IMPROVING CAR AIR CONDITIONING SYSTEMS BY DIRECT NUMERICAL SIMULATION OF DROPLET-WALL INTERACTION PHENOMENA

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Abstract

In this study, the interaction of liquid droplets with dry and wetted surfaces are investigated by using *Direct Numerical Simulation* (DNS). For the computations an inhouse 3D-CFD code (FS3D) has been used. The aim of this investigation was to obtain a correlation describing the splashing threshold of impinging liquid droplets on wetted surfaces and to determine the maximum extension diameter of droplets spreading on a dry surface. Therefore previous experimental investigations from literature have been recalculated by DNS. The new obtained splashing threshold is presented in this paper and a correlation for the maximum spreading diameter is confirmed.

1. Introduction

In many industrial applications the interaction of liquid droplets with dry and wetted surfaces are important. In car industry droplet-wall interaction phenomena are of interest in improving air conditioning systems among other things. Various droplet wall phenomena like splashing, formation of wallfilm or re-entrainment of droplets occur in the so-called waterbox of a car. The waterbox is one of the first parts of the air conditioning system. It is located underneath the windscreen. In case of rain shower, air which is sucked in from the surrounding, can contain water droplets. The aim of the waterbox is to separate the water droplets from the air flow to avoid contamination of the airfilter and unwanted effects like fogging or frosting of the windscreen inside the car.
For numerical simulation of the rain water separation in the waterbox it is necessary to develop numerical models for droplet wall interactions. The aim of this study is to verify previous correlations and to obtain new correlations for various phenomena by using *Direct Numerical Simulation* (DNS) for the commercial CFD-Code *SWIFT* [1].
In most of the correlations, the following dimensionless parameters were taken to describe the

impingement of liquid droplets on surfaces:
Weber number

$$We = \frac{\rho_L u_I^2 d_I}{\sigma_L}, \quad (1)$$

Ohnesorge number

$$Oh = \frac{\mu_L}{\sqrt{\rho_L d_I \sigma_L}}, \quad (2)$$

Reynolds number

$$Re = \frac{\sqrt{We}}{Oh} = \frac{\rho_L u_I d_I}{\mu_L} \quad (3)$$

and dimensionless film height

$$\delta = \frac{h}{d_I} \quad (4)$$

where ρ_L, σ_L, μ_L denote the density, the surface tension and the dynamic viscosity of the liquid, respectively, and u_I and d_I are the impinging velocity normal to the wall and the impinging diameter and h the height of the film.
The impact phenomena of a liquid droplet on a solid surface can be divided into three different cases: the impingement on a high temperature surface (higher than the Leidenfrost temperature), the impingement on a cold dry surface and the impingement on a cold wetted surface. The first case is not considered in this study. In Fig. 1 the investigated phenomena with two different outcomes are shown.

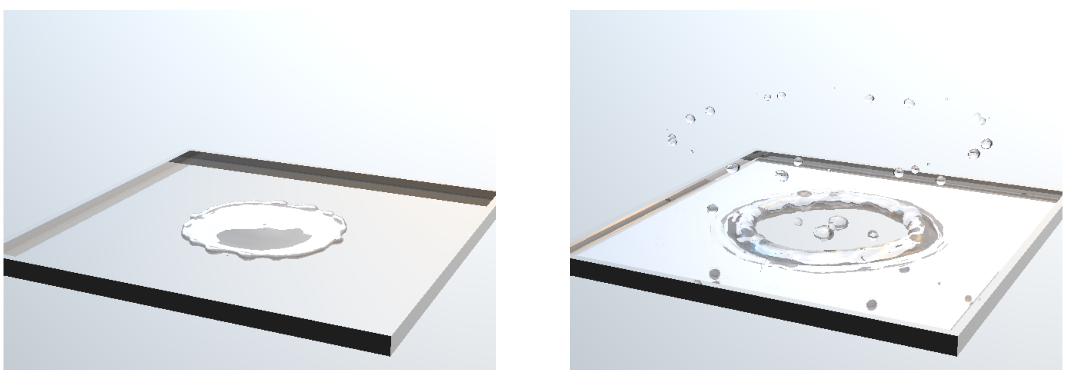

Figure 1: Impingement of a droplet on a cold dry surface (Spreading) [left] and on a cold wetted surface (Splash) [right]

