Influence of surface roughness in spray/wall interaction phenomena

D. Kalantari*, C. Tropea†
* Department of Mech. Engineering, University of Mazandaran (Sanru), PO Box: 578, Sari Iran
† Institute of Fluid Mechanics and Aerodynamics, TU Darmstadt, Darmstadt, Germany
† Center of Smart Interfaces, TU Darmstadt, Darmstadt, Germany

Abstract

This paper presents an experimental study of liquid spray impacting onto different rough and smooth surfaces. Based on the results obtained in this study, the surface roughness has negligible influence on the normal component of the mean velocity ratio (u_a/u_b) of ejected-to-impinging spray. In contrast, the ratio of tangential components of the mean velocity (v_a/v_b) decreases significantly with surface roughness. The ratio (u_a/u_b) falls in the range $0.13 < (-u_a/u_b) < 0.3$ for $We_{nb}>12$. The average drop size ratio (secondary to impacting drop size) consistently increases with increasing surface roughness. Results obtained in this study indicate that the total secondary-to-incident mass and number ratios are also increased with increasing surface roughness.

The surface roughness influences strongly the direction of the secondary droplet motion. In the case of a rough surface, the reflection angle becomes smaller with respect to the wall normal. This can be explained by dissipation of the tangential momentum due to the surface roughness.

Introduction

The importance of surface roughness in droplet/wall interaction has been underlined by numerous investigators; Weiss (1993), Mundo et al. (1995), Mundo et al. (1998), Stow and Hadfield (1981), Cossali et al. (1997), Range and Feuillebois (1998). The outcome of the impacting droplets onto a rigid surface depends not only on the kinematics and fluid properties of the impacting droplets, but also on the ratio of the surface roughness compared to the droplet diameter; Mundo et al.(1995), Kalantari and Tropea (2007a, b).

Mundo et al. (1995) used two rotating discs with different surface roughness ($\bar{\varepsilon}/d_0 \sim 0$ or 1) to study the effect of surface roughness in droplet/wall interaction. Their results indicate that in the case of a rough surface, the droplet size distributions vary only slightly with increasing K value and non-dimensional surface roughness determines the distribution of droplet size ($K=We\cdot Oh^{-0.4}$; We and Oh are impact Weber number and droplet Ohnesorge number respectively, defined by $We_{nb}=\rho u^2 d_0/\sigma$ and $Oh=\mu/\sqrt{(\rho\sigma d_0)}$, where u is the normal velocity component before impact, ρ is liquid density, μ is liquid viscosity and σ is the surface tension). In their experiments, a splash corona could not be observed for the rough surface and the disintegration of the droplet appears to be more immediate. Based on their results, the roughness influences strongly the direction of the droplet motion. In the case of a rough surface, the reflection angle respect to the normal becomes smaller, because the tangential velocity component is reduced. This can be explained by the surface roughness which leads to a dissipation of the tangential momentum. Therefore it seems that due to dissipation of the droplet kinetic energy caused by the surface roughness, the spreading process is faster in the case of a rough surface. In the presence of roughness, the splat thickness increases.

Stow and Hadfield (1981) postulated that splashing threshold parameter ($K_{Cr}=We^{0.5}\,Re^{0.25}$) strictly depends on the surface roughness and K_{Cr} varies dramatically with the non-dimensional surface roughness ($\varepsilon^*=\bar{\varepsilon}/d_0$).

Some of the important empirical derived relationships for the onset of splashing depending on the surface roughness are summarized in the Table 1, based on the experimental data.

Range and Feuillebois (1998) reported that liquid viscosity has a very weak influence on the onset of splashing limits for small Oh numbers varied in the range [0.002, 0.02]. In their experiments, the Oh number has been changed by varying the droplet viscosity, using various water-glycerol mixtures. On the other hand, they found that surface tension has a considerable influence on the splashing limits, as an example ethanol with a lower surface tension splashes at lower impact velocities in compare to water.

Range and Feuillebois (1998) also expressed that their results confirm the observations of Stow and Hadfield (1981) in the case of aluminum plate, but the critical We numbers for the onset of splashing are different for other materials; therefore the expression presented in Table 1 from Stow and Hadfield (1981) is not universal. Range and Feuillebois (1998) proposed a new expression for the onset of splashing shown in Table 1. They suggest that their expression shows a good prediction if the parameters a and b are set carefully for the liquid-surface pair used in the experiments.

