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Heat transfer during simultaneous impact of two drops onto a hot solid substrate

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ABSTRACT

A numerical method based on the Volume-of-Fluid approach has been used for simulating the simultaneous collision of two drops with a solid substrate. Heat transfer in the substrate and in the drop have been evaluated during the drop spreading and receding phases. The numerical model includes the liquid evaporation from the drop surface and especially in the neighborhood of the moving contact line. The evolution of the heat transfer rate at the liquid/substrate interface is also modelled theoretically by considering the development of the thermal boundary layers in the solid wall and in the spreading drop. The theoretical model does not take into account the effect of drop evaporation on the overall heat transport. It is shown that at high Prandtl numbers the heat flow is mainly determined by the instantaneous wetted area while for Prandtl numbers of order unity, the contribution of evaporation is significant. As a result, at high values of Prandtl number the agreement between the theoretical model and numerical prediction is significantly better than at the Prandtl number values of order unity.

1. Introduction

Numerous industrial and natural processes involve drop impact onto a solid substrate. Among these processes are the fuel spray injection into cylinders of internal combustion engines, spray painting, touchless cleaning, printing, spray coating, and many others. Several comprehensive reviews describing the drop impact and the state-of-the-art modeling can be found in [1–3]. Spray cooling [4–8] is one of the promising technologies for removal of high heat fluxes from hot surfaces, for example, for cooling of high-power electronic devices. Spray cooling is also used in metallurgy [9] and in medicine for cryogenic tissue cooling. During spray cooling or thermal spray processes [10,11], the temperatures of the drop and of the substrate are different. In spray cooling, the drops interact with each other on the substrate. The influence of these interactions on overall heat transport rate between the substrate and the spray has not yet been thoroughly studied. The hydrodynamics and transport processes are even more complicated for structured surfaces [12] or for intermittent spray [13].

When a drop impacts onto a solid substrate, it spreads and generates a radial flow in a thin lamella on the substrate. The lamella is bounded by a rim, formed by the action of viscous and capillary forces [14,15]. If the impact velocity is above a certain threshold value, splashing of liquid takes place [16,17]. In case of a non-pinning contact line the spreading phase is followed by a receding phase, where the wetted area shrinks again. The dynamics of spreading and receding is determined by the Reynolds and Weber numbers, $Re = D_0U_0/\nu_l$ and $We = \rho_l D_0 U_0^2/\sigma$, as well as the contact angle θ between the liquid and the substrate material. Here D_0 and U_0 are the initial drop diameter and impact velocity, ν_l, ρ_l and σ are the kinematic viscosity, density and surface tension of the liquid, respectively.

If two drops impact simultaneously onto a smooth, dry, solid substrate, the interaction of the flow in their respective lamellae leads to the emergence of an uprising sheet [18]. However, the free parts of the rim continue to expand, not influenced by the interaction (see Fig. 1). This effect has been observed in the case of inertia dominated drop impacts with high Reynolds and Weber numbers.

A simultaneous impact of two drops onto a smooth, dry and solid substrate has been studied numerically in the framework of the phase-field lattice Boltzmann method [19]. In this numerical work the two drops had different impact velocities. In addition, the effect of the tangential component of impact velocity of one of the drops has been studied. It has been shown that the free part

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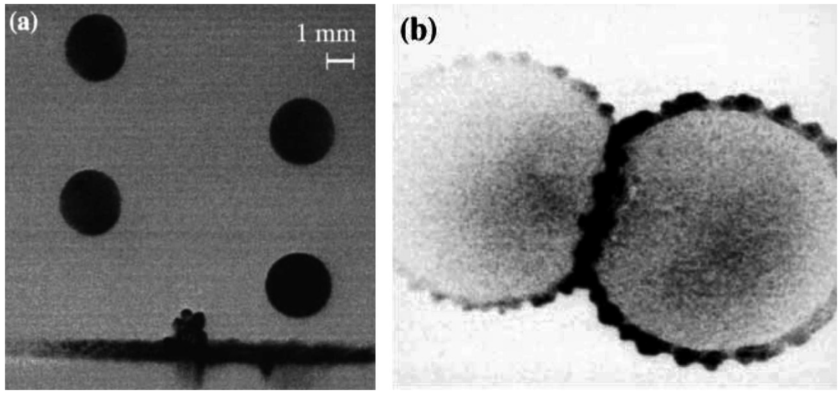

Fig. 1. Impact of two water drops interacting on a steel substrate. $D_0 = 2.5$ mm, $U_0 = 3.36$ m/s, $\Delta t = 0.9$ ms, $\Delta x = 8.4$ mm. (a) Side views at three different times, third exposure at $t = 2.81$ ms; (b) top view, $t = 2.81$ ms; Experiments from [18]. With permission from Elsevier.

of the rim of the drop having the higher impact velocity expands, not influenced by interaction with the second drop.

