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A numerical study of droplet motion/departure on condensation of mixture vapor using lattice Boltzmann method

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A R T I C L E I N F O

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Droplet deformation
Vortex flow

A B S T R A C T

Droplet motion/departure, which is governed by external force acceleration coefficient, droplet radius and surface wettability on solid surfaces under external forces such as gravitational force, play a significant role in characterizing condensation heat transfer, especially when high fractional non-condensable gases (NCG) present. However, due to the challenge in visualizing the vapor/steam velocity field imposed by droplet motion/departure, the detailed mechanism of droplet motion/departure on condensing surfaces has not been completely investigated experimentally. In this study, droplet motion/departures on solid surfaces under external forces and their interactions with steam flow are simulated using two dimensional (2D) multiphase lattice Boltzmann method (LBM). Large external force acceleration coefficient, droplet radius and contact angle, lead to large droplet deformation and high motion/departure velocity, which significantly shortens the droplet residual time on the solid surface. Our simulation shows that steam vortices (lateral velocity) induced by droplet motion/departure can greatly disturb the vapor flow and would be intensified by increasing external force acceleration coefficient, droplet radius, and contact angle. In addition, the location of vortex center shifts in the ascending direction with increase of these factors. The average lateral velocities induced by droplet motion/departure at various conditions are obtained. The mass transfer resistance is substantially reduced owing to the droplet motion/departure, leading to an enhanced heat flux. The experimental results are compared to validate the influence of droplet motion/departure on condensation heat transfer performance, especially for steam–air mixture with the presence of high fractional NCG.

1. Introduction

Droplet dynamics such as droplet motion, droplet drainage, and droplet departure from solid surfaces under forces such as surface tension (Daniel et al., 2001; Peng et al., 2015; Nenad et al., 2013; Macner et al., 2014; Mondal et al., 2015; Nenad and Wang, 2013; Alwazzan et al., 2017a,b), pressure (Torresin et al., 2013), centrifugal force (Yamali and Merte, 1999) and electric force (Miljkovic et al., 2013), plays a governing role in determining steam condensation heat transfer rate. Existing studies show that, during a pure steam condensation process, condensation heat transfer performance is sufficiently high regardless of the droplet drainage methods since the droplets are drained rapidly with smaller radius (Peng et al., 2015). However, the condensation mechanism of steam mixed with non-condensable gas (NCG) could be different from pure steam condensation. The main heat transfer resistance is determined by the diffusion layer where the vapor has to diffuse cross to the condensing surfaces as schematically shown in Fig. 1. With 0.5% air in mass, condensation heat transfer rate is reduced 50% or even more (Minkowycz and Sparrow, 1966) due to the additional thermal resistance resulting from the low conductive gas–vapor boundary layer. Thus, droplet departure should be more critical for steam condensation once the fractional of NCG is high (Ma et al., 2007). Condensation heat transfer performance can be enhanced by enabling rapid droplet departure from the horizontal tubes using hybrid patterns (Alwazzan et al., 2017a,b). Besides the gravity, centrifugal force is also applied to prompt droplet motions (Yamali and Merte, 1999; Yamali and Merte, 2002). High steam velocity can also help speed motions of droplets on superhydrophobic surfaces (Torresin et al., 2013). The rapid droplet rolling and drainage from the surface are reported to significantly prompt condensation heat transfer (Peng et al., 2015,2014). In the recent investigations, gradient surfaces, hybrid surfaces and superhydrophobic surfaces are developed to enhance the droplet motion and drainage and hence, the steam condensation heat transfer. Self-propelled droplet jumping

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Nomenclature

a, b, c, d	coefficients
C	concentration
D	droplet diameter, diffusion coefficient
e	unit velocity vector
EF	heat transfer enhancement factor
f	distribution function
F	external force
g	external force acceleration coefficient
G	parameter in evolution equation
h	droplet height
i	number ($i = 0 \sim 8$)
m	mass flux
p	pressure in particle distribution function
P	pressure
q	heat flux
r	radius
t	time
T	temperature
u	velocity in x direction
v	velocity in y direction
x, y	directions

Greek symbols

α	direction
β	direction, coefficient
γ	parameter
η	viscosity
θ	contact angle
κ	parameter for surface tension
λ	parameter dependent on contact angle
ρ	density
τ	time step
φ	wetting potential

phenomenon induced by superhydrophobic surfaces can significantly enhance steam condensation heat transfer rate at low subcooling degree (Nenad et al., 2013; Nenad and Wang, 2013).

