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Dropwise condensation heat transfer model considering the liquid-solid interfacial thermal resistance

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ABSTRACT

Dropwise condensation is a multiscale process including droplet nucleation, growth, coalescence and departure stages. As the initial stage, droplet nucleation plays a significant role in condensation heat transfer by determining the droplet nucleation radius and nucleation density. In this work, the molecular dynamics simulation is employed to determine the liquid-solid interfacial thermal resistance (ITR) for different surface wettability. To derive the modified model, the liquid-solid ITR is incorporated into the existing heat transfer model for a single droplet, on the basis of which, the effect of liquid-solid ITR is introduced to modify the critical nucleation radius and nucleation density. The results show that the introduction of liquid-solid ITR leads to not only an increasing of critical nucleation radius but also a reduction of nucleation density. Dropwise condensation experiments are conducted and the present model predicts the experimental data we performed and those in the literature, more accurately than the existing model which neglects the liquid-solid ITR, particularly for large contact angles or large sub-cooled degrees.

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1. Introduction

Dropwise condensation has attracted a large amount of attention due to its higher heat transfer coefficient than filmwise condensation and its potentials in many fields such as energy conversion [1–3], water desalination [4], electronic device cooling [5] and water recovery [6,7].

The mechanism of dropwise condensation is explored extensively and a number of models are proposed to predict the heat flux under different subcooled degrees. LeFevre and Rose [8] are the first to propose the heat transfer model by combing the heat transfer model of a single droplet and the distribution function of droplet sizes. Then, Tanaka [9] modified the droplet size distribution for small non-coalescing droplets based on a population balance theory. Two different mechanisms of droplet growth including direct vapor condensation and coalescence with adjacent droplets were introduced. A similar theory was also adopted by Abu-Orabi [10] to estimate the droplet size distribution and develop a model considering the effect of thermal resistance of coating materials. Then the dependence of droplet size distribution on contact angles were evaluated by Kim and Kim [11] and the results showed that small droplets were demonstrated to bear higher heat flux. With superhydrophobic surfaces based on micro/-nanostructures applied to dropwise condensation, a model was developed by Miljkovic et al. [12] to consider the effects of surface geometry, nucleation density and promoter coating on heat transfer performance. In our previous investigation [13], the existing heat transfer model is modified for dropwise condensation on a horizontal tube and the predictions agree with experimental data well. Liu and Cheng [14,15] proposed an improved model in which the critical nucleation radius is determined based on a thermodynamic analysis. In their model, the thermal resistances of coating layer, liquid-vapor interface and curvature were taken into account to calculate the change of Gibbs free energy accurately.

A formation of a droplet begins from a nucleation process of vapor molecules and the critical nucleation radius is determined by the nucleation theory and can be regarded as the size of minimum droplets in heat transfer models. Therefore, it is essential to develop a reasonable heat transfer model to evaluate the nucleation process. In previous studies, nucleation process has been extensively investigated with experimental, theoretical and numerical methods [16–21]. Yamada et al. [16] investigated water condensation on a hybrid hydrophilic-hydrophobic surface to reveal nucleation mechanisms at the microscale. Condensation experiments revealed that droplets could nucleate on the hydrophilic areas under unsaturated conditions. An extended nucleation

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Nomenclature

G	Gibbs free energy (J)
h	interfacial heat transfer coefficient (W m^{-2} K^{-1})
H_{fg}	specific latent heat (kJ kg^{-1})
q	heat flux (W m^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
$N(r)$, $n(r)$	drop size distribution (m^{-3})
N_s	nucleation density (m^{-2})
P	pressure (Pa)
r	radius (m)
$r_{\min}$	minimum droplet radius (m)
r_e	coalescence radius (m)
$r_{\max}$	maximum droplet radius (m)
r_0	minimum droplet radius (m)
r_c	critical nucleation radius (m)
T	temperature (°C)

Greek symbol

Φ	heat transfer rate (W)
ρ	density (kg m^{-3})
σ_{lv}	liquid vapor surface tension (N m^{-1})
θ	contact angle (°)
ε_{ij}	characteristic surface energy (eV)
φ	angle (°)
δ	coating thickness (m)
σ_{ij}	van der Waals radius (nm)
α	inclination angle of the plate