* Corresponding author: d.kalantari@gmail.com

Table 1. Empirical derived relationship for the onset of splashing depending on the surface roughness based on the experimental data

Authors	Relationship	Description
Stow and Hadfield (1981)	$\mathrm{Re}_{cr}^{0.31} \cdot We_{cr}^{0.69} = f_{nd}(\overline{\varepsilon})$	water droplets impinging on rough aluminium surfaces
Wu (1992)	$We_{cr} = a \cdot \log^{b}(d_0/2\overline{\varepsilon})$	data of Stow and Hadfield (1981), a and b are 6.47 and 1.87 , respectively
Cossali et al. (1997)	$K_{Cr}^{1.6} = 649 + 3.76/\varepsilon^{*0.63}$	based on the data of Stow and Hadfield (1981), Mundo et al. (1995) and Yarin and Weiss(1995)
Range and Feuillebois (1998)	$We_{cr} = a \cdot Ln^{b}(\varepsilon^{*})$	rough surfaces at low values of *Oh* numbers

The splashing mechanism may involve a complex coupling between the dynamic wetting and the roughness. Perturbations appear on the edge of the out-spreading film up to the moment when its maximum diameter is reached.

Range and Feuillebois (1998) performed additional experiments with water-ink mixtures on paper and glass surfaces. They selected these liquids in order to obtain clear images of the film on the rough surfaces with the shadowgraph method. They found that the number of perturbations increases with increasing the impact speed, confirming the observations of Lohr, but Eq.(1) overpredicts the number of observed perturbations. They mentioned that this effect might be provoked by surface roughness, porosity of paper surfaces or forces arising from the different chemical treatment of the paper surface.

Materials and Methods

The experimental set-up used in this work is pictured in Fig.1. The spray was created using different full-cone nozzles from Spraying System Co., operated at pressures between 2 and 7 bar and flow rate between 27 and 40 l/hr. Both flow rate and pressure during the experiments were variable and measured. Three aluminium targets with diameter of 15 mm have been used to obtain the results presented in this paper, using the end face of the cylinder.

The nozzles were placed at different positions above the target surface from 20 to 80 mm with interval of 10 mm, e.g. (X_{nozzle}=-20 mm). To characterise the spray, a dual-mode phase Doppler instrument from Dantec Dynamics was used, comprising a transmitting optics with a 310 mm focal length, a receiving optics with a 310 mm focal length, and an "A" type mask at a 36° scattering angle. By using a dual-mode configuration both normal and tangential velocity components of each individual droplet and its diameter were measured by placing the measurement volume 1mm above the target surface (i.e., x= -1mm). The in-going and out-going 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.

For precisely definition of the measurement volume height above the wall, first the blue laser beams in the horizontal plane were blocked and the measurement volume created by the green laser beams was placed precisely at the centre of the target by horizontally or vertically movement of the target, Fig. 2.

The measurement volume is positioned precisely at the target centreline when the target edges touch simultaneously the green laser beams, i.e., points "a" and "b" in Fig. 2a touches the laser beams at the same time. In the next step, the green laser beams in the vertical plane were blocked and the blue laser beams in the horizontal plane were used to find the zero-position of the measurement volume height. In this step, the target moved only vertically to touch the laser beams. The touched position of the target was defined as x_{MV}=0, see Fig. 2b.

