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Experimental analysis of a spray impinging on a conical surface

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Abstract — The details of droplet–droplet and droplet–liquid film interactions on solid surfaces are believed to have significant role in spray impingement phenomena, yet details of this interaction have not been clearly identified. After impact, droplet interactions affect droplet collisions, coalescence and liquid splashing; this interaction affects secondary atomization and droplet dispersion characteristics of the impingement process. In this study detailed measurements are performed in liquid sprays with a phase-Doppler velocimeter: simultaneous measurements of droplet size and velocity are obtained. The analysis is oriented towards secondary droplets behaviour. One general conclusion of this paper is that, working with a mean dimensionless film thickness between 1 and 3, the size and velocity distribution of secondary droplets are sensitive to the film thickness. © 2001 Éditions scientifiques et médicales Elsevier SAS

spray / impigement / droplet / atomization / conical surface / LDA / liquid film

Nomenclature

d	drop diameter	μm
K	dimensionless number	
N	noise	
Oh	Ohnesorge number	
r	distance	mm
R	dimensionless roughness	
Ra	surface roughness	μm
Re	Reynolds number	
S	signal	
t	liquid film thickness	mm
u	horizontal velocity component	$\mathrm{m \cdot s^{-1}}$
v	velocity component	$\mathrm{m \cdot s^{-1}}$
We	Weber number	

Greek symbols

δ	dimensionless liquid film thickness	
μ	liquid viscosity	$\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$
ρ	liquid density	$\mathrm{kg \cdot m^{-3}}$
σ	surface tension	$\mathrm{kg \cdot s^{-2}}$

Subscript

cr	critical

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1. INTRODUCTION

The impact of liquid droplets on a solid surface is a common and important process in a wide range of technical and industrial applications. It is, therefore, of fundamental interest for both design and modelling of such processes to be able to predict the characteristics of impact, in terms of slashed and deposited liquid mass, the dissipated energy and diameter–velocity distributions of droplets after impact.

In the last years the number of works about the spray impingement is strongly increased. One of the reasons is that the phenomenon occurs in many industrial processes where the chance to reduce the material losses and to improve the energy efficiency seems to be very high. Till now the experimental analysis of such a processes has followed two directions. Especially in studying the direct injection for Diesel engines, the attention was focused on the statistical description of the spray dynamic after the impingement, on the radius and the height of the impinging spray, on the different patterns of the wall spray, on the heat exchange between the wall and the two-phase flow and so on. In studying the spray painting a major goal was to study the effect of the wall surface on the deposition, in particular the roughness and the surface curvature. In parallel to this direction, some groups tried to model the impact of spray starting with studying a single droplet impact. In this case a single drop is let to impact on a dry or wetted surface and single impact phenomena are recorded. For a review of these researches, see Rein [1]. In the last years, impact models for different impact conditions (for cold surfaces) were newly proposed: Mundo et al. [2] for the case of impact on a quasi-dry surface, Yarin and Weiss [3] and Coghe et al. [4, 5] for the case of wetted surface. The present work has been undertaken as a first experimental verification of the single droplets impact model in the case of a wetted surface. The idea is to verify the utility of these last models for the spray impingement models, trying to unify the two research directions as other previous research already made.

2. THE MODEL FOR SINGLE DROPLET IMPINGEMENT ON A WETTED SURFACE

Generally it is possible to determine the splashing/deposition limit using only a dimensionless number $K = We\,Oh^{-0.4}$ (where *We* is the Weber number $\rho d v^2/\sigma$ and *Oh* the Ohnesorge number $\mu/(\rho d\sigma)^{1/2}$, and ρ, μ, and σ are respectively the liquid density, viscosity and surface tension and v is the velocity component normal to the impact surface) as a function of the other relevant impact parameters, for example, the film thickness, the surface roughness, the impact frequency, the impact angle and so on. A theoretical foundation of the significance of the number K is given by Yarin and Weiss [3].

In the case of wetted surface, the most important parameter is the dimensionless film thickness δ ($\delta = t/d$), Coghe et al. [5] proposed an empirical correlation in the range $R < \delta < 1$

$$K_{\mathrm{cr}} = f(\delta) = 2\,100 + 5\,880\delta^{1.44} \qquad (1)$$

where $R = R_{\mathrm{a}}/\phi$ is the dimensionless roughness.