Scheller *et al.* [2] investigated the spreading of a liquid droplet on dry surfaces. They obtained a correlation for the maximum spreading diameter depending on Re and Oh. Cossali *et al.* [3] investigated the impact of single droplets on wetted surfaces. The splashing/deposition limit is described as a function of We, Oh and δ.
In the present study the inhouse program Free Surface 3D (FS3D) has been used for testing the correlations mentioned above. This CFD-Code calculates the 3D Navier-Stokes equations for incompressible fluids with free surfaces. All calculations have been done on the Cray T3E, with grids up to $(192)^3$ cells by calculating only a quarter of the droplet because of assumed symmetry. Only impacts normal to the wall have been investigated.
The correlation for the maximum spreading diameter could be confirmed by the calculations. Differences between the correlation for the impingement of a liquid droplet on a wetted surface and the numerical results were found. Therefore, a new correlation for the splashing threshold was evolved.

2. Empirical models

The correlation of Scheller *et al.* [2] describes the maximum spreading diameter as a function of Re and Oh:

$$d^* = 0.61(Re^2 Oh)^{0.166} \qquad ; \quad d^* = \frac{d_{max}}{d_I} \tag{5}$$

Here d^* is the dimensionless maximum diameter defined as the ratio of the maximum diameter d_{max} and the impact diameter d_I. The investigated ranges of the dimensionless parameters are: $0.002 \leq Oh \leq 0.585$ and $19 \leq Re \leq 16400$ and as a result of that $234 \leq Re^2 Oh \leq 549000$. The droplet diameter varied in the range of $2\,mm \leq d_I \leq 4\,mm$ and the impact velocity in the range of $1.3\,m/s \leq u_I \leq 4.9\,m/s$.

Cossali *et al.* [3] presented a correlation for a splashing threshold for the impact of liquid droplets on a wetted surface. The splashing/deposition limit is described in terms of the number K, whereby only the normal component of the velocity is used to determine We.

$$K = Oh^{-0.4} We \tag{6}$$

If an impinging droplet has a K value higher than K_L, splashing occurs. The critical value K_L is in case of a wetted wall a function of δ only.

$$K_L = f(\delta) = 2100 + 5880\,\delta^{1.44} \qquad ; \quad \delta = \frac{h}{d_i} \tag{7}$$

The correlation for the splashing threshold was carried out in a wide range of conditions: $0.0022 \leq Oh \leq 0.141$, $200 \leq We \leq 1600$ and $0.08 \leq \delta \leq 1.2$. The droplet diameter was $d_I = 3\,mm$ and $d_I = 3.5\,mm$.

3. Numerical method

For computations, the inhouse 3D-CFD program FS3D (Free Surface 3D) has been used. This code solves the Navier-Stokes equations for incompressible flows with free surfaces. The equations are solved without a turbulence model by *Direct Numerical Simulation* (DNS). The governing equations are conservation for momentum, mass and energy. In two phase flows additonal information about the interface position between the disperse and the continous phase are needed. In FS3D a Volume-Tracking method, well known as the *Volume-of-Fluid* (VOF) method, is used [4]. In the VOF-method an additional transport equation

$$\frac{\partial f}{\partial t} + \nabla \cdot (uf) = 0 \tag{8}$$

for the volume fraction f (VOF variable) of the dispersed phase is solved. The VOF variable is defined by

$$f = \begin{cases} 0 & \text{in the continous phase} \\ 0 < f < 1 & \text{at the interface} \\ 1 & \text{in the disperse phase} \end{cases} \tag{9}$$

With this variable, the changes in density and viscosity over the surface can be computed by the equations

$$\rho(x,t) = \rho_G + (\rho_L - \rho_G) f(x,t) \tag{10}$$

$$\mu(x,t) = \mu_G + (\mu_L - \mu_G) f(x,t). \tag{11}$$

Other fluid properties can be obtained in a similar manner.
To ensure a sharp interface and to suppress numerical dissipation of the disperse phase in each step the interface is reconstructed with the PLIC-method *(Piecewise linear interface reconstruction computation)* [5]. After the reconstruction, the disperse phase is transported on the basis of its reconstructed distribution. The spatial discretization is realized by a structured Finite Volume scheme on a staggered grid. In each phase the discretization is second-order accurate. Due to the high gradients across the interface a limiter is used to prevent the formation of oscillations and spurious solutions. The program is parallized with domain decomposition using the communication library *MPI*. A multigrid solver is included to solve the Poisson equation for the pressure.

