PAPER • OPEN ACCESS

Numerical simulation of drop impingement and bouncing on a heated hydrophobic surface

To cite this article: N. Samkhaniani *et al* 2021 *J. Phys.: Conf. Ser.* **2116** 012073

Numerical simulation of drop impingement and bouncing on a heated hydrophobic surface

N. Samkhaniani[1], H. Marschall[2], A. Stroh[1], B. Frohnapfel[1], M. Wörner[3]

[1] Karlsruhe Institute of Technology (KIT), Institute of Fluid Mechanics, Kaiserstr. 10, 76131 Karlsruhe, Germany
[2] Computaional Multiphase Flow, Technische Universität Darmstadt, Alarich-Weiss Str. 10, 64287 Darmstadt, Germany
[3] Karlsruhe Institute of Technology (KIT), Institute of Catalysis Research and Technology, Engesserstr. 20, 76131 Karlsruhe, Germany

E-mail: nima.samkhaniani@kit.edu

Abstract. The heat transfer of a single water droplet impacting on a heated hydrophobic surface is investigated numerically using a phase field method. The numerical results of the axisymmetric computations show good agreement with the dynamic spreading and subsequent bouncing of the drop observed in an experiment from literature. The influence of Weber number on heat transfer is studied by varying the drop impact velocity in the simulations. For large Weber numbers, good agreement with experimental values of the cooling effectiveness is obtained whereas for low Weber numbers no consistent trend can be identified in the simulations.

1. Introduction

Heat transfer on drop impact is important for various industrial applications such as spray cooling and fuel injection [1] or injection of urea-water solution sprays into automotive exhaust pipes for selective catalytic reduction [2].

Various parameters such as drop diameter (d_0), drop impact velocity (V_0), gas-liquid surface tension (σ), surface topology and wettability (static contact angle θ_e) determine the droplet behaviour after impact on the hot surface. The main characteristic non-dimensional number is the Weber number $We = \rho {V_0}^2 d_0/\sigma$. The outcome of drop impact can be deposition, rebounding or splash [3]. Also evaporation may occur during contact time based on solid (T_s) and drop temperature (T_d). Surfaces in contact with the water droplet can be classified into hydrophilic ($\theta_e < 90$) and hydrophobic ($\theta_e > 90$). Surfaces which are fabricated with micro/nano textures can become super-hydrophobic ($\theta_e > 130$), see Fig. 1.

Pasandideh-Fard et al. [4] studied the impact of a water droplet on a hot hydrophilic stainless steel surface using a VOF model and compared it with experiments. In another study with the VOF method, Strotos et al. [5] investigate fluid flow and heat transfer during droplet impingement. Their study proposed a simplified model to calculate the cooling effectiveness on droplet impact based on the exact analytical solution of two contacting semi-infinite media. Roisman [6] reported a similarity solution for spreading of the liquid film on a flat plate. The method was applied to estimate the heat transfer of impinging droplets yielding good agreement with experiments [7].

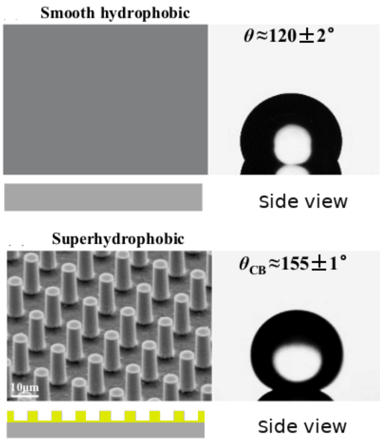

Figure 1. Smooth hydrophobic vs super-hydrophobic fabricated surface. Picture is taken from [8].

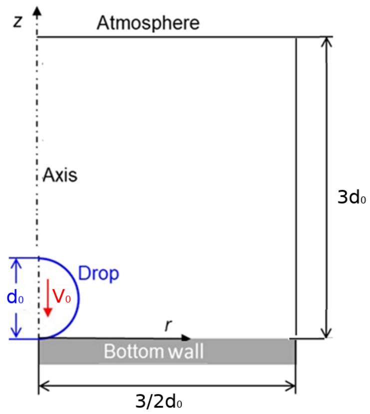

Figure 2. Schematic representation of computational set-up for drop impact on solid surface.

