Colloids and Surfaces A: Physicochem. Eng. Aspects 432 (2013) 57–63

Contents lists available at SciVerse ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

Influence of the governing dimensionless parameters on heat transfer during single drop impingement onto a hot wall

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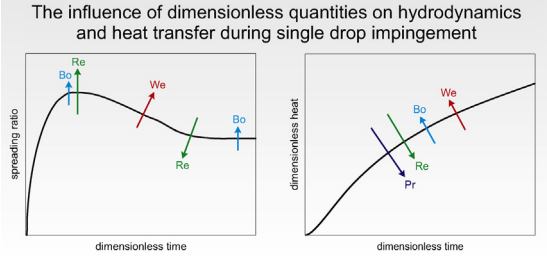
HIGHLIGHTS

- We numerically model heat and mass transfer during single drop impingement.
- A dimensionless analysis is performed.
- The influence of various dimensionless quantities (Re, We, Bo and Pr) on convective and evaporative heat transfer is evaluated independently.
- The heat transfer is increasing with decreasing Reynolds or Prandtl number and increasing Weber or Bond number.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 1 March 2013
Received in revised form 2 May 2013
Accepted 3 May 2013
Available online 10 May 2013

Keywords:
Evaporation
Moving contact line
Drop impact

ABSTRACT

The cooling effectiveness of spray cooling is strongly influenced by droplet size and velocity as well as by the fluid properties. To enhance the understanding of the entire process, first of all basic processes occurring in the spray have to be addressed. Therefore, in this study the heat transfer during a single drop impingement onto a dry, superheated wall is investigated numerically, and the effects of the dominating dimensionless parameters on the convective and evaporative heat transfer are analyzed. In order to be able to distinguish between the influences of the individual dimensionless groups, each parameter is varied individually. The study is performed using fluid properties of the refrigerant FC-72. The droplet is surrounded by a saturated vapor atmosphere. The numerical model accounts for the complex two-phase flow, the transient conductive heat transfer within the solid domain and the evaporative mass transfer. Special attention is paid to the local heat and mass transfer close to the moving three-phase contact line. The spreading phase appears to be dominated by the Reynolds number, while in the receding phase the Weber number has the strongest influence on heat transfer. For the evaporation of a sessile droplet, which is the final stage of the impact process, the heat transfer is governed by the Bond number.

1. Introduction

Modeling spray cooling heat transfer at a hot wall like e.g. done by Landero et al. [1] requires integral sub-models for the hydrodynamic behavior as well as the convective and evaporative heat transfer during droplet-wall collisions depending on a variety of droplet impact parameters.

In the past decades lots of experimental and numerical studies have been performed addressing the hydrodynamic behavior of droplet during drop impingement under isothermal conditions. A comprehensive review on these studies is given by Yarin [2]. Numerical simulations of the hydrodynamics have been done by Fukai et al. [3], investigating also the influence of Reynolds and Weber number on the spreading diameter of the droplet.

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http://dx.doi.org/10.1016/j.colsurfa.2013.05.014

Heat transfer was taken into account by Zhao et al. [4]. They have investigated numerically the effect of initial droplet velocity and the substrate material on convective heat transfer. The highest heat transfer rate was detected during the beginning of the spreading phase. The effect of substrate temperature on heat transfer has been investigated by Nikolopoulos et al. [5] close to the Leidenfrost temperature. For this case, a decrease of heat flow with increasing substrate temperature was observed in the parameter range corresponding to the transition boiling regime. Francois and Shyy [6] studied the effect of contact angle and impact velocity on heat transfer. Additionally, the influences of Reynolds and Weber number have been identified. The average Nusselt number was found to decrease with increasing Reynolds numbers. The effect of Weber number turned out to vary during the impingement process. In the initial phase of the impact the Nusselt number increased with Weber number while it tended to decrease with increasing Weber number in the later stages of the impact.

In all these previous numerical studies the micro-scale heat transfer near the contact line has not been taken into account. However, this contribution to heat transfer has been found to be extremely important in case of boiling [7] and during drop impact [8]. Therefore, in this study we explicitly include the heat transfer near the contact line into our modeling approach.

In experimental investigations it is quite difficult to vary single dimensionless numbers without affecting the other ones. Usually, either the impact velocity is varied [9,10] effecting the Reynolds and Weber number simultaneously, or the effect of substrate temperature is quantified [11–13].