4. Computations

The calculations shown in this study are for droplets with different initial velocities u_I, different diameters d_I and different fluid properties (ρ_L, μ_L, σ_L) to reach certain Weber and Ohnesorge numbers and with different film heights h to obtain certain values for δ. Most computations are done with fluid properties for water because of the application in airconditioning systems. The surrounding gas is air. The size of the computational domain varied between $0.25cm^3$, $0.45cm^3$, $0.6cm^3$ and $1.2cm^3$ dependent on the droplet size and the outcomings of the interaction and the domain has been resolved with a $192 \times 192 \times 192$ grid. Only a quarter of the droplet was calculated due to symmetry. The time discretization has been done by a first-order accurate Euler scheme.

5. Results

For the numerical calculations of the maximum spreading diameter the values of the dimensionless parameters were taken in a related range to the experimental investigations of Scheller *et al.* [2].
In Fig. 2 the numerical results compared with the correlation of Scheller *et al.* [2] for a droplet impinging on a dry wall are displayed. The values of the dimensionless maximum spreading diameter d^* and the range of Re^2Oh are plotted on a logarithmic scale. The continous line is

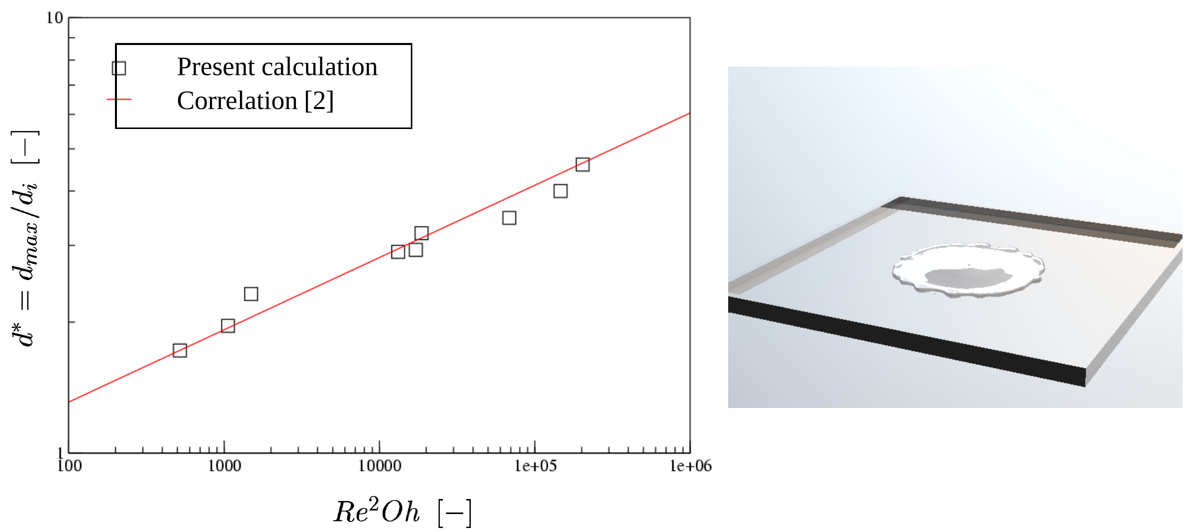

Figure 2: Correlation of the maximum non-dimensional spreading diameter d^* of a droplet impinging on a dry wall and a picture of one of the numerical simulations

showing the correlation and the squares are showing the numerical calculations. There is good agreement with the correlation in the calculated range of Re^2Oh.

To investigate the splashing/deposition threshold a large number of numerical simulations have been done. For this calculations the values of the dimensionless parameters were chosen in the range $0.0022 \leq Oh \leq 0.03$, $85 \leq We \leq 900$ and $0.1 \leq \delta \leq 1.0$. The fluid properties have been chosen similar to the experimental investigations to get comparable results, water and water-glycerin mixtures have been used.