To the authors' best knowledge, the heat transfer during the impact of a single droplet on hydrophobic walls has not been thoroughly investigated before. Therefore, the focus of the present study is simulating this phenomena with the in-house solver phaseFieldFoam extended for heat transfer, and validating it against experimental data of Guo et al. [8].

2. Numerical method

The present computations are performed by a phase field method with the coupled Cahn-Hillard-Navier-Stokes equations for two incompressible and immiscible phases being solved by OpenFOAM-extend. For details on governing equations, numerical implementation and validation of the solver *phaseFieldFoam* the reader is referred to [9, 10]. In this study, the solver has been extended by the energy equation

$$\frac{\partial T}{\partial t} + \nabla(\mathbf{u}T) = \nabla \cdot \left(\frac{k}{\rho C_p} \nabla T \right). \tag{1}$$

Here, $\mathbf{u}$ denotes the velocity field and T is temperature. The thermo-physical properties $\Theta \in [k, \rho, C_p]$ are taken from [8] and are calculated through arithmetic interpolation in the interface region

$$\Theta = \frac{1+C}{2}\Theta_L + \frac{1-C}{2}\Theta_G. \tag{2}$$

Here, C is the order parameter bounded between $-1, 1$; the subscripts L and G represent the liquid and gas phase, respectively. As the inertia force is dominant in the present study, the variation of surface tension with temperature is neglected and the surface tension is $\sigma = 0.072$ N m^{-1}. The drop properties are: $\rho_L = 998$ kg m^{-3}, $C_{pL} = 4200$ J kg^{-1} K^{-1}, $k_L = 0.6$ W m^{-1} K^{-1} and for air: $\rho_G = 1.29$ kg m^{-3}, $C_{pG} = 1006$ J kg^{-1} K^{-1}, $k_G = 0.026$ W m^{-1} K^{-1}.

3. Result and discussion

3.1. Problem definition

The schematic of the problem is shown in Fig. 2. At the bottom wall, no slip condition, constant temperature ($T_s = T_d + 40$°C) and fixed contact angle $\theta_e = 120$ are applied. At atmosphere boundary, the *totalPressure* with homogeneous Neumann boundary condition for velocity and