During a static vapor–air mixture condensation process (assuming the effect of steam velocity on condensation is negligible), if no droplets depart, the steam molecules primarily diffuse on the condensing surface across the diffusion layer. The definitions of the vapor–air mixture condensation with and without droplet departure are schematically shown in Fig. 2(a) and Fig. 2(b), respectively. We assume that the molecular diffusion rate should be much lower than that of convective mass transfer. Therefore, the lateral vapor–air velocity induced by droplet motion/departure should be significant to the mass transfer rate during vapor–air mixture condensation since it would prevent NCG from accumulating in the diffusion layer, reducing the dominant resistance of mass transfer as schematically shown in Fig. 1 on a vertical condensing surface.

It would be effective to enhance the condensation heat transfer of steam–air mixture through intensifying steam convection, for example, by droplet departure. Ma et al. (2007) experimentally demonstrated that the condensation heat transfer rate with droplet departure (Fig. 2a) was about 1.2 ~ 2.0 times higher than that without droplet departure (Fig. 2b) with the air fractions between 0.5% and 4.8%. The average enhancements were 1.40 and 1.65 when the fraction of non-condensable was 0.5% and 4.8%, respectively. Grooten and van der Geld (2011) also showed that the accelerated droplet removal induced by the silicon string can significantly enhance condensation heat transfer of mixed of steam and NCG. The average mass flow rate enhancement was up to 11% when the acceleration droplet removal frequency was only at 0.8 Hz. Moreover, the mechanism was also numerically analyzed by Ma et al. (2014) But, the simulation mainly focused on the influence of vapor velocity (droplets were assumed to be stagnant) rather than the droplet departure process, i.e., the disturbance of vapor phase induced by droplet departure. Droplet removal has been verified to prompt the heat transfer rate in condensation of steam–air mixture. However, the detailed interactions between droplet departure and dropwise condensation of vapor–air mixture are not well understood. It is challenging to experimentally quantify contact line dynamics and velocity field induced by droplet motion/departure.

In this study, the influence of the lateral velocity induced by droplet motion/departure on condensation heat transfer is theoretically

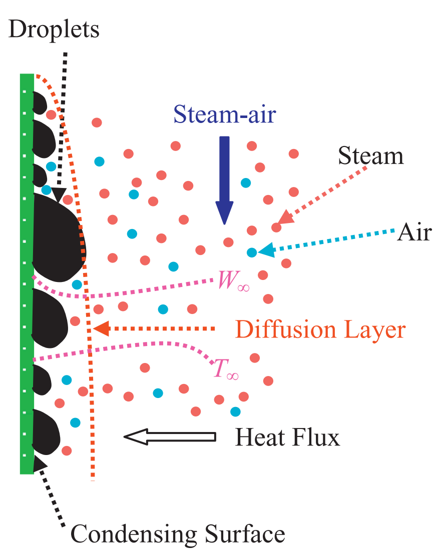

Fig. 1. Schematic diagram of dropwise condensation of steam–air mixtures, the disturbance of the diffusion layer induced by droplet motions reduce the mass transfer resistance of the steam thus, significantly enhances heat transfer.

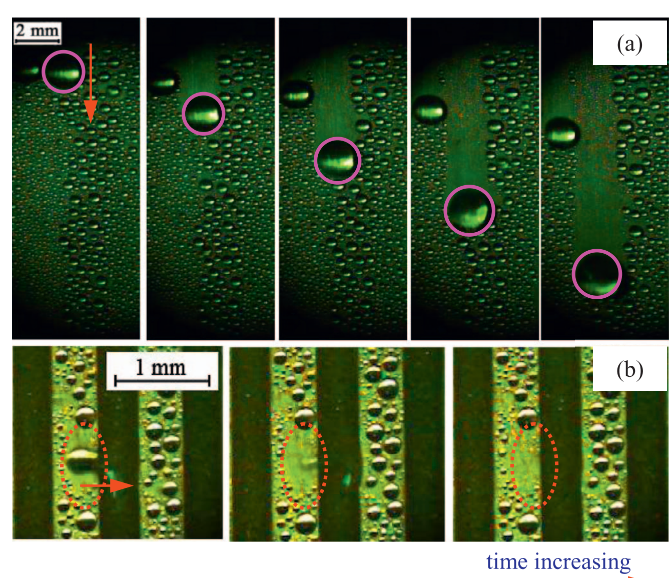

Fig. 2. The definition of the steam–air condensation with and without droplet departures (front view (a) completely hydrophobic surface, droplet depart from the condensing surface under gravity when the droplet is big enough (b) hybrid surface, the droplets are absorbed and drained from the hydrophilic region rather than departs from condensing surface under gravity).