K_{cr} is the critical value of the number K, i.e. if the value of K is greater than the value in the right term of equation (1) a splash phenomenon occurs. In a successive experiment Marengo et al. [6] proposed an empirical impact model describing for different values of K and δ the distribution of the secondary droplets diameter and velocity. As in the case of impacts on heated surface (Al-Roub et al. [7]), the statistical meaning of the equations like equation (1) is considered: given the high nonlinearity of the splashing phenomenon, instead of a unique value of K_{cr}, it is possible to define only a transition region (i.e. a range of K_{cr} where the splashing probability strongly increased) between the deposition and the splashing, especially with very low values of Ohnesorge number.

3. EXPERIMENTAL SET-UP AND PDA SYSTEM

Because of the future employment of this research for a numerical work, the spray is produced in a channel (at $20 \pm 1\,°\mathrm{C}$) to obtain defined boundary conditions for the continuum phase (*figure 1*). The air flows through a first honeycombed grid and then through the measurement zone, finally flowing away through a second grid and an aspiring fan. The installation of the grids is due to the necessity to have a well-defined turbulent air flux with as many as possible parallel streamlines. The channel is build in Plexiglas for the maximum optical accessibility to the measurement region.

The spray is produced by a Schlick hollow cone nozzle with filter, an aperture of 60°, a hole of 0.6 mm diameter with a good atomization and a very small hollow area (*figure 2*). The temperature in the measurement zone can be considered constant (20 °C). To conserve the symmetry of the spray impingement process a conical surface is chosen to be the impact surface. An aluminium cone of 80 mm basic diameter and 90° aperture with polished surface ($R_{\mathrm{a}} = 2 \pm 0.2$ μm) is posed at a distance of 80 mm from the nozzle. First measures at

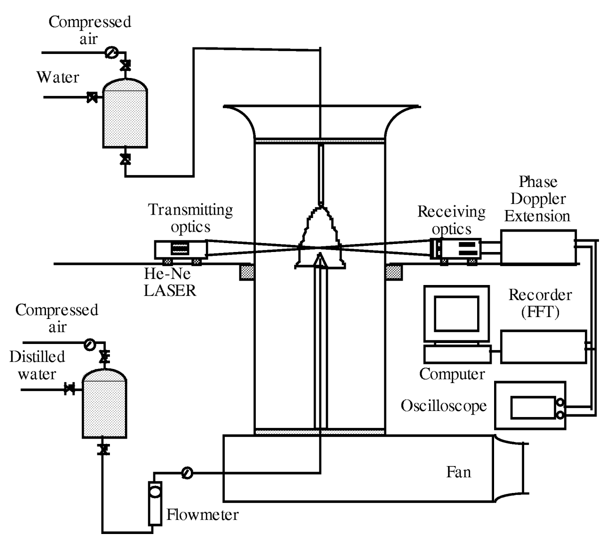

Figure 1. Experimental set-up.

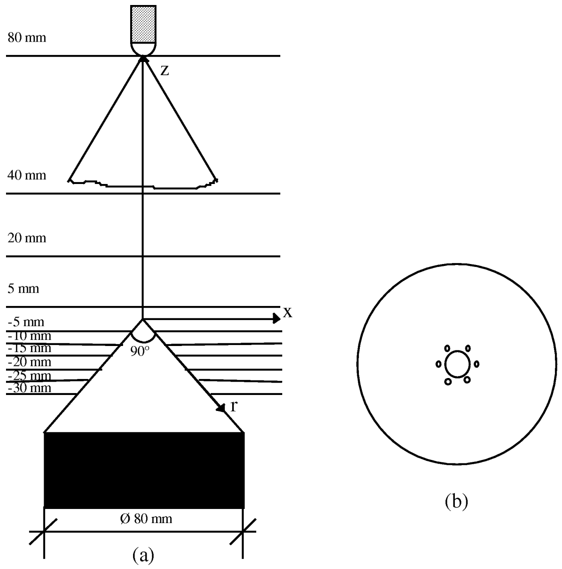

Figure 2. Altitude of the measurements and view of the top of the cone.