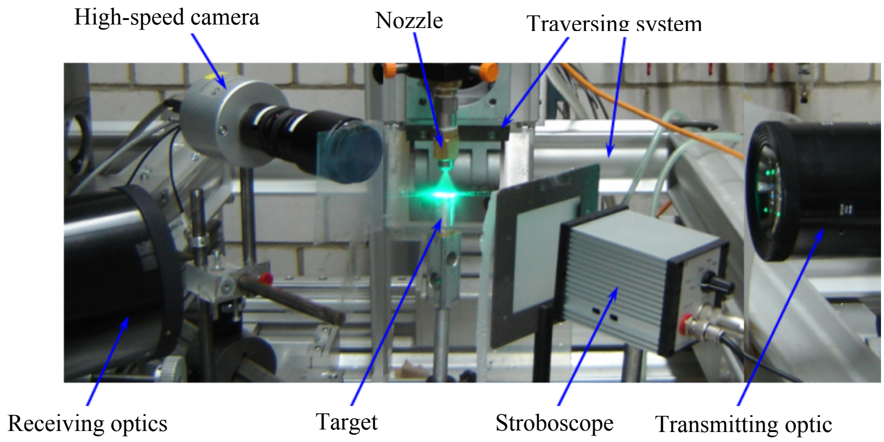


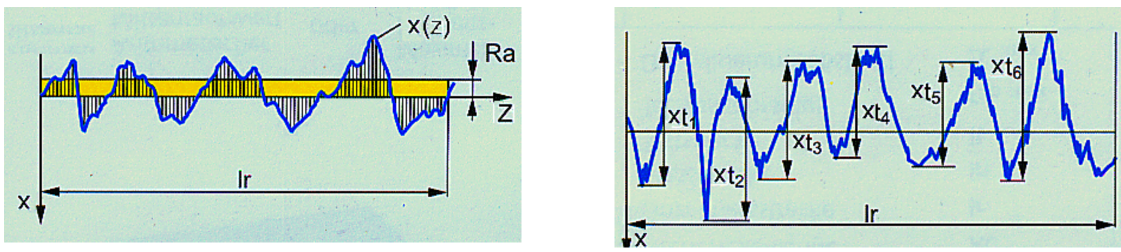
Figure 1. Photograph of experimental set-up used in this study

a b

Figure 2. Sketch for: a) positioning the measurement volume precisely at the target centreline, and b) zero-position of the measurement volume height

Experimentally the accumulated wall film has been characterised using a high-speed CCD camera. The average wall film thickness ($\overline{h}$) is obtained by averaging over several instantaneous images after first removing the reference wall image.

Surface roughness of the rigid targets have been characterized by means of a mechanical profile meter from Hommelwerke Co., type TK300. Mean roughness (R_a or $\overline{\varepsilon}$) of the target surfaces used in this study ($R_a=\frac{1}{lr}\int_0^{lr}|x(z)|dz$, where lr is the measured length on the target surface) varied in the range 0.36 µm<R_a<10.8 µm, whereas mean peak-to-valley roughness (R_Z) of the used targets varied in the range 3 µm<R_Z<46.3 µm ($R_z=\frac{1}{N}\sum_{i=1}^{N}xt_i$, where N is number of the measured points on the target surface), see Fig. 3a and b. In this study, the relative surface roughness in comparison to the mean measured drop size varied in the range $0.04 \le 2\overline{\varepsilon}/d_{10b} \le 1$.



a) b)

Figure 3. a) Mean roughness (R_a or $\overline{\varepsilon}$), and b) mean peak-to-valley roughness (R_Z) of the target surface

Results and Discussion

In the following sections some important results of liquid spray impacting onto targets with different surface roughness varied in the range $0.04 \le 2\bar{\varepsilon}/d_{10b} \le 1$ will be presented. Based on the results obtained in this study, the surface roughness has negligible influence on the normal component of the mean velocity after impact (u_a) and mean velocity ratio (u_a/u_b) of ejected to impinging spray (Fig. 4a). This result is not consistent with the justification of Mundo et al. (1995) that the mean normal velocity component of the splashed droplets for an impact on the rough surface must be larger than the normal component for an impact on a smooth surface.

In contrast, the ratio of tangential component of the mean velocity (v_a/v_b) decreases significantly with surface roughness (Fig. 4b). The ratio (u_a/u_b) falls in the range $0.13 < (-u_a/u_b) < 0.3$ for $We_{nb}>12$, which is consistent with the results obtained by Kalantari and Tropea (2007a). The average drop size ratio (secondary to impacting drop size) consistently increases with increasing surface roughness as shown in Fig. 5a. This result is also consistent with the results of Stow and Steiner (1977) which they postulated that the average size of sprinkled droplets resulting from splashing is larger for rough surfaces.

