact Weber number ($20 < We < 300$) in the form of

$$\frac{m_a}{m_b} = 0.302 \left[1 - \frac{1}{1 + \exp(0.0274\overline{We} - 4.442} \right] \tag{17}$$

$$\frac{N_a}{N_b} = \frac{2767}{\overline{We}^{6.7}} \exp\left[0.938(\ln \overline{We})^2\right] \tag{18}$$

Based on the above given expression, maximum value of the mass flux ratio is limited to 0.302 for a spray impact phenomena, see also e.g., Bai and Gosman (1995); Kalantari and Tropea (2007a). Another empirical model obtained by Tropea and Roisman (2000) indicates that the axial momentum flux ratio η_p, and the kinetic energy flux ratio η_e can be expressed by

$$\eta_p = 0.29\eta_m^{1.19} \tag{19}$$

$$\eta_e = 0.36\eta_m^{1.11} \tag{20}$$

However these models (Eqns. 21 and 22) neglect role (influence) of the velocity component existing inside the axial momentum or kinetic energy, i.e., $E_C = 1/2mu^2$ or $\eta_e = E_{C_a}/E_{C_b} \approx \lambda_m(\lambda_u^2)$. Such correlations however can be proposed if a significant correlation between drop size and drop velocity exists, which is not the case for ejected droplets from the wall (secondary spray), see e.g., Kalantari and Tropea (2007b).

The experimental results obtained by Kalantari and Tropea (2007b) indicate that in the case of normal impact ($\lambda_{Web} < 0.1$; $\lambda_{Web} = We_{e_{tb}}/We_{e_{nb}}$), the secondary-to-incident mass ratio (λ_m) mostly falls in the range $[0.002, 0.85]$, whereas this ratio falls in the range $[0.016, 1.12]$ for oblique impact conditions ($\lambda_{Web} \geq 0.1$). We_{nb} and We_{tb} are the impact Weber number based on the normal and tangential component of the impact velocity, respectively. The upper limit of the mass ratio in the case of oblique impact (i.e., $\lambda_m = 1.12$) clearly indicates that for some conditions more liquid mass is ejected from the wall film than impacts with the drops. Their results indicate that in the case of normal impact conditions ($\lambda_{Web} < 0.1$), the secondary-to-incident mass and number ratio, λ_m and λ_N, increase linearly with the impact Weber number based on the normal component of the impact velocity (We_{nb}).

$$\lambda_m = (m_a/m_b) = 6.74 \times 10^{-3} \cdot We_{nb} - 0.204 \tag{21}$$

$$\lambda_N = (N_a/N_b) = 2.16 \times 10^{-3} \cdot We_{nb} + 8.96 \times 10^{-2} \tag{22}$$

These correlations were derived for the impact Weber number in the range $35 \leq We_{nb} \leq 165$ and $\lambda_{Web} < 0.08$.

The model of Mundo, Sommerfeld, and Tropea (1995) indicates that the deposited mass fraction (m_{dep}/m_b) generated due to single droplets impacting onto a rigid wall (rotating disk in their experiments) is

$$\frac{m_{dep}}{m_b} = 1 - \frac{N_a}{N_b} \cdot \left(\frac{d_a}{d_b}\right)^3 \tag{23}$$

where $\min(1.676 \times 10^{-5} \cdot K^{2.54}, 1000) \cdot N_b$; $K = Oh \cdot Re^{1.25}$. In their experiments splash occurs if $K_{C_r} > 57.7$.

A comparison between the models proposed by Bai and Gosman (1995); Mundo, Sommerfeld, and Tropea (1995); Roisman, Araneo, Mareng, and Tropea (1999); Kalantari and Tropea (2007a) with the experimental results for estimation of the mass and number flux ratios are given in Fig. 5. Note that the values (m_a/m_b) and (m_a/m_b) are the same for a spray impact phenomena.

Schmehl, Rosskamp, Willman, and Wittig (1999) found a correlation for deposition rate of spray impact onto thin liquid film as

$$1 - \eta_{film} = (1 - \eta_{dry-wall})^{\cdot -h^*} \tag{24}$$

where η_{film} is deposited mass fraction in the presence of accumulated wall film, $\eta_{dry-wall}$ is deposited mass fraction for a dry wall, and $h^* = h/d_b$ is non-dimensional film thickness; h is thickness of the thin liquid film. This expression indicates that the splashed mass from the wall decreases with increasing the wall film thickness in an exponential form.