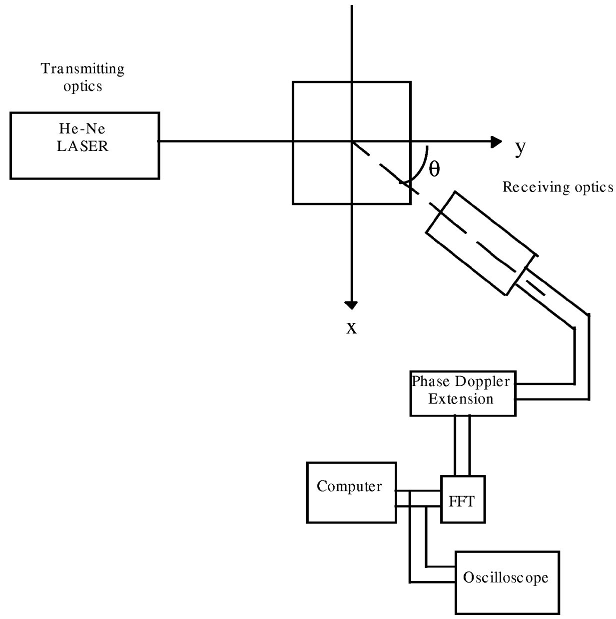

Figure 3. Optics system.

40 and 20 mm under the injector describe the free spray characteristics (*figure 2(a)*). A profile 80 mm under the injector without the cone is executed to obtain a reference value for the measures near the impact surface. The water flows from a pressure tank: the pressure tank (till 15 bar) is provided with a membrane to avoid any mixing between the liquid phase and air phase before the injection.

One of the goals of the present work is to analyse the influence of the liquid film on the surface. It is clear that a liquid is always generated on the impacted surface from the spray itself: the value of the idealised film thickness can be obtained analytically with the simplification that all the liquid mass that impinges in one point the surface deposits in that point. Actually, due to the perturbations induced by the spray and the strong waviness, the real local film thickness is unknown. If now an additional film of known film thickness is added, the impingement characteristics can be considered linked to a sort of reference liquid film thickness: it is possible, for example, to consider a spray impingement on a film with a thickness pretty higher than in the presence of the spray alone. In the first experiment we restrict our attention in analysing if presently, with our measurement devices, it is possible to observe a difference between the two cases: impingement of a spray on a surface covered by (1) the spray-produced film and (2) a film with a given minimal thickness.

For this reason, a dip coating system is built on the top of the cone: a series of 6 holes of 0.6 mm diameter forms a crown around a bigger central hole of 4 mm of diameter (*figure 2(b)*). The total outlet section is 14.3 mm^2. A pressure tank is used to provide the liquid flux on the cone. A flowmeter (0.5–10 L·h^{-1}) measures flux driven through a series of two valves.

The fan can be set to different rotation velocity and the induced air flow around the cone can have a mean velocity between 0 and 8 m·s^{-1} ($Re < 1.3 \cdot 10^5$). Using a Pitot tube the velocity profiles for different fan velocity were measured. When the gas velocity around the cone is greater than 6 m·s^{-1}, the coating of the surface becomes unstable and waviness is induced on the cone: hence, a maximal value of 5 m·s^{-1} (rotation frequency for the fan 250 Hz) is chosen for all the measurements. Both for the film on the cone either for the spray, deionised water is used.

To measure the liquid phase flow near the cone, a single velocity component phase-Doppler anemometer system (PDA) is used. The transmitting optics is a conventional system with two Bragg cells for frequency shifting, a beam separation of 10 mm and a front lens with 400 mm focal length. The self-made phase-Doppler receiving optics module with two detectors is mounted at 50° off-axis angle from the forward scattering direction. The 310 mm focal length collimating lens (80 mm focal length) is located to focus the light onto a slit of 150 μm on the avalanche-photodiode (*figure 3*). The signal processing is based on a hardware processing through a self-made transient recorder and a software post-processing through

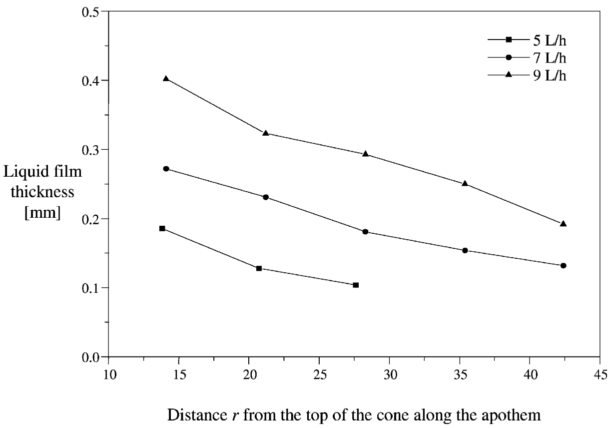

Figure 4. Thickness of the film on the cone in absence of the spray.

