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Droplet size distributions in dropwise condensation heat transfer: Consideration of droplet overlapping and multiple re-nucleation

Wei Xu, Zhong Lan, Qiancheng Liu, Bingang Du, Xuehu Ma *

Institute of Chemical Engineering, Liaoning Key Laboratory of Clean Utilization of Chemical Resources, Dalian University of Technology, Dalian, China

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ABSTRACT

Evolution and distribution of condensate droplets are the most important information in dropwise condensation. For surfaces with larger contact angles, droplet interactions and distributions become more complicated due to their three dimensional profiles. In this study, the effect of droplet overlapping and multiple re-nucleation on droplet size distribution and heat transfer are analyzed quantificationally by numerical simulations. Experimental droplet images obtained by environmental scanning electronic microscope are also presented to support the analyses. The simulated droplet size distributions show that droplet overlapping and multiple re-nucleation can improve the spatial distribution of small droplets for larger contact angle surfaces, and the difference in droplet size distributions decreases as droplet radius is increased. The distributions of larger droplets with radii larger than the critical coalescence size are also affected by the overlapping and multiple re-nucleation effect. The difference between droplet size distributions finally diminish for different contact angles when droplet radius is increased to dozens of microns and the effect of overlapping and multiple re-nucleation become less important in that size range. As contact angle is increasing, surface coverage decreases, while the number density of small droplets is greatly increased, and the overall effect leads to an improved heat transfer performance. The present simulations reveal the effect of droplet overlapping and multiple re-nucleation quantificationally from the perspective of three dimensional droplet profiles, which provide insight into the better understanding of droplet size distributions and extend the dropwise condensation theory.

1. Introduction

Dropwise condensation (DWC) has been widely investigated due to its potential in improving heat transfer performance [1–4]. Several folds of heat transfer improvement can be achieved when the condensation surface is properly treated with micro-nano structures and low surface free energy coatings [1,5–7]. Related fundamental theory and intensification techniques have been developed continuously and DWC also show promising prospect in the application of advanced heat and mass transfer applications [8], including microfluidics, micro channels and heat pipes.

Unlike the filmwise condensation mode, the condensate in DWC form into small droplets with certain contact angles (CA) and very different radii on the condensation surface. These droplets are formed by nucleation process [9,10], and then they start to grow by direct vapor condensation [11,12]. As droplets grow to critical coalescence radius [13,14], droplet coalescence occur to form even larger ones. Finally, the largest droplet departs from the condensation surface when its radius reaches to the departure size [1,11]. After each coalescence and departure, blank surface is exposed into vapor and the blank area will be occupied immediately by another generation of small droplets, which is referred as the re-nucleation. The nucleation, growth, coalescence, departure and re-nucleation occur repeatedly, and form the complete lifecycle of condensate droplets.

The intensification of DWC heat transfer can be attributed into three aspects, including the promotion of DWC mode, acceleration of droplet lifecycle, and the improvement of small droplet size distributions. For the first one, low surface free energy coatings [15–18] and a relatively larger contact angle is required to avoid the formation of liquid film and promote DWC mode. For the second one, the droplet lifecycle is usually accelerated by decreasing droplet departure radius or promoting droplet jumping [19–21].

The droplet size distributions are the most important information in DWC and the increase of small droplet number densities can bring great improvement to heat transfer performance. However, detailed droplet size distributions still require investigations especially when different contact angles, three dimensional droplet profiles and complex droplet interactions are involved. According

* Corresponding author.
E-mail address: xuehuma@dlut.edu.cn (X. Ma).

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Nomenclature

A	width of condensation surface
B	height of condensation surface
d	droplet
CA	contact angle
DSD	droplet size distribution
DWC	dropwise condensation
h_i	interfacial heat transfer coefficient
H_{fg}	latent heat
$n(r)$	droplet population density
$N(r)$	droplet population density (model)
N_s	nucleation sites number density
q	heat flux
r	droplet radius
t	time
t_p	thickness of the promoter layer
T	temperature
x	central coordinates on x axis
y	central coordinates on y axis

Greek symbols

Δ	difference
θ	contact angle
λ	thermal conductivity
ρ	density of the condensate liquid
σ	surface tension
φ_{sl}	simulated surface coverage
φ'_{sl}	calculated surface coverage

