1. INTRODUCTION

In an overall effort to model the impact of liquid sprays onto rigid walls, it has become apparent in recent years that the liquid film formed on the surface plays an important role in determining the velocity and size of ejected droplets as well as the deposited mass fraction [1, 2]. Formation of the wall film often being neglected in spray impact models. However, prediction of average film thickness and average velocity is very important for many industrial applications, especially involving spray cooling systems or for fuel injection sprays onto heated walls because these parameters significantly affect the efficiency of heat transfer in the sprayed surfaces. In some technical applications, it is desirable to eliminate the deposited film on the wall as far as possible, e.g. in internal combustion engines, whereas in some cases the maximum deposition is required, e.g. in spray coating, spray painting or agricultural sprayers. On the other hand, the induced fluctuations in liquid layer formed on the rigid walls may decrease the quality of coated or painted surfaces. Meanwhile, the average film thickness can affect the properties of secondary spray, splashing threshold, ejected mass and number of secondary droplets. It is shown by Cossali et al. (1997) that in the case of a single drop impact onto a stationary liquid film, the number of secondary droplets decreases as the depth of liquid layer is increased. For indicating the influence of the average liquid film thickness on the splash limiting criterion, several expressions have been introduced, e.g. \( K_{Cr} = 2100 + 5880 \cdot \overline{h} \) \( (\overline{h} = \overline{h} / d_0) \), where \( \overline{h} \) is the average film thickness) by Cossali et al. (1997), or \( K_{Cr} = 354 + 1366\overline{h} \) for \( 0.1 < \overline{h} \leq 1 \) by Kalantari and Tropea (2006) based on the measurements data obtained by Wang and Chen (2002). In these criteria, splashing occurs if: \( K = Oh \cdot Re^{0.25} > K_{Cr} \), where \( Oh \) is Ohnesorge number defined as: \( Oh = \sqrt{We / Re} \). Furthermore it seems that the velocity fluctuations inside the accumulated wall film have an influence on the splashing phenomenon, since in a spray impact the crown base radius exhibits a growth rate proportional to \( (r' - r_g)^n \); \( 0.2 \leq n_g \leq 0.32 \), significantly different than that of a single or train of single droplets impacting onto an undisturbed liquid layer, \( - (r' - r_g)^{0.5} \), as investigated theoretically by Yarin and Weiss (1995).

The present work is an experimental study of the liquid film under various well-defined spray conditions in which both the impinging and the secondary spray characteristics are captured. The experimental results are complemented by theoretical expressions regarding the hydrodynamics of liquid films under sprays and preliminary models for the average wall film thickness and secondary spray are formulated.

2. EXPERIMENTAL SET-UP

The experimental set-up used in this work is pictured in Fig.1. The spray was created using two different full cone nozzles from Spraying System Co., operated at pressures between 3 and 7 bars. Both flow rate and pressure during the experiments were variable and measured. Two different stainless steel targets with diameter of 5mm and 15mm (D=5 and 15mm) have been used in this study, using the end face of the cylinders.
instrument from Dantec Dynamics was used, comprising a transmitting optics with a 400mm focal length, a receiving optics with a 310mm focal length, and an “A” type mask at a 34° scattering angle. By using a dual-mode configuration both normal and tangential velocity components of each individual droplet and its diameter were measured 0.5mm or 1mm above each target (e.g., x= -1mm) based on the target diameter. The ingoing and outgoing droplets are distinguished using the sign of the velocity component normal to the target, i.e. positive u denotes an impacting droplet and a negative u denotes a secondary droplet. The overall size distributions were corrected for the size dependent detection volume cross-section using the standard system software. Experimentally the film has been characterised using a high-speed CCD camera. The average wall film thickness \( h \) is obtained by averaging over several instantaneous images after first removing the reference wall image. Another high-speed camera with 32k fps has been used to determine the film fluctuations and to follow the deposited or ejected droplets from the wall.