a PC program that reads and processes the rough data from the first signal processing. A description of the hardware signal processing can be found in Qiu and Sommerfeld [8]. The main features of this system are (1) the detection of the burst and the peak in the signal, that avoid the uncertainties of setting a definite trigger level for the burst validation and (2) the signal analysis in a signal part where the S/N is as high as possible. The software post-processing is based on the LMA (logarithmic mean amplitude) method, i.e. a valuation of the real measurement volume cross-section for every scattering droplet: after a simple calibration with the spray, the accuracy in the local flux and concentration measurement is generally greater than 5 %.

The thickness of the film on the cone in the absence of the spray is measured. A laser beam is directed tangent to the cone surface. A beam scanner is used to verify the waist radius of the beam: if the beam has a contact with the surface, the variation of the beam dimension is rapidly detected. Moving the beam with a micrometer, it is possible to measure the contact point with the solid surface and then with the film surface. The measurement is repeated for three values of the liquid flux on the surface: 5, 7, 9 L$\cdot$h^{-1}. In the ideal case that all the spray flux that impinges in one point of the surface deposits with zero velocity in that point, it is possible to calculate the mean smooth film thickness due to the spray (*figure 4*).

4. EXPERIMENTAL RESULTS AND DISCUSSION

The spray droplets that impinge the cone surface can deposit, rebound and splash: in the first case, the droplets

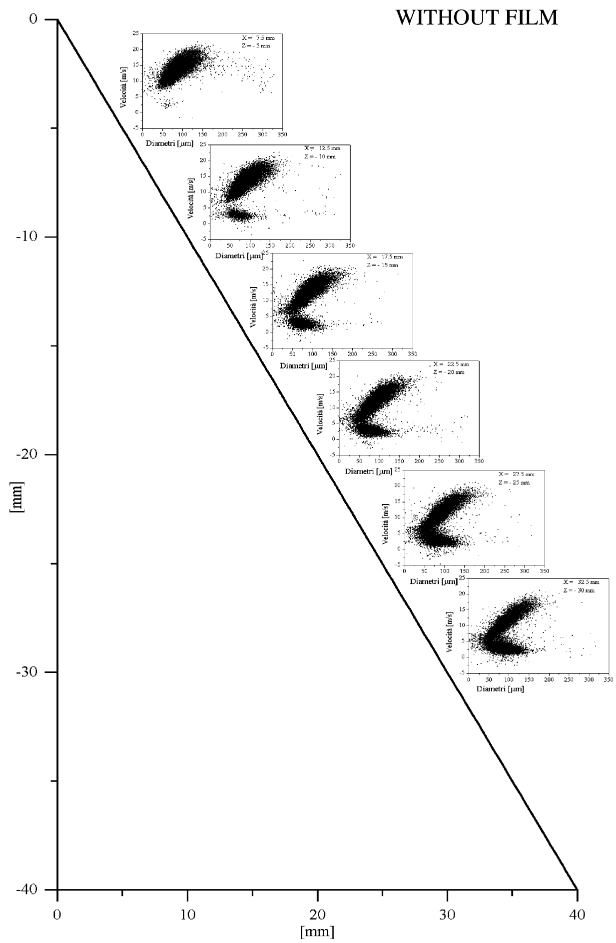

Figure 5. Scatter diagram along the cone without added liquid film.

contribute to the increase of the film thickness, in the second case, the droplets velocity component u and the diameter decrease because of the energy dissipation and of the partial wetting on the surface. In the case of the splashing, a greater effect on the component u should be noticed (the velocity could be also negative, i.e. some small droplets are leaving the surface against the main flow) and the diameter should decrease strongly (actually the average secondary droplets diameter depends on the K, only qualitatively it can be estimated a mean of $0.2d$). In *figures 5* and *6*, the scatter diagrams d–u along the cone at a fixed distance of 0.5 mm are shown. It is clear that, using a one-component PDA and an impinging polydisperse spray, the rebound and splashing regimes are hardly distinguishable: greater (and faster) droplets have a major probability to produce secondary droplets with similar characteristics of the rebounding smaller droplets. No previous studies of the limit for the