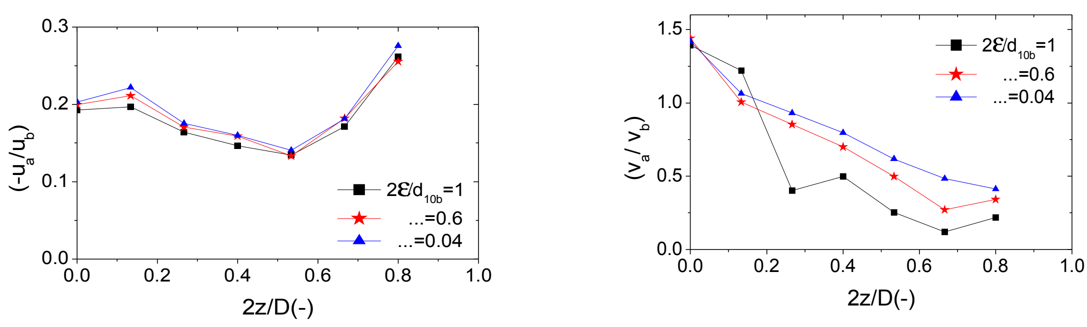
The total local secondary-to-incident mass ratio ($\lambda_m = \dot{m}_a / \dot{m}_b$) is affected by several complex parameters such as droplet Weber number based on the normal component of impact velocity (We_{nb}), impact Weber number ratio ($\lambda_{We_b} = We_{tb} / We_{nb}$), impact Reynolds numbers (Re_{nb}), relative wall roughness ($\bar{\varepsilon}^* = \bar{\varepsilon} / d_b$) and relative wall film thickness ($\bar{h}^* = \bar{h} / d_b$); hence a general correlation for mass ratio is difficult to derive. Generally, total local secondary-to-incident mass ratio ($\lambda_m = \dot{m}_a / \dot{m}_b$) can be expressed in dimensionless form as

$$\lambda = (\dot{m}_a / \dot{m}_b) = f\left(We_{nb}, \lambda_{We_b}, \mathrm{Re}_b, \bar{\varepsilon}^*, \bar{h}^*\right)$$

Results obtained in this study indicate that the total secondary-to-incident mass ratio is increased with increasing surface roughness, see Fig. 5b.

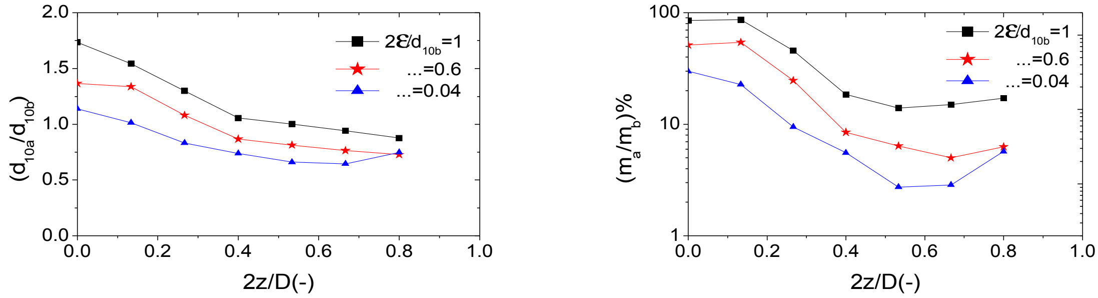
The surface roughness influences strongly the direction of the secondary droplet motion. In the case of a rough surface, the reflection angle becomes smaller respect to the normal. This can be explained by dissipation of the tangential momentum due to the surface roughness, as shown in Figs. 6 and 7; see also Kalantari and Tropea (2007); Bai et al. (2002). One sketch illustrating such effect is shown in Fig. 6.

Based on the results obtained by Mundo et al. (1995), an almost linear relationship between the impingement angle and the reflection angle exist, but in the case of rough surfaces, the reflection angles are shifted to smaller values, especially for small impingement angles, indicating that the tangential velocity component is more dissipated in rough surfaces. Based on their experimental data, refection angle of secondary droplets is 4.5% ,5.5% and 9% smaller for rough surface in compare to does of smooth surface for an impingement angle of 20°,30° or 60°, respectively.(7% in average).



a) b)

Figure 4. Mean velocity ratio of ejected to impinging droplets as a function of non-dimensional target position for different target surface roughness: (a) normal component, (b) tangential component



a) b)

Figure 5. The average secondary to impacting: a) drop size ratio and b) mass ratio, as a function of non-dimensional target position for different target surface roughness

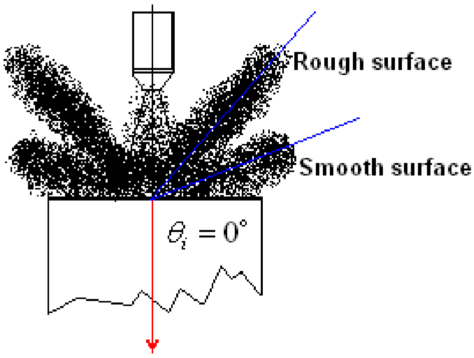


Figure 6. A sketch for direction of the secondary spray in the case of smooth and rough surfaces.