3. FORMATION OF THE WALL LIQUID FILM

In general, spray impingement on walls is characterized by the two different structures: 1) the generated secondary spray, and 2) the accumulated liquid wall film, see Fig. 2. The thickness of the accumulated wall film varies between microns to millimetres, depending on the condition of impacting spray and the boundary conditions on the target. Experimentally it is equally important to also capture the prevailing boundary conditions for any particular film, which in this case comprises the physical boundaries of the rigid surface, e.g. spherical target, flat plate, deep pool etc., and the characteristics of the impacting spray in terms of velocity, size and number density of impacting droplets.

Formation of the liquid film on a rigid-flat wall due to spray impact can be divided into the two different regions (Fig.1); (i) Impingement region that is under influence of the impacting droplets and has lower thickness, and (ii) Outer region that is free of any impact phenomena. Film flow in this region depends on the film Reynolds number; \( \text{Re}_f = \frac{\rho u_f \cdot h}{\mu} \), and can be either laminar or turbulent.

Characterization of the accumulated wall liquid film can be achieved using:
- average film thickness \( \bar{h} \)
- average spreading film velocity \( \bar{u}_f \)
- velocity fluctuations inside the accumulated liquid film \( \bar{u}_f \)

The average film thickness depends on the several parameters of the impacting spray; normal and tangential component of impact velocity \( u_n \) and \( u_t \), flux density of impacting spray \( \dot{q} = q / A \); “\( q \)” and “\( A \)” to be flux of the impacting spray and the reference area over which flux is measured), volume-averaged diameter of impacting droplets \( D_{32b} \), and viscosity of the liquid used in spray \( \mu \) and also the boundary condition of the target; average target surface roughness \( \bar{\varepsilon} \), where \( \bar{\varepsilon} = \varepsilon / D_{10b} \) and target size \( D \). A general expression for the average film thickness can be written as

\[
\bar{h} = \psi \left( u, v, D_{32b}, \dot{q}, \mu, \varepsilon, D_{\text{spray}} / D \right)
\]

where, \( D_{\text{spray}} \) is the diameter of the effective impinging spray on the target defined as: \( D_{\text{spray}} = 2x_{\text{nozzle}} \cdot \tan(\alpha / 2) \), \( \alpha \) is the spray cone angle. The parameters \( u, v, D_{32b}, \dot{q} \), and \( D_{\text{spray}} \) vary with nozzle pressure and nozzle height above the target. The three first parameters may can be combined into an impact Reynolds or Weber number. However \( q \) is not an independent parameter and depends also on the impact Weber number, since flow rate of a atomizer and atomizing pressure (\( P \)) which influences the impact Weber number, are connected to each other with a power law: \( q \sim P^{0.5} \). This dependency can be obtained theoretically by considering the Bernoulli’s equation for inside and outside of the atomizing nozzle or experimentally as examined in this study.

Two exemplary images of thin liquid film formed on the rigid surface are presented in Fig.3, for a relative sparse spray (a) and for a relative dense spray (b). It is apparent from these sample images that in describing the hydrodynamics of the film, e.g. velocity fluctuations inside the film, the capillary pressure will be non-negligible. Furthermore, the local film velocity will be an important parameter determining the outcome of any single drop impact event.

Fig.2: Impingement and outer region of thin liquid film formed under spray impact

Fig.3a, b: Sample images of the liquid film interface formed under spray impact: a) relatively sparse spray, b) relatively dense spray.
Assuming that spray and liquid film formed on the wall are isotropic in the Y-Z plane, the continuity equation of the film thickness for both regions can be written in the form of

\[ \frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial z} + \frac{\partial (hv)}{\partial x} = \Gamma_w \]

(2)

and the momentum equation is

\[ \frac{\partial (pu)}{\partial t} + \frac{\partial (pau)}{\partial z} + \frac{\partial (pav)}{\partial x} = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 u}{\partial z^2} + \frac{\partial^2 u}{\partial x^2} \right) + \rho g \]

(3)

In the following sections, different source of the pressure term (P), influence of the gravity term (g) and mass source term (\(\Gamma_w\)) of the wall film will be discussed in more details.