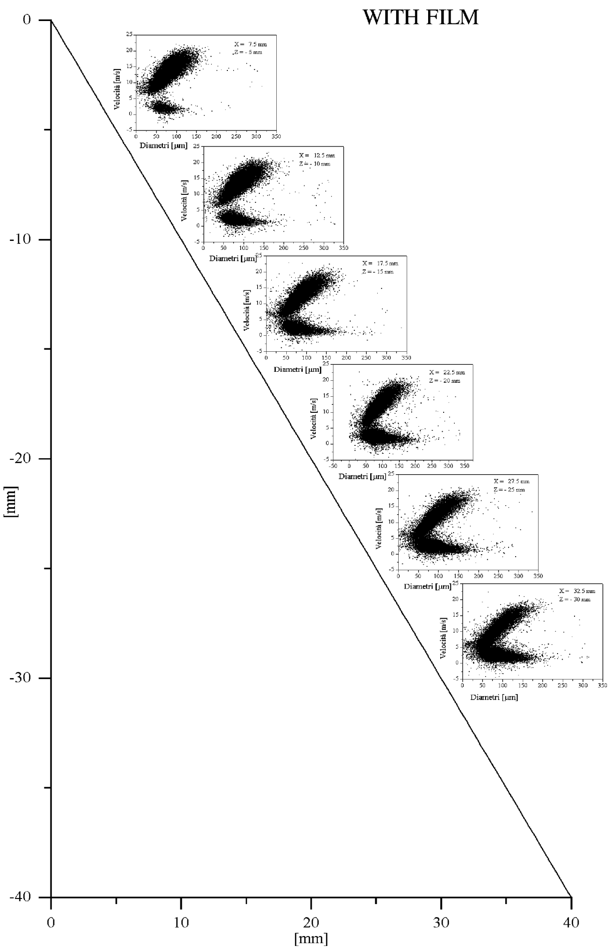

Figure 6. Scatter diagram along the cone with added liquid film.

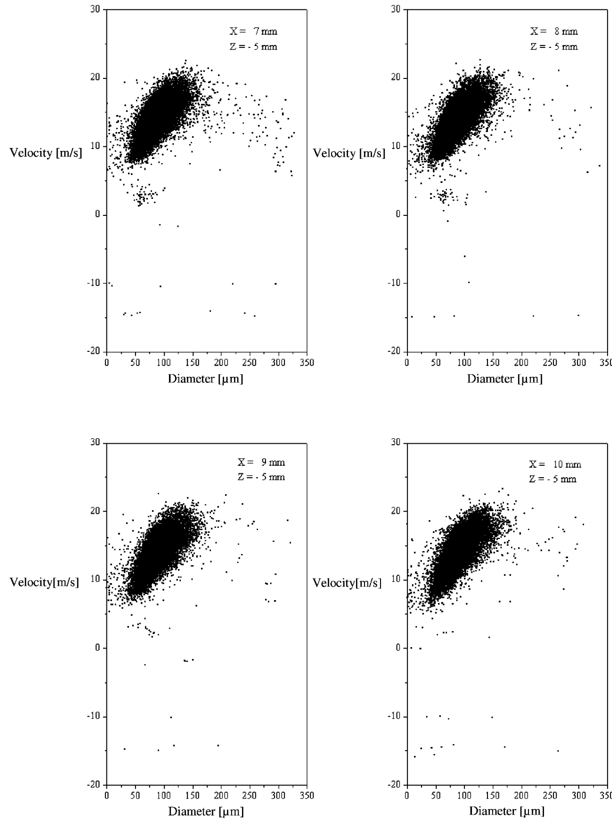

Figure 7. Scatter diagram along an x-axis without added liquid film.

rebound in similar conditions are known: hence, a limit in interpreting the next results will be the impossibility to recognise the origin and the characteristic values of the real secondary droplets. Nevertheless, a first separation between "secondary droplets" and primary droplets is possible in terms of the velocity u. In fact, near the wall, a number of droplets, coming from the rebound and the splashing, has a velocity component u smaller than $5\ \mathrm{m{\cdot}s^{-1}}$: a two-phase accelerating flow is present and the smaller droplets reach the velocity of the gas flow near the wall. In the next part of the paper, we will call the droplets with a velocity u smaller than $5\ \mathrm{m{\cdot}s^{-1}}$ *secondary droplets* (SD), no matter if these are splashing or rebound droplets. In *figures 7* and *8* the scatter diagrams d–u along an x-axis profile are shown: the SD in the presence of the added film appeared to reach further points than in the case without added film.

