Heat transfer mechanisms at drop/wall interactions: experiments and theory

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Abstract

The present paper concerns the experimental and theoretical study of the thermal behaviour of drop impacts onto heated solid substrates. The experiments address the measurement and determination of the instantaneous substrate and contact temperatures at drop impact within a wide range of conditions. The experimental analysis is complemented with a theoretical model for a flow and temperature fields in a spreading drop and concerning the accurate determination of the contact temperature.

The results are in rather good agreement with the model and emphasize that besides its dependence on the thermal effusivities of the liquid and of the substrate, the contact temperature is a function also of the Prandtl number.

Introduction

The study of the heat transfer mechanisms occurring at drop/wall interactions is motivated by a variety of applications, from ink jet printing to cooling applications (*e.g.* in metallurgy [1], electronics [2] or laser dermatological procedures [3]). The accurate description of the heat transfer processes occurring at drop/wall interface is of major importance to optimize the cooling performance of such systems. In this context, the present work addresses the experimental and theoretical analysis on the heat transfer mechanisms occurring between single drops and heated solid substrates. The experiments encompass the measurement and determination of the instantaneous substrate and contact temperatures, for different impact conditions and a variety of thermodynamic properties of the liquid and the solid. A theoretical model is proposed to describe the heat transfer occurring between the spreading drop and the solid substrate, particularly focusing on the analysis of the liquid-solid contact temperature.

Additionally, the effect of surface topography is also investigated using micro-textured surfaces of different materials, to infer on an adequate way to include this effect in the theoretical description of the phenomena observed during drop interactions with the heated wall.

Materials and Methods

Drops of various liquids fall onto the substrates by action of gravity onto solid heated surfaces with different characteristics, within a wide range of impact velocities ($1.3\ \mathrm{ms}^{-1} < u_0 < 3.1\ \mathrm{ms}^{-1}$).

Instantaneous substrate and contact temperatures are obtained at drop impact for substrates of different materials, heated from ambient temperature up to slightly above the boiling temperature of the working fluids (maximum initial surface temperature, $T_{w0,max}$=120ºC).

A theoretical model for impact and spreading of a single drop onto a hot substrate is based on a self-similar analytical solution of the full Navier-Stokes equations for the flow in the lamella [5]. The similarity solution of the energy equation yields the expression for the temperature fields in the drop and in the target in the form of expanding thermal boundaries. The theory is able to predict the heat flux and the contact temperature. The model is validated by comparison of the theoretically predicted contact temperature with the experimental data.

Sample Results and Discussion

When the surface temperature is low enough to prevent liquid phase change, the impinging drop spreads over the surface as a thin lamella bounded by a rim. Since the temperatures of the drop and of the substrate are different, the temperature at the interface (i.e. the contact temperature) is determined by heat conduction in the substrate and by convection in the spreading drop. The value of the contact temperature determines the rate of heat exchange between the drop and the target. An explicit expression for the contact temperature was early proposed in [6] from the solution available for two-semi-infinite solids as $T_{c,\text{“conventional”}}=[(T_w.\ \varepsilon_w+T_l.\varepsilon_l)/(\ \varepsilon_w+\varepsilon_l)]$, be-

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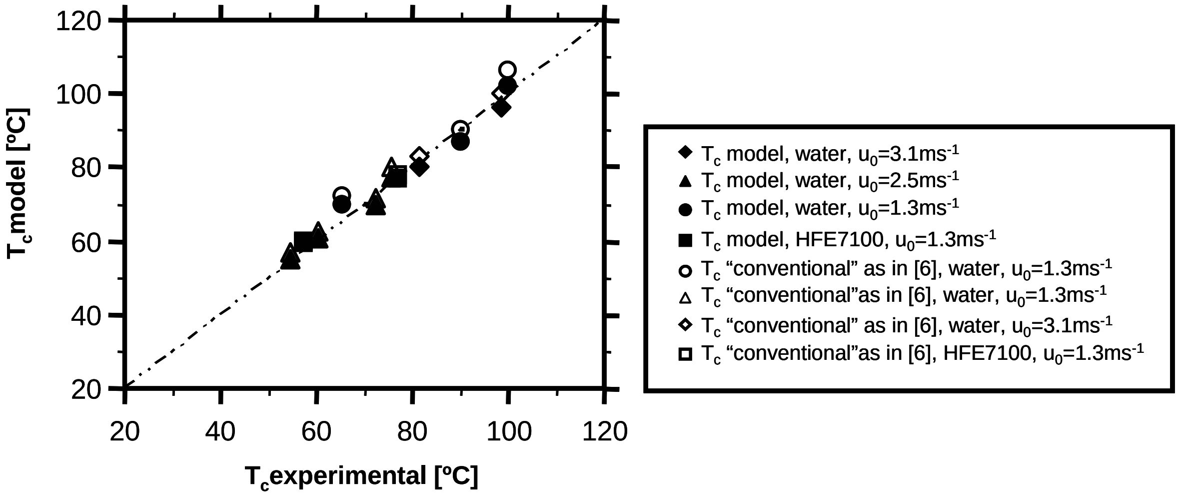

Figure 1. Comparison between the contact temperatures determined by the proposed model and the expression suggested in [6], for different impact conditions on a smooth stainless steel surface (R_a=0.311μm, R_z=2.32μm).

ing ε_w and ε_l the thermal effusivities of the substrate and of the liquid, respectively, with $\varepsilon=(\rho k C_p)^{1/2}$, where ρ is the density, *k* the thermal conductivity and C_p the specific heat. The model proposed here suggests an alternative expression, valid for times when the thickness of the thermal and viscous boundary layers is smaller than the thickness of the lamella generated by drop impact. In a dimensionless form such times can be usually written as $\tau = tD_0/u_0 < 2$, with D_0 being the initial drop diameter,

$$T_c=[(T_{w0}.\ \varepsilon_w.\mathrm{I}(\mathrm{Pr},0,\infty)+T_{d0}.\varepsilon_l)/(\ \varepsilon_w.\ \mathrm{I}(\mathrm{Pr},0,\infty)+\varepsilon_l)] \tag{1}$$

where I is a function of the Pradtl number obtained from the theory. Figure 1 shows that the predictions of this model agree well with the experimental results, for impacts on smooth surfaces, and even seem to be better suited than the "conventional" contact temperature, at higher surface temperatures, for the cases at which the variation in the Prandtl number is larger.

Additional studies are performed with micro-structured surfaces, which are known to affect significantly the thermal and fluid-dynamic phenomena occurring at drop/wall interactions. Hence, with the aim of relating the topographical parameters with the phenomena described in the existing theories, the effect of the micro-structures is quantified by the dimensionless topographical parameter R_a/λ_R (being R_a the mean roughness and λ_R the fundamental wavelength, i.e. the pitch between the rough grooves) and by a modified contact angle θ_R. The results show a relation between these parameters, and particularly of R_a/λ_R with the instantaneous surface temperature, in agreement with the observations reported in [7].

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