### 3.1. Hydraulic pressure source in the wall liquid film

The source of the pressure term for the liquid film is

\[ P = -P_\sigma + P_s + P_{\text{hyd}} \]

(4)

Where \(P_\sigma\) is the Laplace pressure due to the curvature of the air-liquid film interface, \(P_s\) is the pressure exerted from the ambient gas (air flow) onto the air-liquid interface and \(P_{\text{hyd}}\) is the hydrodynamic pressure exerted from impacting droplets. The hydrodynamic pressure produced by the impinging droplets is the main source responsible for spreading out and thinning of the liquid wall film in the impingement region.

On the other hand, the non-continuous nature of the impacting droplets causes the wavy form of the spreading liquid film interface in both regions (Fig.2 and Fig.3), therefore the capillary pressure gradient (\(P_\sigma\)) arises from film interface curvature either in the inner or in the first part of the outer zone, expressed by

\[ P_\sigma = -\frac{\sigma}{\left(1 + (dh/dz)^2\right)^{3/2}} \frac{\partial^2 h}{\partial z^2} \]

(5)

To a first approximation, we may neglect the nonlinear terms involving the slope of the liquid-air interface to have a simpler and linear set of conditions at the interface, yielding

\[ P_\sigma = -\sigma \frac{\partial^2 h}{\partial z^2} \]

(6)

In the second part of the outer region (ii\(_b\)), the Laplace pressure induced by the curvature of the air-liquid film interface are stabilized and all fluctuations are negligible, since the wavy surface has been stabilized. With such assumptions derived above, the velocity profile in the second part of the outer region can be considered in a quasi-steady-state form.

The main factor responsible for the spreading and thinning of the liquid film in the impingement region is the hydrodynamic impingement pressure generated by the impacting droplets. The normal component of the hydrodynamic force exerted on the wall by an impacting drop is given by

\[ F_{\text{hyd}} = \left( m_b \cdot u_b - m_a \cdot u_a \right) / t \]

(7)

where subscripts a and b refer to after and before impact, respectively.

Defining the volume flux of the impacting drop by \(q = V / t\), Eq. (7) can be rewritten as

\[ F_{\text{hyd}} = \rho \left( q_b \cdot u_b - q_a \cdot u_a \right) \]

(8)

Assuming that the rebounding drop has the same size and velocity as that of the primary drop, i.e. \(d_a = d_b\) and \(u_a = -u_b\); then the hydrodynamic pressure \((P_{\text{hyd}} = F_{\text{hyd}} / A)\) exerted on the wall by a rebounding drop is

\[ P_{\text{hyd-reb}} = 2 \rho q_b u_b \]

(9)

where \(q\) is the flux density of impacting droplets, defined as: \(q = q / A\). The same procedure for a deposited droplet gives

\[ P_{\text{hyd-dep}} = \rho q_b u_b \]

(10)

In the case of a spray impact, some droplets rebound, some other deposit on the wall, whereas some of them splash, therefore a constant factor \(\beta\) depending on the number of rebounding or depositing droplets should be considered for hydrodynamic pressure exerted on the wall by an impacting spray, defined as

\[ P_{\text{hyd}} = \beta \cdot \rho \cdot \dot{q} \cdot \bar{u}_b \cdot q ; 1 < \beta < 2 \]

(11)

For a spray, the coefficient \(\beta\) can be estimated based on the number of ejected droplets from the wall in comparison to all the primary droplets, defined as

\[ \beta = 1 + N_{\text{dep}} / N_b \]

(12)

