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Numerical investigation of droplet spreading and heat transfer on hot substrates

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ABSTRACT

Droplet spray cooling has wide applications in electronic cooling, steam generators, evaporators and condensers etc due to its high efficiency. The cooling effect depends on the droplet spreading dynamics greatly. In our study the transient two-dimensional axisymmetric model for droplet cooling is developed with a level set method, where the dynamics of the moving contact line is described with the Molecular Kinetic Theory (MKT). After validation with experimental data, the effect of impact velocity, surface tension, initial droplet radius, equilibrium contact angle and liquid viscosity on droplet spreading is investigated. It is found that the dynamics of the moving contact line can be described accurately with MKT, and the predicted droplet spreading radius agrees quite well with the experimental data, while the Constant Contact Angle (CCA) model overpredicts the droplet spreading rate. The maximum heat flux occurs at the point when the droplet spreading transits from capillary-inertial spreading to capillary-viscous spreading. The droplet spreading rate will increase with the increasing impact velocity, surface tension and initial radius, or decreasing equilibrium contact angle and liquid viscosity. Due to the effect of thermo-capillary force, the cold substrate can promote the droplet spreading, and the hot substrate can retard the droplet spreading. These findings may be of great significance for effective droplet spreading cooling.

1. Introduction

Spray cooling is an effective way for rapid heat removal from the solid surfaces, it is widely used in electric cooling [1], steam generators, liquid evaporators, condensers in industry [2]; furthermore, it can also be used in medicine to cool down the outer layer of the human skin during dermatological laser treatments [3]. During spray cooling there are mainly two distinct stages, named the initial spreading stage and the later evaporation stage [4]. Although the spreading stage is much shorter than the evaporation stage, and the amount of heat transfer during this stage is insignificant, the initial droplet spreading has substantial effect on the liquid coverage and the subsequent evaporation heat transfer [5], hence comprehensive studies have been carried out in this area.

Pasandideh-Fard et al. [6] studied the water droplet impinging cooling on a hot surface, they revealed that increasing impact velocity can enhance the heat flux from the substrate by only a small amount, due to the effect that the wetting area for heat transfer is not increased too much under high impact velocity. They also found that at a fixed Reynolds number the cooling efficiency increases with Weber number, however, at large Weber numbers, the cooling efficiency depends only on the Prandtl number, independent of the droplet impact velocity or size. Moon et al. [7] studied the effect of wetting states (i.e., non-wetting, partial-wetting and total-wetting) on the heat transfer of an impinging droplet on textured substrate; they also examined the effect of impact Weber number, surface temperature and textured area fraction on the heat transfer. They further studied the spreading and receding characteristics of a non-Newtonian droplet impinging on a heated surface [8], and found that the maximum spreading diameter for a Newtonian DI-water droplet is larger than that of a non-Newtonian droplet because of the difference in liquid viscosity. In the spreading regime, the dynamic contact angle is almost similar for the Newtonian and non-Newtonian droplets, but in the receding regime, it substantially changes with temperature due to the variation of viscosity with temperature. Ganesan et al. [9] investigated the non-isothermal droplet impact on a heated solid substrate with circular heterogeneous wettability. The heterogeneous wettability was incorporated into the arbitrary

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Nomenclature

A	fitting parameter	δ	dirac delta function
B	fitting parameter	ε	non-dimensional thickness of interface
Bo	Bond number	ϕ	distance function
Ca	Capillary number	λ	non-dimensional thermal conductivity $\lambda = H + (1-H)\lambda_g/\lambda_l$. Distance between adsorption sites on the solid surface
C_p	non-dimensional specific heat, $C_p = H + (1-H)C_{p,g}/C_{p,l}$	κ	curvature
H	Heaviside function	μ	non-dimensional viscosity, $\mu = H + (1-H)\mu_g/\mu_l$
k°	equilibrium frequency of molecular displacement	θ	contact angle
k_B	Boltzmann constant	ρ	non-dimensional average density, $\rho = H + (1-H)\rho_g/\rho_l$
Ma	Marangoni number	ρ_0	density
n	number of sites of solid-liquid interaction per unit area	σ_0	surface tension
$\vec{n}$	normal vector	σ_T	variation coefficient of surface tension over temperature
Nu	Nusselt number	ci	capillary-inertial
Oh	Ohnesorge number	cl	contact line
p	non-dimensional pressure	d	density, dynamic
r	ratio	g	gas
r_0	droplet radius	l	liquid
Re	Reynolds number	s	surface
t	non-dimensional time	w	wall
T	non-dimensional temperature		
u	non-dimensional velocity		
We	Weber number		
x, y	coordinates		