Subscripts

c	condensate
cur	curvature
d	droplet
l	liquid
s	solid
sub	subcooled
sat	saturated
v	vapor

model taking into account the attracted water molecules on the hydrophilic surface was used to explain the measured droplet intervals. Mu et al. [17] experimentally studied the relationship between nucleation density and surface topography on surfaces of magnesium in nanoscale. The results showed that the surface topography had a great influence on nucleation density and larger fractal dimensions would lead to more nucleation sites. Zeng and Xu [18] developed a thermodynamic model to capture the formation of a droplet embryo on fractal surfaces. The results showed that the differences between the critical size of the embryos on the fractal surfaces and those on the flat surfaces were negligible for the hydrophobic nucleation. Molecular dynamics simulation was also used to investigate the droplet nucleation on a solid surface [19]. The nucleation rate, critical nucleation size and the required free energy obtained from the simulation agreed with classical heterogeneous theory for the smaller cooling rate or less wettable solid surface. Sheng et al. [20] investigated the onset of surface condensation for different surface wettability using molecular dynamics simulation. Different condensation modes including the no-condensation, dropwise condensation and filmwise condensation were quantitatively analyzed in the simulation by temporal profiles of surface clusters. Sun and Wang [21] used molecular dynamics simulation to investigate the early and developed stages of surface condensation and they revealed the competition mechanism of thermal resistances that the interfacial thermal resistance dominates at the onset of condensation while the condensate bulk thermal resistance gradually takes over with condensate thickness growing.

The nanoscale droplet embryo forms during the nucleation process. As we know, the interface effect plays a significant role in nanoscale heat transfer [22]. However, the effect of liquid-solid ITR has not been considered during the droplet nucleation process. Actually, the liquid-solid ITR on phase-change processes has been investigated extensively [23–26]. Ghasemi and Ward [23] showed that a large liquid-solid ITR would impede the heat transfer normal to the liquid-solid interface effectively in their investigation of the evaporation for water droplet on Au substrates. Hu and Sun [24] also showed that the reduced liquid-solid ITR caused by the effect of nanopattern could enhance the heat transfer during the boiling of water on a gold surface using molecular dynamics simulation. A temperature jump is generated at the liquid-solid interface during a rapid solidification process and would lead to a reduced solidification rate [25]. In our previous work [26], we employed the molecular dynamics simulation in examining the role of liquid-solid ITR in nanoscale condensation of water vapor onto surfaces with different wettability. The results showed that, at the onset of condensation, the filmwise has a higher heat transfer efficiency than the dropwise condensation, while the dropwise is higher at macroscale. This is because the liquid-solid ITR dominates in the total thermal resistance when other ones are extremely small at nanoscale.

Although the theoretical and experimental investigations for dropwise condensation heat transfer have been widely carried out, and the effects of interfacial thermal resistance on the evaporation [23], boiling [24] and solidification [25] processes have also been investigated, the effect of liquid-solid ITR on droplet nucleation and dropwise condensation heat transfer performance has not been reported. Therefore, the liquid-solid ITR is worth considering for predicting heat transfer of dropwise condensation. In this study, we will propose a modified heat transfer model considering the effect of liquid-solid ITR. Furthermore, the experimental measurements are performed to validate the model.

This paper is organized as follows. In Section 2, the modified heat transfer is derived and in Section 3, the dependence of liquid-solid ITR on surface wettability is determined using molecular dynamics simulation. Section 4 presents the experiment system while in Section 5, the experimental data are employed to validate the present model with a detailed discussion. Finally, Section 6 gives a conclusion.

2. Heat transfer model

A droplet experiences the nucleation, growth, coalescence and departure processes in an existence cycle. Formation of droplets in dropwise condensation is based on two different mechanisms: by direct vapor condensation and by coalescence with adjacent droplets. Therefore, droplets on surfaces can be divided into two groups: one is the droplets of small sizes with $r_{\min} < r < r_e$, and the other is the droplets of large sizes with $r_e < r < r_{\max}$, where r represents the radius of droplets: $r_{\min}$, $r_{\max}$ and r_e denote the minimum droplet radius, the maximum droplet radius and the coalescence radius, respectively. The maximum droplet radius is also

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