As an asymptotic condition, if all of the impacting droplets rebound from the wall or deposit on the wall, then the expression (12) gives \(\beta = 2\) or \(\beta = 1\), respectively. A value between 1 and 2 accounts implicitly also for those droplets which result in partial deposition. In the case of a normal impact condition \((\lambda_{uv} < 0.1)\), the ratio \(N_{\text{dep}} / N_b\) can be estimated as, see Fig.4.
\[ \lambda_N = (N_a/N_b) = 2.16 \times 10^{-3} \cdot We_{nb} + 8.96 \times 10^{-2} \]  

(13)

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

(15)

The correlations (13) and (15) were derived from numerous measurements conducted in the range \( 35 \leq We_{nb} \leq 165 \) and \( \lambda_{m_{wb}} < 0.08 \), Figs 20a and b.

3.2. Influence of the gravity in the wall liquid film

In general, the shape of the air-liquid film interface is determined by the capillary (Laplace) length, defined by

\[ L_c = \sqrt{2\sigma / (\rho g)} \]  

(14)

If the capillary length is large compared to the dimensions of the system, i.e. depth of the liquid film, then gravity does not play a significant role in determining the shape of the air-liquid film interface and hydrodynamics of the liquid film. As an example, the typical film thickness in this study was in the range \( 10 \mu m \leq h \leq 110 \mu m \). Considering the average depth of the liquid film equal to \( 60 \mu m, \sigma = 73 \times 10^{-3} N/m \) and \( \rho = 1000 kg/m^3 \) for water droplets, the dimensionless capillary length gives \( L_c / h = 200 >> 1 \), suggesting that the gravity can be neglected in the hydrodynamics of the spreading liquid film in this study. The same condition is consistent for most of the inertial spray impacting onto a rigid-flat surface. Neglecting the unnecessary gravity term in hydrodynamics of a spreading liquid film can significantly reduce the time required for the numerical computations.

3.3. Mass source term of the wall liquid film (\( \Gamma_m \))

Results obtained in this study indicate that in the case of a normal spray impact (\( \lambda_{w_{wb}} < 0.1 \)), the secondary-to-incident mass ratio (\( \lambda_{m_{wb}} \)) mostly falls in the range \([0.002, 0.85]\), whereas this ratio falls in the range \([0.016, 1.12]\) for oblique impact conditions (\( \lambda_{w_{wb}} \geq 0.1 \)).

The results also indicate that in the case of a normal impact condition (\( \lambda_{w_{wb}} < 0.1 \)), the secondary-to-incident mass and number ratio, \( \lambda_m \) and \( \lambda_N \), increase linearly with the impact Weber number based on the normal component of the impact velocity (\( We_{nb} \)).

\[ \lambda_N[\%] = 0.216 We_{nb} + 8.96 \]  

Fig.4: Total secondary-to-incident number ratio as a function of impact Weber number based on the normal velocity component.

\[ \lambda_m[\%] = 0.674 We_{nb} - 20.4 \]  

Fig.5: Total secondary-to-incident mass ratio as a function of impact Weber number based on the normal velocity component.

Therefore, the mass source term of the wall liquid film in governing continuity equation (2) can be expressed as

\[ \Gamma_m = m_{dep} / (\rho A) = q_{dep} \]  

(16)

where \( m_{dep} = 1 - m_b \) for the inner region of the wall liquid film and can be obtained from (15) as

\[ m_{dep} = (1 - \lambda_m) \cdot m_b \]  

(17)

Therefore the mass source term for inner region can be expressed in the form

\[ \Gamma_m = (1 - \lambda_m) \cdot q_b \]  

(18)

For the outer region of the liquid film, \( \Gamma_m = 0 \).