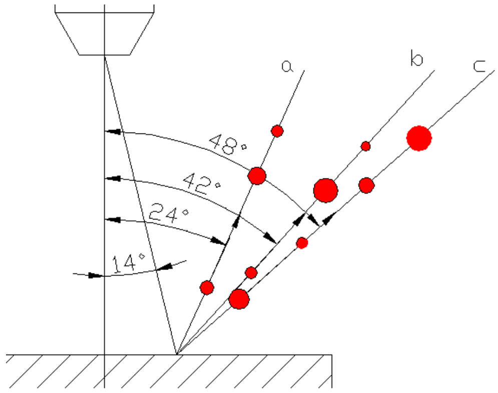


Figure 7. Mean direction of the secondary droplet in the case of smooth and rough surfaces (a: $\bar{\varepsilon}^* = \bar{\varepsilon}/d_d \approx 1$, b: … ≈ 0.6, and c: …≈ 0.04).

Conclusions

Some of the important results obtained in this study are as following:

- The average size of the droplets in secondary spray (d_{10a}) decreases with increasing the impact Weber number and decreasing the surface roughness. In other words increasing the surface roughness will yields in increasing the size of secondary spray.
- The total secondary-to-incident mass and number ratios are increased with increasing surface roughness.
- Surface roughness has no significant influence on the normal component of velocity after the impact.
- Surface roughness has its maximum influence on the total secondary-to-incident mass ratio in the case of inertial normal impact condition (i.e., $\lambda_{We_b} = We_{tb}/We_{nb} < 0.1$). This means that influence of the surface roughness on the total secondary-to-incident mass ratio becomes weaker if the ratio of We_{tb}/We_{nb} increases (i.e., oblique impact condition).
- The reflection angle of the secondary spray becomes smaller respect to the normal with increasing the surface roughness.
- Dissipation of tangential momentum of impacting spray increases with increasing the surface roughness whereas surface roughness has no significant influence on the normal momentum of impacting spray.
- In the case of a rough surface, dissipation of tangential momentum of impacting spray is stronger at larger value of tangential velocity component of impacting spray.

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References

[1] Bai, C., H. Rusche, H., Gosman, A.D., Modeling of gasoline spray impingement, *Atomization and Sprays* 12: 1-27 (2002).

[2] Cossali, G.E., Coghe,A., Marengo, M., The impact of a single drop on a wetted surface, *Experiments in Fluids* 22: 463-472 (1997).

[3] Kalantari, D., Tropea, C., Spray impact onto flat and rigid walls: Empirical characterization and modelling, *International Journal of Multiphase Flow*, 33: 525-544 (2007a).

[4] Kalantari, D., Tropea, C., Phase Doppler measurements of spray impact onto rigid walls, *Experiments In Fluids* 43: 285-296 (2007b).

[5] Mundo C, Sommerfeld M, Tropea C., Droplet-wall collisions: experimental studies of the deformation and breakup processes, *International Journal of Multiphase Flow* 21: 151-173 (1995).

[6] Mundo C, Sommerfeld M, Tropea C., On the modeling of liquid sprays impinging on surfaces, *Atomization and Sprays* 8:625-652 (1998).

[7] Range, K., Feuillebois, F., Influence of surface roughness on liquid drop impact, Journal *of Colloid and Interface Science* 203, 16-30 (1998).

[8] Rioboo R, Marengo M, Tropea C., Outcomes from drop impact on solid surfaces, *Atomization and Sprays* 11: 155-164 (2001).

[9] Stow, C., and Hadfield, M. G., An experimental investigation of fluid flow resulting from the impact of a water drop with an unyielding dry surface, *Proc. R. Soc. Of London, Ser*. A373 (1981).

[10]Wang, M., Watkins, A.P., Numerical modelling of Diesel spray impaction phenomena, *International Journal of Heat Fluid Flow* 14: 301-311 (1993).

[11]Wu, Z., Mode´lisation et cacul implicite multidomaine decoulements diphasiques gas-gouttelettes, Ph.D. Thesis, *Universite´ Pierre et Marie Curie*, Paris, France (1992).