From the last considerations, it seems clear that, with the present device, considerations about the characteristics of real secondary droplets are not simply described by the single impact models. Nevertheless, having introduced the presence of an added film on the surface leads to analyse the effect of the film thickness for the spray impingement.

With the added film, the SD show a diameter 10 % bigger than in the case without the added film. The single drop impact model [5, 6] foresees an increasing droplets diameter with increase in δ. The velocity of the secondary droplets is, as expected, lower in the case with added film, because of the higher energy dissipation during the impact. In the case with added film the SD concentration near the wall can be higher than in the case without added film, especially on the lower part of the cone. This could mean that the presence of a thicker film is not in principle inhibitory for the SD formation, but, giving enough impact energy, the number of the SD (in the sense that we give) increases with the film thickness. The greater concentration of the SD in the case with added film is also partially explained because of the

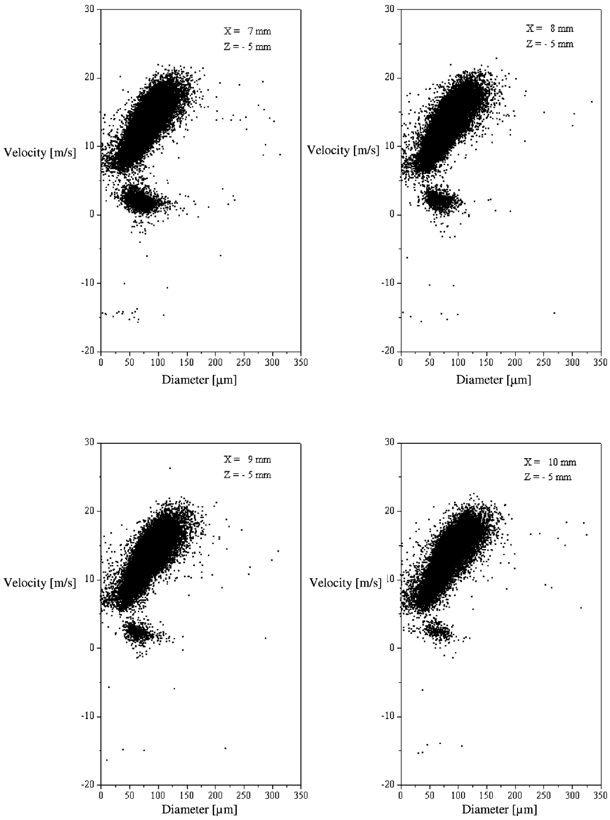

Figure 8. Scatter diagram along an x-axis with added liquid film.

smaller velocity of the rebound droplets: the droplets that, rebounding, maintain a velocity component u greater than 5 m$\cdot$s^{-1} in the case without added film, are present in the samples with added film. This explanation gives also some insights for the increasing concentration of SD along the cone apothem.

Actually, the presence of the film has also an effect for the "primary" droplets: the concentration of droplets with a velocity component u greater than 5 m$\cdot$s^{-1} is overall lower in the case with added film. This is a clear sign that also in the group of the "primary" droplets, rebound droplets are included: it is physically consistent that the presence of the film inhibits the number of high velocity rebound droplets, reducing the concentration in the "primary" spray. This phenomenon, together with the higher SD diameter, can explain the longer trajectories of SD in the case with added film: the lower drag coefficient associated with a lower environmental droplet concentration let the droplets reach further points.

From the cumulative probability distribution function for the values of K near the wall, we can found that the possibility to have splash for the primary droplets is higher in the case without added film than in the case with added film.

The conclusions can be summarised as follows:

- secondary droplets, in the case with added film, remove a part of film;
- the deposition of droplets is greater in the case with added film, and consequently, the thickness of the film and droplets concentration near the surface is higher;
- in the case without added film the rebound of the primary droplets is higher;
- in the case with added film the secondary droplets meet with a less dense spray, and so being smaller the probability to have coalescence, they go farther.

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