4. ASYMPTOTIC SOLUTION FOR THE WALL FILM THICKNESS

In the impingement region of a sparse, symmetric and stationary spray, we may assume that the frequency of the impacting drops low enough, such that the velocity fluctuations inside the film and also the air-liquid film interface fluctuations are damped out (\( \lambda \gg h \) or \( \varepsilon \ll h \), see Fig 6a) between the impact of two neighbor droplets. Under these conditions, the Laplace pressure arising from air-liquid film interface can be neglected. We may assume that the velocity inside the liquid film has only a horizontal component (\( u_f \)), therefore the continuity equation can be
simplified as

\[
\int_0^L \bar{u}_f \cdot dh = \int_0^L (1 - \lambda_m) \cdot q_b \cdot dz \tag{19}
\]

which after integrating yields

\[
\bar{h} = (1 - \lambda_m) \cdot q_b \cdot L \bar{u}_f \tag{20}
\]

where \( L \) is size of the control volume in Z-direction, i.e. diameter of the impact area on the rigid target exposed to the impacting spray. On the other hand, the momentum equation of the wall film yields

\[
- \frac{\partial P}{\partial z} + \mu \left( \frac{\partial^2 u}{\partial x^2} \right) = 0 \tag{21}
\]

Fig. 6a, b: a) Curvature of the liquid film-air interface, and b) Control volume (C.V.) for a spreading wall liquid film.

One possible solution for this differential equation (21) can be derived by considering that both terms of the equation are constant. After inserting the boundary condition \( (z = 0, u = 0) \) and \( (z = \bar{h}, \sigma_{zz} = \mu \frac{\partial u}{\partial z} = 0) \), (21) yields

\[
u_f = A(\bar{h}x - x^2 / 2) \quad ; \quad A = \frac{1}{\mu} \left( \frac{\partial P}{\partial z} \right) \tag{22a, b}
\]

where \( u_f = \bar{u}_f + u_f \cdot \). With the help of (22), the average velocity inside the liquid film can be expressed as

\[
u_f = \frac{1}{\bar{h}} \int_0^\bar{h} A(\bar{h}x - x^2 / 2) dx = \frac{1}{3} A \bar{h}^2 \tag{23}
\]

Substituting the obtained expression (23) inside Eq. (20), we obtain

\[
\bar{h} = 3\mu \cdot (1 - \lambda_m) \cdot q_b \cdot L \left( \frac{dP}{dz} \right)^{-1} \tag{24}
\]

However this expression is difficult to use for estimating the average thickness of the deposited liquid film, because the values of \( dP/dz \) must be first estimated. Neglecting the pressure terms associated with the ambient gas flow and from the Laplace pressure, and assuming a simple form \( dP/dz = C_i \cdot P_{hyd}/L \), (24) yields

\[
\bar{h} = C \left[ 3\mu \cdot (1 - \lambda_m) \cdot q_b \cdot L^2 \cdot P_{hyd} \right]^{1/3} \tag{25}
\]

In this expression, the coefficient \( C \) \( (C = C_i^{1/3}) \) depends on the surface roughness, wall temperature and maybe the surface material, found to be equal to 20 for the measurements reported in this study.

In the case of an inertial spray impact, i.e. \( \text{We}/\sqrt{\text{Re}} \gg 1, \) and using the dimensional analysis Eq. (1) for characterizing the average film thickness accumulated on the wall due to spray impact, the following find expression can be derived:

\[
\left( \frac{\bar{h}}{d_{30b}} \right) = \left[ \left( \frac{1}{\text{Re}_b} \right) \left( \frac{q_i}{u_i} \right) \right] \tag{26}
\]

This is as far as dimensional analysis can predict. In this expression, \( d_{30b} \) is the volume averaged droplet diameter defined as:

\[
d_{30b} = \sum_{i=1}^N d_i^b / \sum_{i=1}^N d_i^2 \cdot .
\]