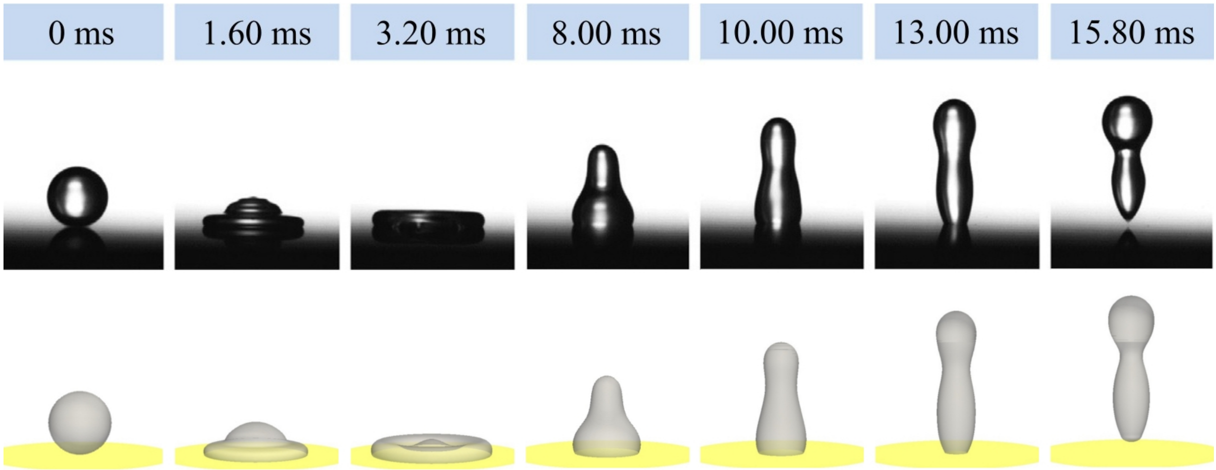

Figure 3. Image sequence of bouncing droplet ($d_0 = 2.3$ mm, $We = 20, T_{d,0} = 20°C$) on the smooth hydrophobic surface ($\theta_e = 120, T_s = 60°C$). Top: experiment [8], bottom: simulation.

order parameter are used. The solver is capable of 3D simulations, but the drop behavior in our range of interest is axisymmetrical, so in order to reduce the computational cost, a 2D axisymmetric computational domain is chosen. The grid is created with the OpenFOAM mesh generator *blockMesh*. The domain size is $1.5d_0 \times 3d_0$, filled with uniform cells of width $d_0/200$ corresponding to Cahn number $Cn = \varepsilon/d_0 = 0.01$ where ε is the interface thickness.

3.2. Validation

In Fig. 3, the sequence of drop impact ($d_0 = 2.3$ mm, $We = 20$) on a smooth heated surface is compared with experimental data [8]. After impact, the drop spreads over the plate, the numerical simulation resolves the capillary waves on interface at time $t = 1.6$ ms where the drop has a cupcake shape. The stretching continues until the drop reaches its maximum spreading at $t = 3.2$ ms, then recoiling starts and the drop eventually bounces back from the surface. The spreading ratio ($\beta = d/d_0$) is plotted in Fig. 4 For quantitative comparison. Fig. 5 shows the effect of increased impact velocity (We number), for which the drop wets a larger area and reaches its maximum spreading ratio β_{max} in a smaller time interval $t_{\beta_{max}}$. In contrast, the contact time t_c remains in the range $t \in [14, 16]$ ms. Thus, a thinner liquid film layer forms for larger impact velocities and a larger portion of the drop is in direct contact with the heated solid. In consequence, the mean droplet temperature T_d increases rapidly during the spreading stage as shown in Fig. 6. The drop mean temperature increases till the middle of recoiling stage. Afterwards, the drop cools down since a large part of the drop surface is in contact with the cool ambient air and the related heat loss outweighs the heat transfer from the hot solid.

The overall cooling effectiveness is defined as $\chi = (T_{df} - T_{d0})/(T_w - T_{d0})$, where T_{df} refers to droplet temperature right before the second impact onto the surface. It represents the ratio of the actual heat transfer to the maximum heat that could be transferred to the droplet [4]. The spreading ratio β and contact time t_c defines the value of heat transferred to the drop. The numerical results compared with experimental data [8] are shown in Fig. 7 for $We \in [5 - 40]$. It indicates the increase in drop impact velocity (We number) in general increases the cooling effectiveness. But the non-linear profile is compatible via variation of drop spreading ratio β and contact time t_c with We number in Fig. 5.

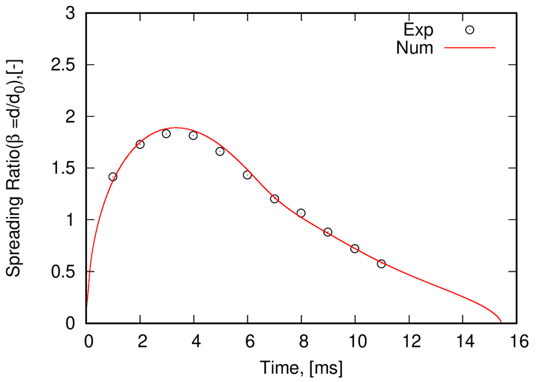

Figure 4. Spreading ratio in experiment [8] and simulation ($We = 20$).