If a drop impacts onto a hot substrate, the possible outcomes can be subdivided into several regimes: drop deposition, nucleate boiling, transition and film boiling regimes [20–22]. Examples of different hydrodynamic regimes of drop impact onto a hot substrate are shown in Fig. 2, illustrating the deposition (A), partial rebound, associated with the nucleate boiling (B), complete rebound during film boiling regime (C) and atomization (D). Heat transfer during different regimes of drop impact has been investigated experimentally [23–27] and modeled numerically [28–31].

In [30] the hydrodynamics and heat transfer during single drop impact onto a substrate heated above the saturation temperature in the deposition regime have been simulated numerically using the Volume-of-Fluid approach and studied experimentally. To the best of our knowledge, this is a first work in which the interaction between the hot solid wall and the impacting drop has been modelled taking into account evaporation at the free boundary and the microscopic thermodynamic effects near the three-phase contact line. In [30] three phases of drop dynamics have been considered: initial spreading phase, in which the fluid motion is dominated by inertia, the receding phase, and finally the sessile drop evaporation phase. The evolution of global heat transfer rate and the contribution of different heat transfer mechanisms have been quantified during different phases of the drop dynamics. It has been found that for the set of parameters studied ($Re = 956$, $We = 14$) the maximal heat transfer rate is reached during the spreading phase, in which the heat transfer between the solid wall and the fluid is dominated by heat convection.

The main subject of the present study is to model the heat transfer during simultaneous impact of two drops onto a hot solid substrate in the deposition regime. Simultaneous impact of two

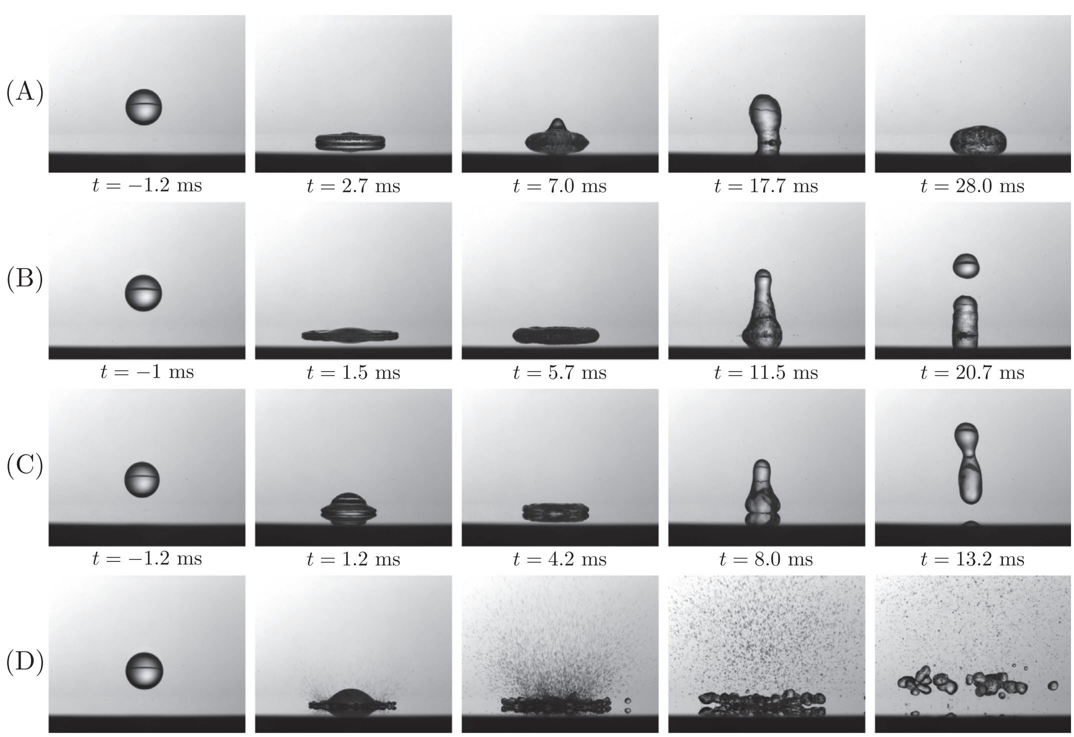

Fig. 2. Examples of different hydrodynamic regimes of a water drop impact onto a hot substrate: (A) deposition ($T_{w0} = 393$ K, $D_0 = 2.2$ mm, $U_0 = 0.72$ m/s), (B) partial rebound ($T_{w0} = 413$ K, $D_0 = 2.2$ mm, $U_0 = 1.50$ m/s), (C) total rebound ($T_{w0} = 563$ K, $D_0 = 2.2$ mm, $U_0 = 0.72$ m/s), and (D) atomization ($T_{w0} = 563$ K, $D_0 = 2.2$ mm, $U_0 = 1.50$ m/s).