Measurement, modelling and evaluation of the spray transport phenomena with wall interactions

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Abstract

In this study, summary of the some existing spray/wall interaction models are given and then evaluated with the available experimental data. Results obtained in this study address the limitations, difficulties and complexities of modeling and capturing the spray impact phenomena. This work also indicates the limitations and disadvantages of importing the results from isolated single drop to a spray impact.

Introduction

Spray transport phenomena with wall interactions are 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 fluxes, e.g., number, mass, momentum etc. Of these measurements, the phase Doppler instrument is the most widely used for sprays in which the drop diameter is mostly micron size, see e.g., [1-5]. An important prerequisite for using the phase Doppler instrument is that the droplets are spherical, which due to surface tension, is generally fulfilled for almost droplets and for droplets experiencing lower aerodynamic deformation forces. However, 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 condition of the rigid wall, e.g., size of the target, or target position related to the nozzle exit has significant influence in the outcome of spray impact phenomena, [6, 7].

Much of the existing models on the topic of spray impact phenomena usually being restricted to the normal impact of single droplets onto a solid dry or wetted wall or sometimes onto a thin liquid film, where generally the impact conditions can be carefully controlled, see e.g. [1]; [3]; [8-11], and such results serve as a basis for model formulations. To illustrate drawback of the models formulated based on the single drop impact in isolation, it is enough to mention 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, see e.g. [6]; [12]. In a spray impact phenomena, splashing crowns are mostly non-symmetric. The main source for the non-symmetry of the splash is the impact of a neighbouring droplet during the splash, [6].

Specific Objectives

In this paper, we will try to

- Summarize some of the previous models for spray impact and single drop impact,
- compare the outcome of drop impact in isolation and in a spray, and determine the source of differences between impact of a droplet in isolation and in a spray, and
- evaluate the existing spray/wall interaction models formulated based on the outcome of single drop impacts in isolation and based on the mean statistics over many events in the spray.

Results and Discussion

In the following section a summary of the some previous models for spray impact and single drop impact is presented and the results are compared with the experimental results.

Velocity of the ejected (secondary) droplets

Based on the work of Wang and Watkins (1993) [11], 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

$$u_a = \kappa . u_b ,\quad v_a = -\kappa . v_b \qquad \text{(1a, b)}$$

where $\kappa = \sqrt{1 - 0.95 \cdot \sin^2 \theta_b}$.

$$d_a = d_b \qquad (2)$$

$$N_a = 1 \qquad (3)$$

The empirical model of Bai and Gosman (1995) [1] based on the results of single drop impact gives other expressions for the velocity of a rebounded droplet in the form of

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$$u_a = 0.714.u_b,\ v_a = \xi.v_b \qquad (4a, b)$$

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

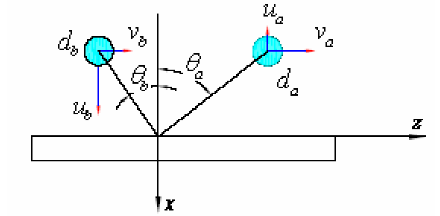

Fig. 1: Nomenclature for impinging and ejecting droplets from wall.

According to the model of Marengo and Tropea (1999) [3], 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 $\delta=h_0/d_b$):

$$u_a^{\ *} = (0.056 + 0.057\delta) + 0.038 \cdot 10^{-3}(K - K_{Cr}) \qquad (5)$$

$$v_a^{\ *} = (0.311 - 0.077\delta) - (0.009 + 0.024\delta) \cdot 10^{-3}(K - K_{Cr}) \qquad (6)$$

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 et al. (1995) [4] 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 this study a rotating disk was used as a rigid wall in order to generate a tangential velocity component for a normal impacting droplet.

$$u_a = \left[1.337 - 1.318\left(\frac{d_a}{d_b}\right) + 2.339\left(\frac{d_a}{d_b}\right)^2\right] \cdot u_b \qquad (7)$$

$$v_a = \left[-0.249 - 2.959\left(\frac{d_a}{d_b}\right) + 7.794\left(\frac{d_a}{d_b}\right)^2\right] \cdot v_b \qquad (8)$$

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

In Fig. 2 normal and tangential velocity components of the secondary droplets as a function of droplet size are plotted based on the model of Mundo et al (1995) for $d_a/d_b \le 1$, 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 $0 \le (d_a/d_b) \le 1$, (Fig. 2). For $d_a/d_b \le 0.45$, 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 can be in neglecting influence of the rotating disk in analyzing the experimental data.

