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Local heat transfer and phase change phenomena during single drop impingement on a hot surface

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ABSTRACT

Heat and mass transfer at a droplet impinging on a hot wall is investigated experimentally and numerically. The experiments are conducted with refrigerant FC-72 within a saturated vapour atmosphere. The droplet dynamics and the heater temperature very close to the solid–fluid interface are captured with high spatial and temporal resolution. The boundary conditions for the numerical simulations are chosen according to the experiments. The simulation accounts for the complex two-phase flow including evaporative mass transfer. Special attention is given to the local heat and mass transfer close to the moving three-phase contact line. Numerical and experimental results are compared to give insight into the basic heat transport mechanisms occurring during drop impact and to quantify their relevance for the overall heat transfer. It turns out that convective heat transfer is dominant during the initial stage of the impact corresponding to the droplet spreading, while at the final stage of the impact, corresponding to evaporation of a sessile droplet, a considerable part of the total heat transfer occurs in the direct vicinity of the three-phase contact line.

1. Introduction

Spray cooling can be a very efficient means of heat removal in numerous technical applications ranging from electronics cooling to metal quenching. Both, single phase convective heat transfer due to the fast moving liquid at the wall and heat removal by partial evaporation of the liquid contribute to the overall heat transfer performance. To enhance the fundamental understanding of the entire process it is necessary to take a detailed look at the basic mechanisms governing the spray cooling, including droplet–droplet collisions and the impact of single droplets onto a heated wall. This work is attributed to the latter process.

Most of the literature dealing with drop impact focuses on the isothermal case, in which heat transfer and evaporation are negligible. A comprehensive review on the hydrodynamic phenomena and flow patterns during the impingement process of droplets onto dry and pre-wetted walls is given by Yarin [1]. Fukai et al. [2] performed numerical calculations of the isothermal drop impact using a moving mesh approach. The gas phase was not included in their simulations. Ŝikalo et al. [3] investigated the effect of the dynamic contact angle model by Kistler [4] on the time evolution of the spreading radius utilising the VOF-method [5]. They reported only little effect of contact angle on the impact process in the spreading phase, but major influence of contact angle dynamics in the receding phase. Roisman et al. [6,7] used a theoretical approach for the description of the hydrodynamics during drop impact, accounting for the dynamic contact angle as well.

Heat transfer at the solid–liquid interface during droplet impingement onto cold walls has been studied numerically by Zhao and Poulikakos [8] using the approach of Fukai et al. [2] extended to heat transfer. Highest Nusselt numbers were found in the initial phase of the impact. Pasandideh-Fard et al. [9] included solidification of the liquid phase and performed also three dimensional simulations.

If the wall temperature is above the saturation temperature of the fluid, evaporation significantly affects the heat transfer during droplet impact. In this case the behaviour of the droplet is influenced by the wall superheat. If the surface temperature is above the Leidenfrost temperature, the droplet does not wet the surface, which leads to a drastic decrease of the heat transfer rate. Chatzikyriakou et al. [10] performed experiments for single droplets impinging on hot surfaces in this regime. They recorded the temperature at the solid–fluid interface and calculated the local wall heat flux.

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Nomenclature

A	dispersion constant (J)
Bo	Bond number
c	specific heat (J kg^{-1} K^{-1})
D_0	initial droplet diameter (m)
E^*	dimensionless heat
F	volume fraction
f	volumetric force (N m^{-3})
g	gravitational acceleration (m s^{-2})
h	energy source term (W m^{-3})
h_{lv}	enthalpy of vaporisation (J kg^{-1})
M_{evap}	evaporated mass (kg)
p	pressure (Pa)
Pr	Prandtl number
$\dot{q}$	heat flux (W m^{-2})
Q	heat (J)
$\dot{Q}_{cl}$	integrated contact line heat flux (W m^{-1})
R	radius (m)
Re	Reynolds number
R_{gas}	ideal gas constant (J kg^{-1} K^{-1})
R_{int}	interfacial heat resistance (m^2 K W^{-1})
S_{int}	area of liquid–vapour interface (m^2)
T	temperature (K)
t	time (s)
u	velocity (m s^{-1})
V	volume (m^3)
We	Weber number