Subscripts

v	saturated vapor
p	promoter layer
w	water

to the DWC model [3,11,13,14,22–24], heat transfer performance can be expressed as a function of droplet growth rate and droplet size distribution. A two-section model is widely adopted to describe the size distributions. For larger droplets that are undergoing coalescence, a semi-empirical formula [1,11,25] was obtained from experimental data fitting. The original data were obtained from earlier experiments where surface coatings including paraffin wax, dioctadecyl disulphide, polytetrafluoroethylene were used, which promoted typical contact angles of 100–115°. In recent years, due to the development of advanced functional materials, DWC can be maintained on surfaces with even larger contact angles [26–30] and a part of them have exceed 150°. For these hydrophobic and superhydrophobic surfaces, the semi-empirical formula [1,11,25] is directly used [11,13] without any verification or modification. For small droplets that are growing mainly by direct vapor condensation, their size distributions are either obtained from extended semi-empirical formula [31] or calculated by population balance method [32]. Detailed droplet size distribution investigations on those two groups of droplets are still in demand. On the other hand, the three dimensional droplet profiles and complex droplet interactions also complicate the droplet size distributions. As the droplet sizes are significantly different in DWC, a small droplet may be hidden underneath a larger one for surfaces with larger contact angles. The effect of droplet overlapping on the spatial distribution of droplets should also be examined.

Numerical simulations have become an important tool for the investigation of DWC in recent years. Burnside and Hadi [33] conducted a computer simulation of DWC and studied the growth and coalescence of droplets from the nucleation to a maximum radius of several microns. The results showed that the maximum drop radius reached by growth/coalescence process was four to five times that reached by a growing drop. Mei et al. [34] performed a numerical study on the growth mechanism of DWC using a intrinsic droplet growth rate. The results demonstrated that the apparent growth rate of droplets was strongly dependent on the number of initial droplets. The simulations also obtained drop size distributions that was consistent qualitatively with that from experimental observations. Sikarwar et al. [14,22] performed a series of DWC simulations from the atomic level to the macroscopic droplets with the consideration of various fluids and substrate inclination angle. These simulations were based on solid assumptions that was developed from thermal analysis and the simulated results also accord satisfactorily with experiments. Unlike experimental investigations, numerical simulations are not restricted by spatial and time resolutions, and experimental conditions. It is able to provide more detailed information on the evolution of condensate droplets with sufficient accuracy.

In the present study, DWC droplet size distributions are investigated by numerical simulations with the consideration of different contact angles and the effect of three dimensional droplet profiles. The study focuses on the droplet overlapping and multiple re-nucleation phenomena and demonstrates their effect on droplet size distribution and heat transfer. A simulator is conducted to reproduce the complete lifecycle of condensate droplets from equilibrium size to departure size. A modified coalescence criterion is introduced in the simulator to treat droplet coalescence with the consideration of three dimensional droplet profiles. The transient droplet size distribution evolution, surface coverage, steady-state droplet size distribution and heat transfer are analyzed in detail. These results can provide another perspective to show how contact angle and three dimensional droplet profile affect the spatial distribution of condensation droplets and provide insight into the better understanding of DWC droplet size distributions.

2. Model and computational methodology

2.1. Simulation procedure

The simulations are based on the following assumptions [14,33]: (1) The nucleation process follows the fixed nucleation site theory and nucleation sites are randomly distributed on condensation surface; (2) Nucleation occurs instantaneously and the fixed nucleation sites that exposed into vapor will be occupied immediately by a droplet with critical size; (3) Droplet coalescence occurs instantaneously and the droplet can recover its spherical shape after coalescence; (4) The new droplet that formed after each coalescence is located on the mass center of the original droplets. The above assumptions were also widely used in other investigations [14,33] and were proved to be suitable to describe the complete droplet lifecycle in DWC.

In addition to these universal assumptions, the effect of contact angle are introduced in the present simulator by taking into account of the thermal resistance of droplets with different contact angles [11]. A modified droplet central distance criterion is used to describe the effect of three dimensional droplet profile to coalescence. Detailed information on this treatment is presented in Section 2.2.