Based on the results obtained by [6], 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.

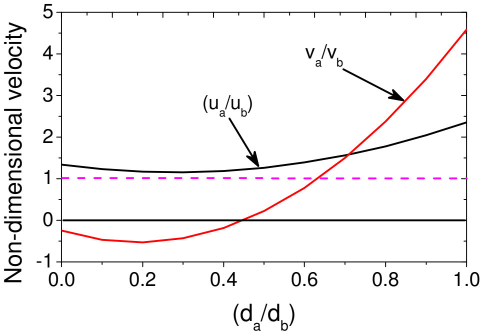

Fig. 2: Normal and tangential velocity components of secondary droplets as a function of droplet size based on the model of Mundo et al (1995).

The model of Kalantari and Tropea (2007) [6] shows that the ratio of the normal component of velocity (u_a/u_b) decreases with increasing 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_{na}/u_{nb}) falls in the range $0.15< u_{na}/u_{nb} <0.5$ for $10<We_{nb}<160$. This model gives a general correlation for normal component of velocity as

$$u_a/u_b = -1.1 \cdot (We_{nb})^{-0.36} \qquad (9)$$

, and a linear correlation between the tangential component of velocities before and after impact in the form of

$$v_a = 0.862 \cdot v_b - 0.094 \qquad (10)$$

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, 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 gives a poor estimation for the normal velocity component. Model of Bai and Gosman (1995) gives only an acceptable prediction for the tangential velocity component, whereas model of 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. Model of Mundo et al (1995) give unrealistic estimation for both components of the velocity as explained above and illustrated in Fig. 2.

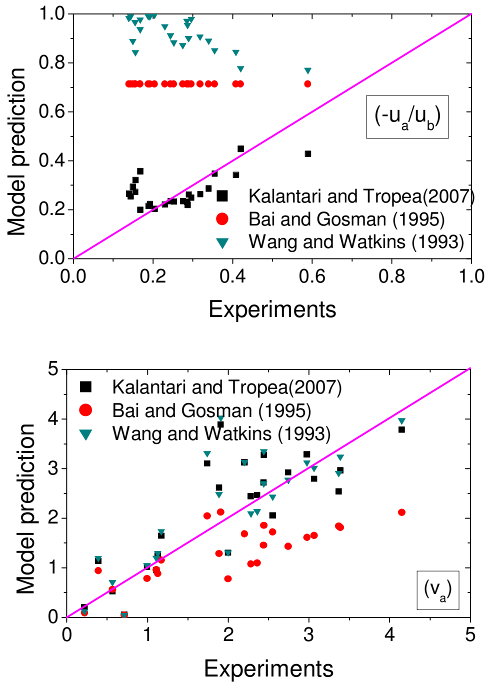

Fig. 3: Comparison between the empirical models for velocity of the secondary droplets with the experimental results; a) normal component, and b) tangential component.

Examination the model of Marengo and Tropea (1999) was failed, 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 compare to the millimeteric droplets which used in their experiments to derive the model; as an example a 30 μm droplet has 10 times larger *Oh*-number in compare 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

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, size of the ejected secondary droplets from a splashing crown increases from a minimum value to the maximum during the ejection phenomena [13]. Experimental investigation of [6] 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) [14]

$$\theta_a = 0.266\theta_b + 65.4^\circ \tag{11}$$

- Mundo et al. (1995) [4]

$$\theta_a \cong 0.316\theta_b + 62.24^\circ \tag{12}$$

- Kalantari and Tropea (2007a) [6]

$$\theta_a[^\circ] = 0.623\cdot\theta_b[^\circ] + 41^\circ \tag{13}$$

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

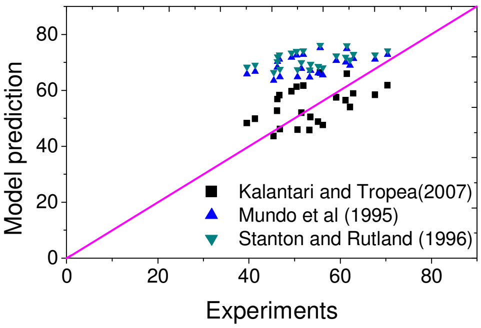

Fig. 4: Comparison between the empirical models for the ejection angle of the secondary droplets with the experimental results.