An asymptotic solution of the average wall film thickness for a relative sparse spray can be obtained from result of a single drop impact onto a flat-rigid surface if the time period between the impacting droplets is much larger than the time scale required for complete spreading of the deposited liquid droplet (Fig. 7). This can be expressed in the following term

\[
\overline{T_{i,i-1}} \gg \tau_{sp} \cdot d_{dep} \cdot \bar{u}_{dep} \tag{27}
\]

where \( \overline{T_{i,i-1}} \) is the average time period between the two neighbour impacting droplets, i.e. indicating the frequency of the impacting droplets \( (\tau = 1/\overline{T_{i,i-1}}) \). Also \( \tau_{sp} \) is the dimensionless time required for complete spreading of the deposited droplet, \( d_{dep} \) and \( \bar{u}_{dep} \) are the average diameter and velocity of the deposited droplets before the impact, respectively. Dimensionless time \( \left( \tau_{sp} \right) \) required for complete spreading stage is 8/3 found by Pasandideh-Fard et al. (1996) or \( (\text{We}/6)^{0.5} \) proposed by Fedorchenko and Wang (2004).
In the case of a single drop impact, results of theoretical work [8] indicates that impact of a single droplet onto a flat-rigid wall produces a splat with the maximum dimensionless diameter of

$$\xi = \frac{D_{\text{max}}}{d_0} = \sqrt[3]{\frac{We + 12}{3(1 - \cos \theta_{ad}) + 4We} Re}$$ \hspace{1cm} (28)

Experimental observations indicate that the maximum advancing dynamic contact angle ($\theta_{ad}$) mostly falls in the range $110^\circ \leq \theta_{ad} \leq 140^\circ$ for different liquid droplets and will be considered equal to $110^\circ$ for a water droplet impinging onto the rigid surface [8].

Considering the Reynolds number outside from (26), yielding

$$h_{\text{ad}} \simeq h_{\text{fs}} \equiv \sqrt{30} Re$$ \hspace{1cm} (27)

In the conducted measurements in this study, the ratio $We/\sqrt{Re}$ falls in the range; $3.5 < We/\sqrt{Re} < 16$.

It is interesting to note that based on the work of Roisman et al. [9], the crown lamella thickness ($h_\epsilon$) is expressed in the form of $h_\epsilon/d_0 = 0.9Re^{-1/3}$ for low impact Reynolds numbers and in the form of $h_\epsilon/d_0 = 6.3Re^{-1/2}$ for high impact Reynolds numbers. Based on this result and Eq. (31) for dimensionless film thickness on the wall due to a single drop impact, we may emphasize Reynolds number as a scaling parameter of droplet outcome dynamics.

One simple form of the (32) can be written as

$$\bar{h} = \alpha \cdot d_{300} \cdot Re_b^{-1/2} \left( \frac{q}{u_b} \right)^\gamma$$ \hspace{1cm} (33)

Where $\alpha$ and $\gamma$ are constant values found to be 4 and -0.5, respectively. These constants have been found based on the measured data in this study for a stainless steel target with 5 mm in diameter ($D = 5mm$), negligible surface roughness ($\varepsilon^* \ll 1$ and $\varepsilon^* \ll \bar{h}$) and normal impact condition ($\lambda_{ad} \leq 0.023$).

### 4. RESULTS AND DISCUSSION

The dimensionless average film thickness accumulated on the flat-rigid wall as a function of Reynolds number before the impact is presented in Fig. 8 together with the predictions obtained from Eq. (25). Results in this figure indicate that the dimensionless average film thickness decreases significantly with the Reynolds number before the impact. Results presented in this figure also indicate that the theoretical prediction presented in this study (Eq. (25)) yield good agreement with the experimental data, mostly for the thin liquid film condition, $\bar{h} \leq 1$ [6]. In the experiments presented in this figure (Fig. 8), the normal velocity component varies in the range $8 \text{ m/s} \leq u_b \leq 18 \text{ m/s}$, the flux density of the impacting spray varies in the range $0.5 \text{ m/s} \leq q_b \leq 16 \text{ m/s}$, and the volume averaged droplet size varies in the range $53 \mu m \leq d_{300} \leq 75 \mu m$. The coefficient $C$ is found to be 20 based on the measurements condition reported above for a stainless steel flat-rigid target with the smooth surface condition, i.e. $\varepsilon^* \ll 1$. 