In Fig. 3 and Fig. 4 the Weber number as a function of the dimensionless film height δ for numerical and experimental investigations for two different Ohnesorge numbers is shown. The filled symbols are the experimental data, the open symbols are the numerical results. Circles are the symbols for deposition and triangles for splashing. In the numerical calculations splashing occurs at lower Weber numbers than in experimental investigations.

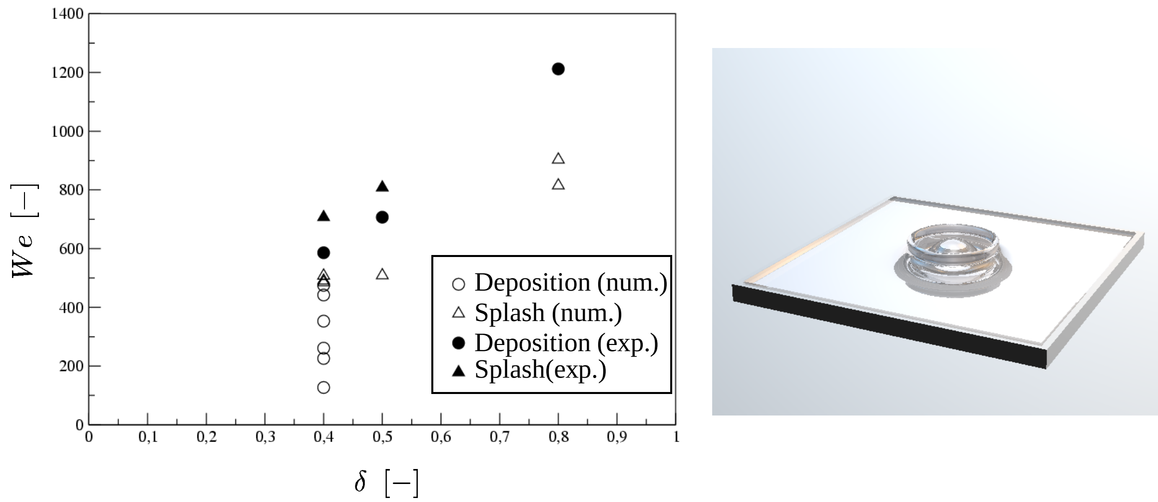

Figure 3: Comparison of experimental and numerical Weber numbers for the splashing threshold at different values of δ at $Oh = 0.0106$ and a picture of a numerical simulation of a deposition

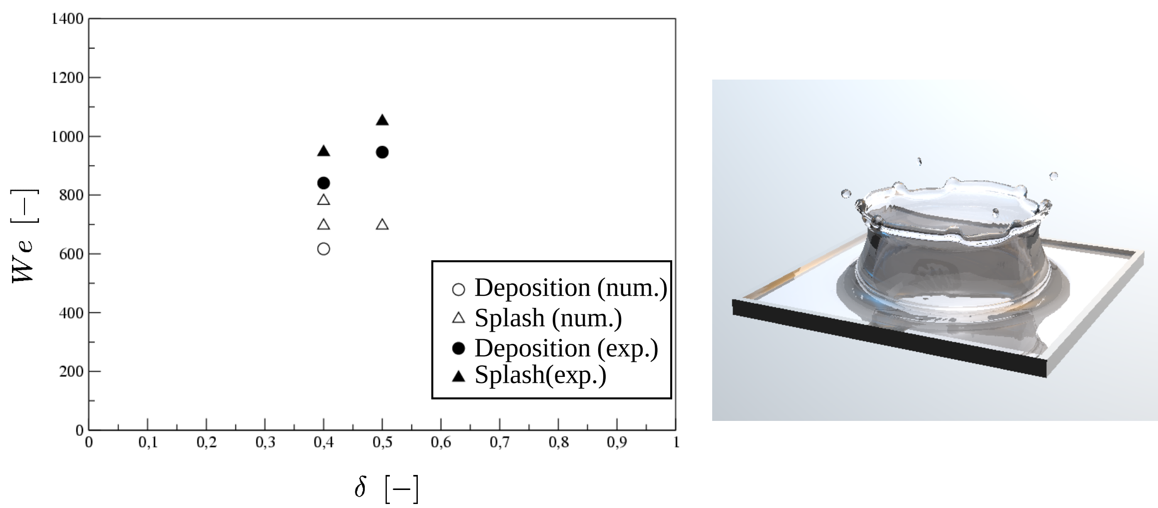

Figure 4: Comparison of experimental and numerical Weber numbers for the splashing threshold at different values of δ at $Oh = 0.031$ and a picture of a numerical simulation of a splash

