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The exact regulation of temperature evolutions for droplet impact on ultrathin cold films at superhydrophilic surface

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HIGHLIGHTS

- Droplet impact on cold thin films at superhydrophilic surface is studied in detail.
- The temperature distribution of cold film after drop impact is precisely controlled.
- The recognition and regulation of the flow field after droplet impact on thin films.
- Different temperature distribution regions are determined by *We* and film thickness.

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ABSTRACT

The present study reports a study of water droplets impacting on cold thin water films on a superhydrophilic surface. A thermal infrared imager was used to record the surface temperature distribution after the droplet impact on the liquid films. A ring-shaped high temperature zone was found after impact with the temperature first increasing and then gradually decreasing in the radial direction. Numerical simulations were then used to study the velocity distribution and the droplet motion inside the liquid film. The droplet spreading motion was restricted by liquid in the film for lower *We* which then reduces the heat transfer in that area and causes the formation of a ring-shaped high temperature distribution. The ring structure shape then changes with the increasing of *We*. This hot ring becomes wider and the temperature difference between the ring and the impact center decrease with the increasing of *We*. As *We* continues to increase, the ring-shaped temperature distribution disappears with the highest temperature at the center and the temperature in radial direction monotonically decreasing from the center to the edge. The initial film thickness also affects the temperature distribution after droplet impact. A thicker film causes the ring-shaped hot region to gradually move inward until it reaches the center and forms a hottest region in the impact center. Thus, the ring-shaped temperature distribution only occurs for lower *We* and thinner films. The shape and position of the temperature distribution after droplet impact on the cold, thin liquid films can then be precisely controlled by regulating the impact *We* and the initial film thickness. These results will greatly facilitate the design of precision spraying processes.

1. Introduction

Since the pioneering work of Worthington studying the dynamic behavior of water drops impacting solid surfaces in 1876 (Worthington, 1876), the droplet impact dynamics have attracted much attention among scholars. There have been many studies of the droplet hydraulic behavior after impact on walls or liquid pools (Yarin, 2006; Bisighini et al., 2010; Raman et al., 2016; Oguz and Prosperetti, 1990). These phenomena have been widely applied in a broad range of industries including water desalination, irrigation, icing control, spray cooling, fuel injection in internal combustion engines and microfluidic applications (Clanet et al., 2004; Crooks et al., 2001; Xie et al., 2013; Meuler et al., 2010).

Most previous studies of the drop impact process sought to characterize the parameters influencing the behavior of a single drop, such as the velocity (Rioboo et al., 2001) and incidence angle (Silk et al., 2006). More recently, the advent of methods to create new surface structures has led to studies on how to control the behavior of droplets after impact on various surface structures (Bird et al., 2013; Almohammadi and Amirfazli, 2017).

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Nomenclature

Roman symbols

c_p	specific heat [J kg^{-1} K^{-1}]
D	droplet spreading scale
d	droplet diameter [mm]
d_{drop}	equivalent droplet diameter [mm]
d_h	equivalent droplet diameter in the horizontal direction [mm]
d_v	equivalent droplet diameter in the vertical direction [mm]
g	gravity [m^2 s^{-1}]
H	liquid film thickness [μm]
k	thermal conductivity [W m^{-1} k^{-1}]
$\widehat{n}_w$	unit vector tangential to the wall
P	pressure [pa]
S	source term
T	surrounding temperature [°C]
T_w	substrate temperature [°C]
t	time [s]
$\widehat{t}_w$	unit vector
v	droplet velocity [m s^{-1}]
V	characteristic velocity [m^2 s^{-1}]

Dimensionless

Bo	Bond number, $\rho g d_{drop}/\sigma$
Ca	Capillary number, $\mu V/\sigma$
We	Weber number, $\rho v^2 d_{drop}/\sigma$
Oh	Ohnesorge number, $\mu/(\rho\sigma d_{drop})^{1/2}$
τ	dimensionless time, tv/d_{drop}
H_{non}	dimensionless thickness, H/d_{drop}