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
δ	film thickness (m)
η	coordinate normal to wall (m)
θ	contact angle (°)
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ξ	coordinate parallel to wall (m)
ρ	density (kg m^{-3})
$\dot{\rho}$	mass source term (kg m^{-3} s^{-1})
σ	surface tension (N m^{-1})
χ	accommodation coefficient

Subscripts

ad	adsorbed film
cl	contact line
f	fluid
int	interface
l	liquid
sat	saturation conditions
s	solid
v	vapour

The highest heat flux at the solid–fluid boundary is expected for a surface temperature between the saturation and the Leidenfrost temperature. Experiments for different wall temperatures in this range have been performed by Chandra and Avedisisan [11]. They have investigated the effect of temperature on flow patterns and the total evaporation time of the droplets. Lee et al. [12] used a feedback-controlled heater array to ensure a nearly constant surface temperature during the drop impact. They reported a maximum heat flow during the spreading phase and a smaller second maximum during the droplet receding phase. Nikolopoulos et al. [13] and Strotos et al. [14,15] performed numerical simulations including the evaporation process into an air atmosphere. They accounted for the conjugated heat transfer between the hot solid substrate and the fluid.

Measurements of the local temperature distribution close to the solid–fluid interface have been presented by Sodtke et al. [16] and Weickgenannt et al. [17] for sessile droplets evaporating in a saturated and unsaturated atmosphere, respectively. A sharp decrease of surface temperature has been observed underneath the droplet, but no local temperature minimum near the three-phase contact line has been reported.

However, during pool boiling [18–22] a temperature minimum close to the three-phase contact line has been observed. Experimental and numerical studies confirmed that this temperature minimum is caused by a strong maximum in heat flux in this region. Further it has been shown that in case of pool boiling the heat transfer close to the contact line can contribute considerably to the overall heat transfer. For example, Wagner et al. [23] reported that a fraction of 20–30% of the overall heat is transferred in this region. Even though no temperature minimum has been reported at the contact line in measurements of drop impact, it can be suggested that evaporation near the three-phase contact line plays a significant role in heat transfer by a single drop impact, too.

To the authors' knowledge, up to now no attempt has been made to model the interactions between a heated solid wall and an impacting droplet taking into account evaporation at the free boundary as well as microscopic thermodynamic effects near the three-phase contact line.

2. Experimental setup

A schematic of the core of the experimental setup is depicted in Fig. 1. It consists of a closed chamber with several windows providing optical access. The walls of the chamber are held at constant temperature in order to keep the temperature inside the test chamber homogeneous and close to saturation conditions at atmospheric pressure. The fluid used is the refrigerant FC-72. The saturation temperature of this fluid is 329.75 K at atmospheric pressure. To ensure a pure vapour atmosphere within the test chamber, the gas atmosphere is exhausted several times prior to the experimental run. Thereby residual air is removed and the purity of the vapour atmosphere is increased.

At the top of the chamber a small needle is placed which is slightly subcooled against the saturation temperature. A droplet is formed at the needle tip by condensation of the surrounding vapour. Since the detachment of the droplet is controlled by the balance of gravity and surface tension forces, the diameter of the droplet is highly reproducible. By changing the distance between the heater and the needle the impact velocity can be varied.

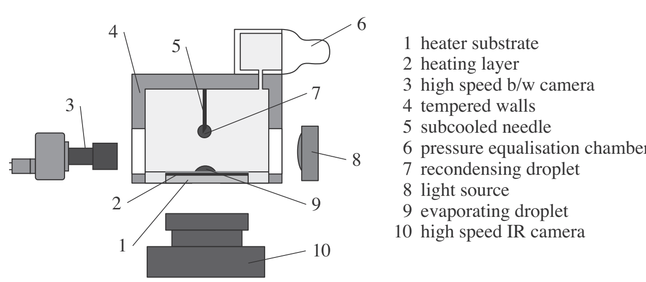

Fig. 1. Experimental setup.