Lagrangian-Eulerian (ALE) model through the space-dependent contact angle. They found that the equilibrium position depends on the wettability contrast and the diameter of the inner circular patterned region, the heat transfer is higher at smaller wettability contrast or larger inner patterned region. The total heat transfer increases with increasing impact Weber number. They also adopted the dynamic contact angle with variation of local temperature, and studied droplet impact dynamics and heat transfer under different values of Reynolds number, Weber number, solid phase initial temperature and reference equilibrium contact angle [10]. They found that the temperature-dependent contact angle is negligible in partially wetting droplets, but it becomes essential for non-wetting and highly wetting droplet impact.

Berberovic et al. [2] studied the impact heat transfer of a cold liquid droplet onto a dry heated substrate, the thermophysical properties of droplets varies with temperature. In their computational model based on the volume of fluid method, the air flow surrounding the liquid droplet was considered; the numerical results agree quite well with experimental and theoretical results in terms of droplet spreading pattern, associated heat flux and temperature distribution. Diaz and Orgega [11] investigated the gas-propelled liquid droplet impinging onto a heated surface through numerical simulation; the volume of fluid model was adopted with a constant contact angle. They found that the heat transfer is mainly dominated by diffusion during the early stage of impact. The heat transfer enhancement is expected to occur when the ratio of kinetic energy of carrier gas over droplet is larger than 0.1. Strotos et al. [12] studied the water droplet impinging cooling with volume of fluid method, in this model the droplet dynamics, heat conduction in solid substrate and droplet evaporation were coupled together, the predicted droplet shape, temperature, flow and vapor distribution agree well with experimental observations. They also summarized the non-dimensional parameters for predicting the cooling effectiveness of droplet impinging on the solid surfaces [13]. Bhardwaj et al. [14] numerically studied the influence of liquid properties and interfacial heat transfer during microdroplet deposition onto a glass substrate. Four liquids (i.e., isopropanol, water, dielectric fluid and eutectic tin-lead solder) were studied under both isothermal and non-isothermal conditions. The coupled influence of interfacial Biot number and hydrodynamics on the initiation of phase change was studied.

As seen from the literature review above, the spray cooling is affected by quite a number of parameters. For the spray cooling, the impact velocity (Weber number) is usually quite large, the impact kinetics is dominant, thus the splashing, injection and fingering may happen, which are not desirable in spray cooling. On the contrary, the droplet spray cooling under low impact Weber number is seldom studied, in these cases the capillary force becomes dominant instead of impact kinetics. In this paper we will focus on the droplet spreading under low impact Weber number; the effect of impact velocity, equilibrium contact angle, liquid viscosity, surface tension, droplet radius, thermo-capillary effect, Prandtl number on the droplet spreading and the heat transfer will be studied. In computational modelling of droplet spreading, simulation of moving contact line is one of the main challenges. It has been well established that the dynamic contact angle is not constant during droplet spreading, and it involves different length scales from nanometer to micrometer [15–17]. In the present study, the Molecular Kinetic Theory (MKT) [18] will be adopted to describe the relationship between the dynamic contact angle and velocity of moving contact line. The simulation will be tested by experiments.

In the following sections, the physical model and mathematical formulation with dynamic contact angle model will be introduced first, followed by the validation of current model with our experimental data. After that, the effect of several key parameters of liquid on droplet spreading and the resultant heat transfer is studied. Finally, some conclusions will be drawn for spreading cooling.

2. Physical model and mathematical formulation

In Fig. 1 the schematic diagram of droplet spreading cooling on the hot substrate is shown. When the spherical droplet approaches the solid substrate, the air between the droplet and substrate will be pushed away, the air cushion will be formed no matter how low the droplet approaching velocity is. Firstly, the droplet will skate on the air cushion, usually with a thickness at the order of nanome-