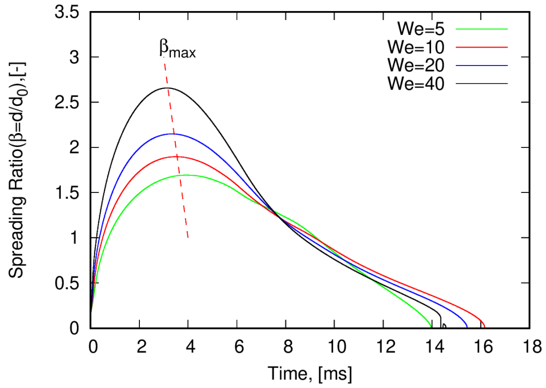

Figure 5. Effect of We on maximum spreading ratio (β_{max}) for $d_0 = 2.3$ mm.

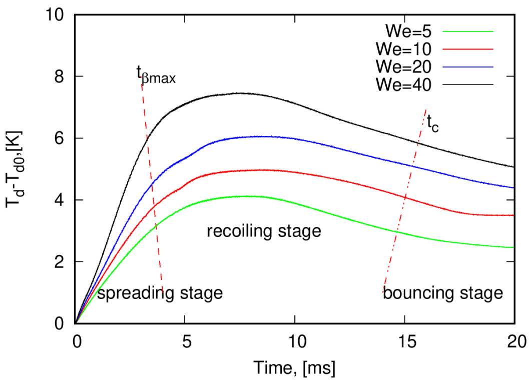

Figure 6. Effect of We for $d_0 = 2.3$mm on time evolution of mean drop temperature.

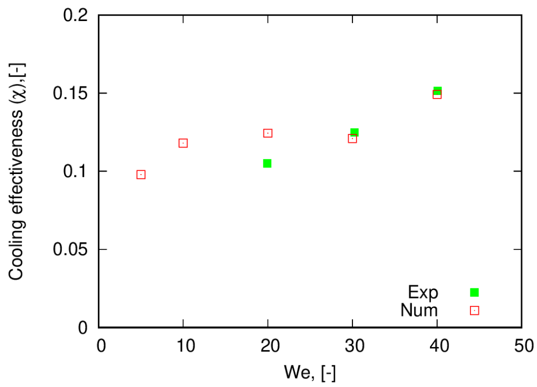

Figure 7. Influence of We on cooling effectiveness (experimental data from [8]).

4. Summary

The in-house solver *phaseFieldFoam* has been extended by the energy equation and is used to study heat transfer during drop impingement. The solver is validated by a comparison of the numerical results with experimental literature data. While good agreement is found for higher Weber numbers, no consistent trend for cooling effectiveness can be identified for low Weber numbers. This deserves further investigations. The present study is limited to the smooth surfaces with contact angle $\theta_e = 120$. In future studies, we intend to investigate heat transfer during drop impingement on computationally resolved non-smooth surface structures.

References

[1] Liang G and Mudawar I 2017 *Int. J. Heat Mass Transfer* **106** 103–126
[2] Börnhorst M and Deutschmann O 2018 *Int. J. Heat Fluid Flow* **69** 55 – 61
[3] Rioboo R, Marengo M and Tropea C 2002 *Exp. Fluids* **33** 112–124
[4] Pasandideh-Fard M, Aziz S, Chandra S and Mostaghimi J 2001 *Int. J. Heat Fluid Flow* **22** 201–210
[5] Strotos G *et al.* 2011 *Int. J. Thermal Sciences* **50** 698–711
[6] Roisman I V 2010 *J. Fluid Mech.* **656** 189–204
[7] Batzdorf S *et al.* 2017 *Int. J. Heat Mass Transfer* **113** 898–907
[8] Guo C, Maynes D, Crockett J and Zhao D 2019 *Int. J. Heat Mass Transfer* **137** 857–867
[9] Cai X, Wörner M, Marschall H and Deutschmann O 2016 *Catalysis Today* **273** 151–160
[10] Cai X, Marschall H, Wörner M and Deutschmann O 2015 *Chem. Eng. Technol.* **38** 1985–1992