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Dynamic wetting and heat transfer characteristics of a liquid droplet impinging on heated textured surfaces

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ABSTRACT

This article reports the dynamic wetting behavior during spreading and receding phases and the heat transfer characteristics for impinging droplets on heated textured surfaces. In particular, the present study suggests newly the modified equations of the total thermal energy absorbed by droplet and the cooling effectiveness for textured surfaces with consideration of three different wetting states: non-wetting, partial-wetting and total-wetting states. Captured images by using the high-speed cameras were analyzed to examine the influence of impact Weber number, surface temperature, and texture area fraction. It was found that for the textured surfaces, the maximum contact diameter of impinged droplet decreased owing to decrease in the surface energy. At increased surface temperatures, the maximum contact diameters slightly increased and the maximum recoil diameters decreased because of change in liquid viscosity. For the textured surfaces, the cooling effectiveness increased with the Weber number and its change substantially depended on the wetting state. In case of the total-wetting state, the cooling effectiveness increased with the texture area fraction, because of change in liquid–solid interface area. It shows that the control of wetting state would be important in heat transfer of an impinging droplet on solid surface.

1. Introduction

The wetting dynamics during droplet impact and heat transfer on surfaces have been active research topics in many industrial applications. The fundamental study of droplet dynamics and heat transfer on a solid surface is necessary to clarify the important and controllable factors closely associated with surface wettability, impact conditions, and fluid properties [1–7]. Unfortunately, there have been few studies on the heat transfer during droplet spreading and receding phases below the saturation temperature. At surface temperature below 100 °C, water droplet evaporation is negligible in spreading and receding phases [3]. Because the droplet temperature spatially and temporarily changes, it is difficult to measure the temporal evolution of the heated droplet.

Up to date, some studies have reported on spatial and temporal evolutions of a droplet impinging on a heated surface by using numerical and analytical methods. Pasandideh-Fard et al. [8] studied the influence of droplet diameter and impact velocity on the heat transfer characteristics after a droplet impact on a flat surface, and developed the mathematical model of cooling effectiveness. On the basis of the previous model [8], Strotos et al. [9–12] suggested the modified equation of cooling effectiveness and they conducted numerical simulations to predict the contact diameter required for estimating cooling effectiveness. In addition, they used transient heat conduction equation in analyzing heat transfer characteristics of impinging droplet on the flat surface [9–11]. However, it is noted that the cooling effectiveness models mentioned above cannot be used intrinsically for textured surfaces. Meanwhile, Roisman [3] analytically examined the flow and heat transfer characteristics of impinging droplets with consideration of phase change. They used the similarity solutions of the Navier–Stokes equation and the energy transport equation, and discussed detailed physics behind phase change, heat flux evolution, and contact temperature [3]. Besides, Herbert et al. [13] investigated the hydrodynamics and heat transfer during droplet impact with the use of important dimensionless numbers, and showed that the wall heat transfer was the strongest during spreading phase.

Surface texturing method has been regarded as one of controllable ways causing the significant change in contact area, heat and mass transfer, and surface wettability. Ahn et al. [14] studied the wetting behaviors of an impinging droplet on a heated textured surface, and examined the variation in the evaporating meniscus by measuring the dynamic contact angle. Alizadeh et al. [15]

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Nomenclature

Roman symbols

c_p	specific heat of a droplet, J/kg·K
d	hole diameter, m
d_o	equivalent droplet diameter, m
d_x	measured horizontal droplet diameter, m
d_y	measured vertical droplet diameters, m
h	hole depth, m
k	thermal conductivity, W/m·K
q''	heat flux from surface to droplet, W/m^2
$q''_{c,th}(t)$	theoretical heat flux on the impact point, W/m^2
$q''_{liq}(t)$	mean heat flux absorbed from the droplet
r_s	roughness ratio of the solid surface, –
s	edge-to-edge spacing between textured holes, m
t	elapsed time, s
t^*	dimensionless elapsed time, tv_0/d_0
A_1	contact area of a droplet at the top of the solid surface, m^2
A_2	contact area of a droplet at the basal and wall of the hole-patterned surface, m^2
A_c	contact area of a spreading and receding droplet and solid surface, m^2
C_q	correction factor for the heat flux absorbed from the droplet, –
$D(t)$	contact diameter with time, m
D^*	dimensionless contact diameter with time, $D(t)/d_o$
I_0	correction factor, –
R_a	average roughness, m
T_{dr0}	droplet temperature when a droplet impacts, °C
T_{w0}	wall temperature when a droplet impacts, °C
$Q_{liq,tot}(t)$	total thermal energy absorbed by the liquid droplet, J
$Q_{liq,max}$	maximum thermal energy absorbed by the liquid droplet, J
v_0	impact velocity, m/s