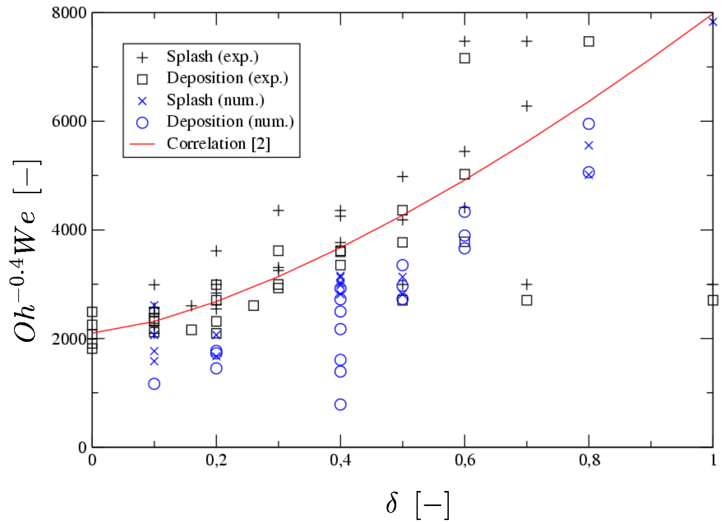

Figure 5: Splashing-threshold of *Cossali et al.* [3] dependent on non-dimensional film thickness δ

In Fig. 5 the numerical results together with the experimental results and the correlation of Cossali te al. [3] are shown. All numerically investigated cases are below the experimentally obtained splashing threshold. Reasons for that may be inaccuracies in experimental measurements, like problems in reproducing the film height and surface, and disturbances in the equipments which can not be modelled in the numerical simulations. Due to this inaccuracies it is not possible to determine a sharp splashing/deposition threshold, neither in experiment nor in numerical simulations.

As a result of the differences between the numerical and the experimental results, a new threshold was obtained accounting for both, the numerical and the experimental results. In terms of the application most calculations have been done with water. Therefore, the first step is to derive a correlation for water droplets.

The influencing values of the impact on a wetted wall investigated in this study are: density ρ, viscosity μ, surface tension σ, droplet impact diameter d_I, impact velocity v_I and film height δ. Using dimensional analysis [6], it is possible to determine the characteristic dimensionless parameters. These are the Weber number, Ohnesorge number and the dimensionless film height. Accounting for the numerical results of water droplets, a correlation for a splashing/deposition threshold is obtained, which is shown in Fig. 6. The correlations are of the form

$$\frac{We^n}{Oh^m} = f(\delta). \tag{12}$$

In Fig. 6 the splashing threshold for water droplets is displayed. The numerically obtained splashes are denoted by triangles, the depositions by circles. The continous line is the correlation for water droplets mentioned in Eq. 12.

The correlation devides the investigated range into two regions, below the line there are only depositions, above the line there are only splashes. As mentioned before in spite of the correlation for water droplets it is not possible to obtain a sharp splashing threshold. By considering the numerical results for other species values it is evident that the correlation does not hold for all numerical results. Thus a correlation was obtained, holding for both, all numerical and experimental results. For that a lower and an upper limit was obtained. In Fig. 7 all three correlations are shown together with all numerical and the experimental results. The lower and the upper limit devides the domain into three regions: a deposition region and a splashing