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 *We* number, droplet *Re* or *La* number, wall roughness and wall film thickness. 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] for a wetted wall, Bai and Gosmn (1995) [1]. 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

$$\lambda_m = 0.2 + 0.6rnd(1) \quad \text{for a dry wall} \tag{14}$$

$$\lambda_m = 0.2 + 0.9rnd(1) \quad \text{for a wetted wall} \tag{15}$$

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

$$\mathrm{N_a} = 5\cdot\left(\frac{\mathrm{We}}{\mathrm{We_{Cr}}} - 1\right) \tag{16}$$

where We_{Cr} is the critical Weber number for the onset of splash assumed to be We_{Cr}=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

$$(m_a/m_b) \cong (0.36 + 0.24\delta)\left[(K - K_{cr})10^{-3}\right]^{(2.93-1.52\delta)} \tag{17}$$

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

$$\mathrm{N_a} = \max\left(0{,}1 + 0.363 \cdot 2^{\beta} \cdot \left(1 + 10^{-3} \cdot \frac{\mathrm{K} - \mathrm{K_{Cr}}}{1 - e^{\mathrm{K}-\mathrm{K_{Cr}}}}\right)\right) \cdot \mathrm{K} \cdot 10^{-3} \cdot \mathrm{N_b} \tag{18}$$

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

Correlations obtained by Roisman et al. (1999) [15] and Tropea and Roisman (2000) [16] 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

$$\frac{\dot{\mathrm{m}}_{\mathrm{a}}}{\dot{\mathrm{m}}_{\mathrm{b}}} = 0.302\left[1 - \frac{1}{1 + \exp\left(0.0274\overline{\mathrm{We}} - 4.442\right)}\right] \tag{19}$$

$$\frac{\dot{\mathrm{N}}_{\mathrm{a}}}{\dot{\mathrm{N}}_{\mathrm{b}}} = \frac{2767}{\overline{\mathrm{We}}^{6.7}} \exp\left[0.938\left(\ln \overline{\mathrm{We}}\right)^{2}\right] \tag{20}$$

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., [1], [6]. 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

$$\eta_p = 0.29\eta_m^{1.19} \tag{21}$$

$$\eta_e = 0.36\eta_m^{1.11} \tag{22}$$

However these models neglect role (influence) of the velocity component existing inside the axial momentum or kinetic energy. 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., [7].

Experimental results obtained by [7] indicates that in the case of normal impact ($\lambda_{\mathrm{Web}}<0.1$; $\lambda_{\mathrm{Web}}=We_{\mathrm{tb}}/We_{\mathrm{nb}}$), 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 ($\lambda_{\mathrm{Web}}\geq 0.1$). The upper limit of the mass ratio in the case of oblique impact (i.e., $\lambda_{\mathrm{m}}=1.12$) 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 ($\lambda_{\mathrm{Web}}<0.1$), the secondary-to-incident mass and number ratio, $\lambda_{\mathrm{m}}$and λ_{N}, increase linearly with the impact Weber number based on the normal component of the impact velocity (We_{nb}).

$$\lambda_m = (\dot{m}_a / \dot{m}_b) = 6.74\times10^{-3} \cdot We_{nb} - 0.204 \tag{23}$$

$$\lambda_N = (\dot{N}_a / \dot{N}_b) = 2.16\times10^{-3} \cdot We_{nb} + 8.96\times10^{-2} \tag{24}$$

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

Model of Mundo et al. (1995) indicates that the deposited mass fraction (m_{dep}/m_b) generated due to single droplets impacting onto a rigid wall (rotating disk in this experiments) is

$$\frac{\mathrm{m_{dep}}}{\mathrm{m_b}} = 1 - \frac{\mathrm{N_a}}{\mathrm{N_b}} \cdot \left(\frac{\mathrm{d_a}}{\mathrm{d_b}}\right)^{3} \tag{25}$$

where $\mathrm{N_a}=\min(1.676\times10^{-5}\cdot \mathrm{K}^{2.54},1000)\cdot \mathrm{N_b}$; $K=Oh\cdot Re^{1.25}$. In their experiments splash occurs if $K_{\mathrm{Cr}}>57.7$.