Greek symbols

α	thermal diffusivity, m^2/s
γ	thermal effusivity, J/m^2 s$^{0.5}$
$\varepsilon(t)$	cooling effectiveness, –
ϕ_s	texture area fraction, –
μ_o	dynamic viscosity, Pa·s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ_{LV}	surface tension between liquid and gas phases, N/m
θ_a	apparent contact angle on the flat and textured surface, °
θ_{CB}	contact angle of Cassie–Baxter state on the textured surface, °
θ_Y	young's Contact angle on the flat surface, °
ω_s	area fraction of partial-wetting, –
Γ	weighting factor, –
$\Theta_{c,th,0}$	dimensionless contact temperature relative to boiling and freezing point, $(T_{c,th,0} - T_{fr})/(T_b - T_{fr})$
Θ_{dr0}	dimensionless droplet temperature relative to boiling and freezing point, $(T_{dr0} - T_{fr})/(T_b - T_{fr})$

Dimensionless numbers

Pr	Prandtl number (=$c_p\ \mu/k$)
Re	Reynolds number (=$\rho v_o d_o/\mu_o$)
We	Weber number (=$\rho v_o^2 d_o/\sigma_{LV}$)

examined spreading and receding dynamics on the hydrophilic and hydrophobic textured surfaces with different contact angles and temperatures ranging from 0 °C to 100 °C. In this study, contact diameters and contact area at the final equilibrium state were measured for temperatures without considering heat transfer characteristics [15]. Negeed et al. [16] considered the effect of surface roughness and an oxidation layer on the dynamic behaviors of droplets impinging on heated textured surfaces. Also, Tran et al. [17,18] studied the phase change of droplet impacts on superheated surfaces. They suggested the regimes of contact boiling, Leidenfrost phenomena, and film boiling with droplet impact velocity and surface characteristics [17,18]. In fact, there were abundant studies regarding Leidenfrost phenomena of a droplet on a textured surface [19–21]. Although a number of researchers reported on cool droplet impact on a heated solid surface, there was a lack of experimental data for explaining intimate relations between droplet dynamics and heat transfer for textured surfaces below the saturation temperature.

Thus, the present study aims to examine the wetting dynamics of impinging droplet on the flat and textured surfaces and to investigate the heat transfer characteristics influenced by surface temperature and impact velocity. In particular, this study suggests the modified equations of total thermal energy absorbed by droplet and cooling effectiveness with considering three different wetting states such as non-wetting, partial-wetting, and total-wetting states. In the current study performed at the surface temperature below saturation temperature, boiling and evaporation effects are ignored because of very short spreading and receding times [3]. Transient behaviors of dimensionless contact diameter, cooling effectiveness, and total thermal energy absorbed by droplet are analyzed for different wetting states, surface temperatures, Weber numbers, and texture area fractions.

2. Experimental description

As shown in Fig. 1(a), we used the Newtonian fluid, deionized (DI) water, for an impinging droplet, which was detached owing to its weight from a flat-tipped metal needle (33-gage, Hamilton) connected to a syringe pump (LSP01-1A, LongerPump). A detached droplet had 2.02 ± 0.02 mm equivalent droplet diameter estimated from $d_o = (d_x^2 \times d_y)^{1/3}$ [22]. Using the equivalent diameter and liquid properties, the density of DI-water was estimated based on the weight measured by a microbalance (AC121S, Sartorius). Impact velocity was adjusted by changing the height between the needle tip and the top of a solid surface. In the present study, Weber numbers, defined as $\rho v_o^2 d_o/\sigma_{LV}$, of 5.41, 27.1, 54.2, and 82.3 were used. Because the present study focused on the spreading and receding phases where the Weber numbers were relatively low [2,4,23], only spreading and receding phases of the droplet were examined.

A cylindrical copper specimen (99.97% purity), with height of 20 mm, was used as a target solid surface. Roughness was controlled by polishing with silicon carbide abrasive sandpaper to reach an average roughness R_a of 0.05 μm. The polished copper flat surfaces were drilled by a μ-CNC machine (EGX-350, Roland) to generate a textured surface. With a 150-μm diameter drill bit and spindle speed of 16,000 rpm, the hole depth (h) and hole diameter (d) were set to 150 μm at a 15.2 mm/s feed rate. The edge-to edge spaces between two textured holes were fixed at 94 μm and 51 μm for different