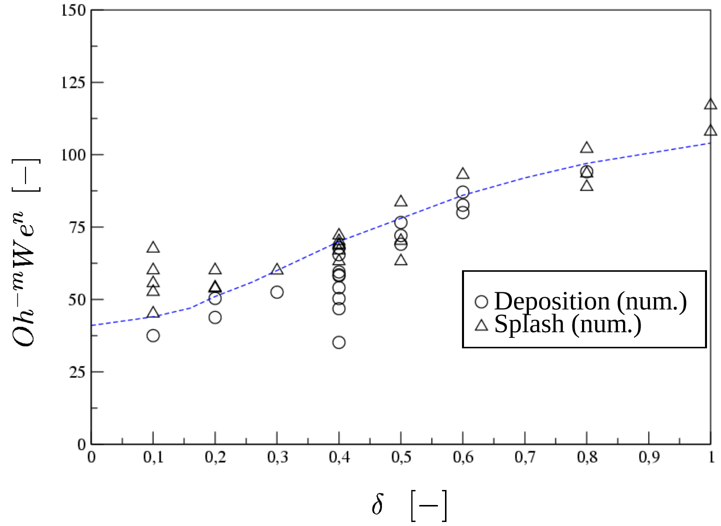

Figure 6: Splashing-threshold for water dependent on non-dimensional film thickness δ

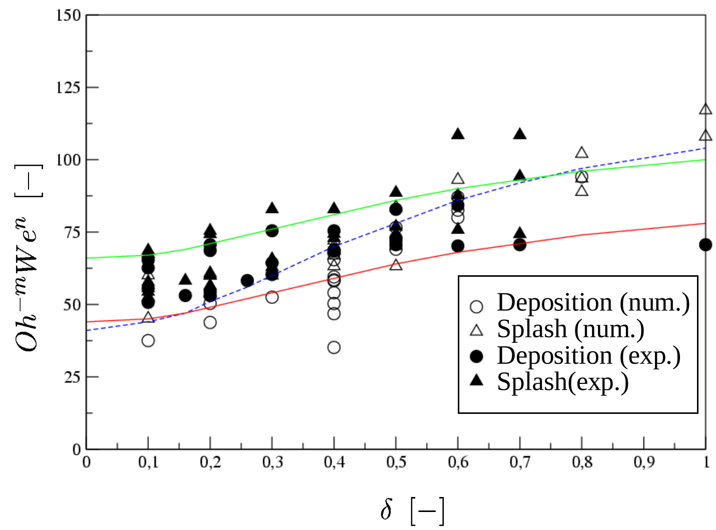

Figure 7: Splashing-threshold for water and the upper and lower limit dependent on non-dimensional film thickness δ

region and a transition area between this two regions in which both, deposition and splashing, can occur. The differences between the correlations are only constant values. In terms of the application in numerical models this is a great advantage. The width of the transition area is constant.

$$\Delta = \left(\frac{We^n}{On^m}\right)_{upper} - \left(\frac{We^n}{On^m}\right)_{lower} = 22. \tag{13}$$

The difference between the velocities belonging to the upper and lower limit is dependent on the species values and the droplet diameter as shown in Eq. 14:

$$\Delta u = \Delta \cdot \left(\frac{\sigma^3 \mu^2}{\rho^5 d^5}\right)^m. \tag{14}$$

For a water droplet with diameter $d_I = 1 \cdot 10^{-3}\, m$, the velocity range in the transition area

is $\Delta u = 1.47\,m/s$. For this droplet the critical velocity range for an impact on a film with height $h = 5 \cdot 10^{-4}\,m\,(\delta = 0.5)$ is $4.27\,m/s \leq u_I \leq 5.73\,m/s$, that means splashing occurs above an impact velocity of $5.73\,m/s$, while between $4.27\,m/s$ and $5.73\,m/s$ there is no exact declaration possible.
Because of the need of different correlations for different fluid properties it is supposed that there are other parameters which influence the droplet impact on a wetted wall not investigated in this study.

6. Conclusion

Two different phenomena of droplet wall interactions have been investigated in this study. The spreading of a droplet on a dry wall and the impact of a droplet on a wetted wall. These phenomena have been calculated by using *Direct Numerical Simulation*. Two previous investigations about these phenomena were found in literature and were recalculated in this study. A correlation for the maximum extension of a droplet impinging on a dry surface could be confirmed, and a new splashing/deposition threshold has been developed.

7. Acknowledgement

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