![Fig.8: Average dimensionless film thickness accumulated on the flat-rigid wall as a function of Reynolds number before the impact.](image)
for the average film thickness is presented together with the many individual measurements data as a function of Reynolds number before the impact. In this figure each individual average film thickness ($\bar{h}$) is normalized by the volume averaged droplet diameter before the impact ($d_{30b}$).

The results presented in this figure indicate good prediction of the average film thickness obtained from dimensional analysis (Eq. 33). Results presented in this figure also indicate that the Reynolds number before the impact is the main factor responsible for spreading and thinning the liquid film accumulated on the flat-rigid walls and indicates that the average impact Reynolds number must be appeared in the characteristic length scale of the average film thickness. Influence of the impact Reynolds number on the average film thickness can be obtained also from the theoretical expression derived for the averaged film thickness (Eq. 25).

In Fig.9, the prediction of the dimensional analysis for the average film thickness is presented.

In Fig.10a and b, the total secondary-to-incident mass ($\lambda_m$) and number ($\lambda_N$) ratio of the impacting spray as a function of the average wall film thickness is presented. Results presented in this figure indicate that the total secondary-to-incident mass and number ratio decreases significantly with increasing the average wall film thickness. Note that the impact Weber number is not constant for measurements presented in this figure (Fig.10a, b) and the average film thickness changes due to the variation of the impact Weber number. Impact Weber number based on the normal velocity component varies within the range $20 \leq W_{en} \leq 165$ in this figure.

Fig.9: Prediction of the dimensional analysis for the average film thickness.

For illustrating the influence of the average wall film thickness on the total secondary-to-incident mass and number ratio, simple correlations are obtained:

$$\lambda_m = (m_i/m_o) = 0.173 \cdot (\bar{h}/d_{10b})^{1.75}$$

(34)

$$\lambda_N = (N_i/N_o) = 0.201 \cdot (\bar{h}/d_{10b})^{-0.91}$$

(35)

Note that these expressions for $\lambda_m$ and $\lambda_N$, cannot be entered or multiplied in the expressions (13) or (15) given for the total secondary-to-incident mass and number ratio, since the wall film thickness is not an independent quantity and varies with the impact velocity, i.e. impact Weber or Reynolds number. In other words, one of Eqs. (15) or (34) must be used for estimating the total secondary-to-incident mass ratio. For illustrating the influence of the wall film thickness on the mass ratio in the case of constant impact Weber numbers, some exemplary results are presented in Fig. 11. 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 splashing droplets (resulting in a decrease of the number of ejected droplets from splashing droplets), but increasing 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 mentioned complex phenomena are engaged in generating the secondary spray and reflected as 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.10a, b: Total secondary-to-incident: a) mass ratio ($\lambda_m$), and b) number ratio ($\lambda_N$).
Note that in the conducted experiments, the entire target surface was exposed to the impacting spray, i.e., $D_{\text{spray}} / D > 1$. In this definition, $D_{\text{spray}}$ is the diameter of the effective impinging spray on the target defined as: $D_{\text{spray}} = 2x_{\text{migle}} \cdot \tan(\alpha / 2)$, $\alpha$ is the spray cone angle.

5. DISCUSSION

This paper presents a new simplified theoretical model for predicting the average film thickness as a function of mean Reynolds number of impacting drops, flux density of the impacting droplets, and the average drop diameter. Theoretical derivation for the average film thickness shows good agreement with the measured data in the thin liquid film condition, i.e. $h = \tilde{h} / d_{\text{film}} \leq 1$. Predictions of the obtained expression for the average film thickness based on the dimensional analysis indicate also good agreement for most of the many individual measurements. Results obtained in this study indicate a significant influence of the Reynolds number on the average film thickness accumulated on the flat-rigid wall due to a liquid spray impact.

In the case of constant impact Weber numbers, the average film thickness has a complex and non-predictable influence on the total secondary-to-incident mass ratio for different constant impact Weber numbers.

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7. REFERENCES