A comparison between the models proposed by Bai and Gosman (1995), Mundo et al (1994), Roisman and Tropea (1999) and 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 ($\dot{m}_a/\dot{m}_b$) and (m_a/m_b) are the same for a spray impact phenomena.

Schmehl et al. (1999) [17] found a correlation for deposition rate of spray impact onto thin liquid film as

$$1 - \eta_{\mathrm{film}} = \left(1 - \eta_{\mathrm{dry-wall}}\right) \cdot e^{-h^{*}} \tag{26}$$

where η_{film} is deposited mass fraction in the presence of accumulated wall film, $\eta_{\mathrm{dry\text{-}wall}}$ 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 splashed mass from the wall decreases with increasing the wall film thickness in an exponential form.

Results obtained by Kalantari and Tropea (2006) [18] 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 Weber number has a strong influence on the total secondary-to-incident mass ratio in the case of a normal impact condition.

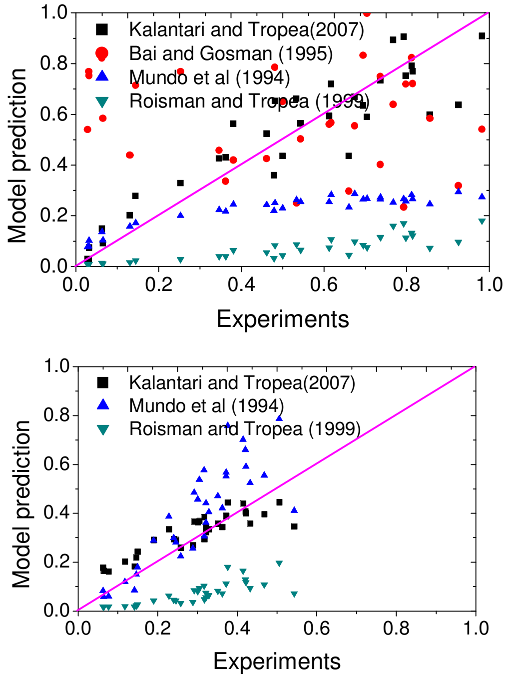

Fig. 5: Comparison between the empirical models with the experimental results; a) mass flux ratio, and b) number flux ratio.

Conclusions

In the present study, predictions of the previous empirical models are compared with the available measurement results for spray impact conditions. The model of Wang and Watkins (1993) properly estimates the tangential velocity component of the secondary spray, whereas strongly overestimates the normal velocity component. The same behavior can be seen for the model of Bai and Gosman (1995). Models proposed by Stanton and Rutland (1996) and Mundo et al. (1995) slightly overestimates trajectory angle of the secondary spray. For the secondary-to-incident mass flux ratio, the models given by Kalantari and Tropea (2007a) and Bai and Gosman (1995) can be used, whereas for the secondary-to-incident number flux ratio models proposed by Kalantari and Tropea (2007a) and Mundo et al (1995) are in good agreements with the measurement data used in this study.

In general, none of the existing models formulated based on the results of single drop impact can predict all characteristics of the secondary spray generated by a liquid spray impact onto a rigid wall. Each of the existing models predicts only one or two aspects of the secondary spray but on the other hand, gives a very poor estimation for other aspects of the secondary spray. These results suggest that simply extrapolation the results of single droplet impact to the case of a spray-wall interaction by simple superposition of many individual droplets is not a correct way in modelling spray/wall interaction, since such simplified models neglect to consider numerous effects regarding spray-wall interaction such as 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; effect of film fluctuations on the outcome of impacting droplets; effect of multiple droplet interactions and also the creation of the central jets and droplets due to break-up of the liquid film under impacting drops or to the interaction between uprising jets or crowns with impacting drops or other splashing droplets.

In overall, model of Kalantari and Tropea (2007a) shows a good agreement with the experimental data for different characteristics of the secondary spray. This 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.

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