Kalantari and Tropea (2006) indicate that for a liquid spray impacting onto a rigid wall, the average wall film thickness has non-predictable and complex influence on the mass ratio in the presence of a constant impact Weber number. Their results indicate that the impact Reynolds number has a strong influence on the total secondary-to-incident mass ratio in the case of a normal impact condition.

3 Conclusions

In the present study, predictions of existing empirical models have been compared with available measurements for spray impact. Some conclusions can be given as follows:

The model by Wang and Watkins (1993) seems to properly estimate the tangential velocity component of the secondary spray, whereas it strongly overestimates

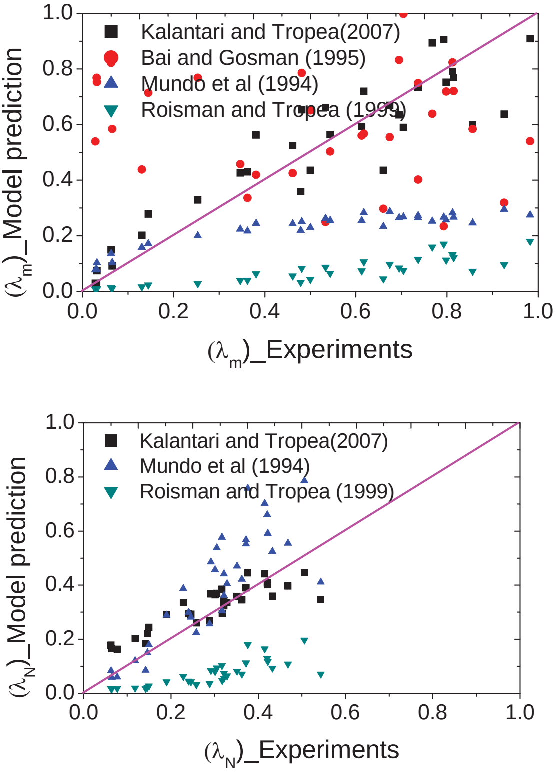

Figure 5: Comparison between the empirical models with the experimental results; a) mass flux ratio, and b) number flux ratio.

the normal velocity component. The same behavior can be seen for the model of Bai and Gosman (1995). The models proposed by Stanton and Rutland (1996) and Mundo, Sommerfeld, and Tropea (1995) slightly overestimate the trajectory angle of the secondary spray. For the secondary-to-incident mass flux ratio, the models elaborated by Kalantari and Tropea (2007a); Bai and Gosman (1995) can be used, while for the secondary-to-incident number flux ratio, the models proposed by Kalantari and Tropea (2007a); Mundo, Sommerfeld, and Tropea (1995) provide a better agreement with experimental data.

In general, none of the existing models formulated on the basis of single drop impacts can predict all characteristics of the secondary spray generated by a liquid spray impacting onto a rigid wall. Each model seems to be able to predict only a limited number (one or two) of aspects related to the secondary spray, while giving a poor estimation for other aspects. The present analysis suggests that the simple extrapolation of the results related to a single droplet impact to the case of a spray-wall interaction, by simple superposition of many individual droplets, is not a correct way to proceed. Indeed, such simplified models do not consider/predict properly numerous important effects, in particular:

- the influence of the deposited film on the secondary spray
- the tangential momentum of oblique impacting droplets that exists in the case of real spray impact conditions
- the effect of film fluctuations on the outcome of impacting droplets
- the effect of multiple droplet interactions
- the creation of the central jets and droplets due to break-up of the liquid film under impacting drops
- the creation of the central jets and droplets due to the interaction between uprising jets or crowns and impacting drops or other splashing droplets.

The model by Kalantari and Tropea (2007a) seems to show a good agreement with the experimental data for different characteristics of the secondary spray. The main reason for such good agreement is that this model has been formulated on the basis of average quantities of spray before and after impact (i.e. results from single drop impacts are not used as a basis for the model formulation).

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