In this study, the influence of respective dimensionless parameters characterizing the hydrodynamic and thermal properties of a droplet on convective and evaporative heat transfer is shown. The usage of a numerical approach enables varying individual parameters independently and thereby identifying the key parameters in optimizing heat transfer.

2. Problem description

A schematic of the computational domain used in this study is given in Fig. 1. The thickness of the solid substrate and of the initial thermal boundary layer are kept constant to obtain identical thermal conditions for all cases. In contrast, the size of the fluid domain is scaled by the initial droplet diameter D_0. A locally refined block

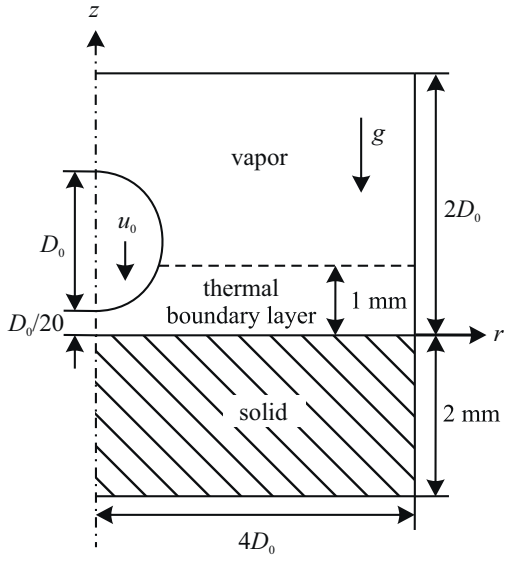

Fig. 1. Geometrical definitions and initial conditions of the drop impact.

Table 1
Mesh size in the fluid domain; the spacing is equal in r- and z-directions.

Radial coordinate, r	Axial coordinate, z	Cell size
$r \le 2D_0$	$z \le 0.5D_0$	Δx_{min}
$2D_0 < r \le 2.5D_0$	$0.5D_0 < z \le D_0$	$2\Delta x_{min}$
$r > 2.5D_0$	$z > D_0$	$4\Delta x_{min}$

structured mesh is used. The minimum cell size can be found in the interaction zone near the solid–fluid boundary, i.e. the region where the contact line and thereby the largest temperature gradients can be expected. Its value is set to $\Delta x_{min} = \min\{D_0/500, 2\,\mu m\}$ which results in an overall cell number of at least 429,500 cells in the fluid domain. The exact grid sizes in the different zones of the mesh in the fluid domain are given in Table 1. Doubling the minimal cell size results in a change in the maximal spreading ratio (spreading phase heat transfer) of about 0.8% (1.4%) for a typical parameter combination. So the presented results can be considered to be almost grid independent.

All calculations are performed on an axisymmetric grid as droplet deposition without any three-dimensional effects like splashing is expected in the investigated range of impact parameters. For example, Mundo et al. [14] observed splashing for $K = We^{0.5}Re^{0.25} > 57.7$ while in this study K is always smaller than 37.7. The droplet has initially a spherical shape and a uniform velocity but will produce a wake including a non-uniform velocity field inside the droplet before it touches the wall.

2.1. Initial and boundary conditions

The droplet and vapor temperature outside the thermal boundary layer are set equal to saturation temperature. The solid domain is initially uniformly superheated by $\Delta T_0 = T_{wall,0} - T_{sat}$. In the boundary layer between these both regimes a linear temperature profile is initialized. All outer boundaries of the domain are adiabatic.

For the fluid the material properties of the refrigerant FC-72 and for the solid the thermal properties of calcium fluoride glass are used.

2.2. Relevant dimensionless numbers

The hydrodynamic behavior of the droplet can be described by the Weber number

$$We = \frac{\rho_l D_0 u_0^2}{\sigma} \tag{1}$$

describing the ratio of inertial to surface tension forces and the Reynolds number

$$Re = \frac{\rho_l D_0 u_0}{\mu_l} \tag{2}$$

representing the ratio of inertial to viscous forces. In addition, sometimes the Ohnesorge number $Oh = We^{0.5}Re^{-1}$ is used in the literature. The influence of gravitational force is typically represented by the Bond number

$$Bo = \frac{\rho_l g D_0^2}{4\sigma} \tag{3}$$

For the definition of a dimensionless time τ the hydrodynamic time scale equal to the ratio of the initial droplet size to its velocity is used:

$$\tau = \frac{u_0 t}{D_0} \tag{4}$$