Greek symbols

ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
μ	viscosity [Pa s]
α	Heaviside function
κ	interfacial curvature in the level-set function
Φ	smoothing function in level-set function
ε	interface numerical thickness

The surface temperature distribution is an important indicator to judge the droplet evolutionary behavior after impact. The surface temperatures can be used to evaluate the impact process and which greatly influence the hydraulics characteristics of the droplet (Tran et al., 2012; Liang et al., 2016; Herbert et al., 2013). Castanet et al. (2009) accurately characterized the interaction between a droplet and a heated wall using two-color laser-induced fluorescence thermometry. Recently, the temperature variations during droplet jumping and the influence of the ambient temperature on the droplet behavior were studied using infrared temperature measurements (Li et al., 2018). Gao et al. (2017) used an infrared camera to analyze the heat transfer distribution during the impact of a single water droplet on a heated flowing water film and found that the thermal recovery time decreases with increasing film flow rate. Girard et al. (2011) experimentally investigated the temperature evolution in a water droplet deposited on a heated substrate to calculate the heat transfer in a droplet during spreading on a solid surface. That study showed that the temperature increased from the center to the edge of the droplet and that the surface temperature increased linearly with time.

Nowadays, further studies are needed to understand the droplet behavior after impact on a cold wall due to problems such as frozen transmission lines or industrial equipment during the winter and ice accretion resulting from the impact of water drops onto a surface at subfreezing temperatures (Schremb et al., 2017; Jung et al., 2012). It is critical to precisely regulate the drop distribution and achieve rapid heat and mass transfer during impact. Besides, the surface will be quickly covered with a thin film after the first impact when many droplets are hitting the surface. Subsequent droplets will then hit the liquid film instead of the solid wall. Therefore, the interactions between the film and the droplets must be carefully studies since this will significantly affect the results.

The many previous studies of droplet impacts on liquid films have focused more on the hydraulic characteristics after impact, such as the liquid motion and splashing (Vander Wal et al., 2006; Agbaglah and Deegan, 2014; Liang and Mudawar, 2016). Thus, there is still a lack of understanding about the droplet motion after it impacts the liquid film and the temperature evolution after a hot droplet impacts onto a cold thin film. However, these effects are very important in many industrial processes. For example, the droplet distribution can be regulated to achieve point to point connections of the thermal effects for various target shapes. In addition, knowledge of the temperature variations after impact can be used to accurately locate the coldest position or points where icing will occur and the icing direction on surfaces for industrial processes having irregular operating conditions. Moreover, regulate the spray rate and control the film thickness could also reduce the unnecessary waste in the precise cooling process. In this study, a droplet was observed to impact a thin film on a superhydrophilic surface at a cold substrate. Since the drop rapidly merges with the liquid film, thermal tracing method is an efficient way to track the droplet behaviors and distributions after impact. The surface temperature distribution as a water drop impacted a cold film was observed by a high speed camera and a sensitive infrared camera with numerical simulations then used to explain the observed phenomena.

2. Experimental setup and procedure

2.1. Surfaces preparation and characterization

The surface was the top surface of a copper block that had been polished with emery paper (from #400 to #3000) to remove the oxidation layer with the surface then cleaned by ultrasonic waves in absolute ethanol after polishing. The superhydrophilic surface with micro/nanostructures formed by immersing the cleaned block into hot (96 ± 2 °C) alkaline solutions composed of $NaClO_2$, NaOH, $Na_3PO_4{\cdot}12H_2O$ and deionized water (3.75:5:10:100 wt%) for 15 min (Zheng et al., 2017).

The micro/nanostructures were characterized by a Scanning Electron Microscope (KYKY2800B China and Quanta200, FEI, Holland). SEM images of the superhydrophilic surface with different magnifications are shown in Fig. 1. The superhydrophilic surface had a large number of nanorods formed by the oxidant etching process that turned the surface color from shinny copper to black. The contact angle was measured by a contact angle meter (OCAH200, Data physics, Germany) at ambient temperature using the sessile drop method. The surface contact angle after chemical etching was close to 0°.

2.2. Experimental system

An experimental platform was built to investigate the droplet temperature distributions after droplet impact on the thin films.