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Dynamic heat transfer analysis of condensed droplets growing and coalescing on water repellent surfaces

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ABSTRACT

We present the dynamic heat transfer analysis of condensed droplets growing and coalescing on hydrophobic (HPo) and superhydrophobic (SHPo) surfaces using a full 3D numerical simulation. In the model, two water droplets surrounded by fully-saturated water vapor grow on a horizontal surface through condensation until they coalesce together. The dynamic changes in the interfacial areas, temperature distributions and heat flux through each interface were analyzed. The effects of vapor phase temperature distribution, parasitic thermal resistance and surface flooding on the heat transfer rate are also quantified. The results show that a relatively high heat transfer rate through solid–vapor interface on SHPo partially compensates the low heat transfer rate through solid–liquid interface. The parasitic thermal resistance of the suggested SHPo may reduce the heat transfer performance over 30%. When the flooding occurs on HPo, the heat transfer rate rapidly decreases below a half of the value obtained at the beginning of coalescence. This work shows the importance of the heat transfer analysis considering dynamic changes in the interfacial area and resulting 3D temperature distributions, and will help develop the optimal condensation heat transfer surfaces.

1. Introduction

Condensation is a crucial process in a wide range of energy and environmental applications including water harvesting, power generation, air-conditioning, desalination and thermal management [1–5]. Condensation may occur in two distinct modes including the filmwise condensation on wettable surfaces and dropwise on non-wettable. Previous studies have demonstrated that the dropwise condensation can offer significantly higher heat transfer coefficient than the filmwise due to the continuous removal of droplets via gravity and resulting decrease in the thermal resistance [6–9].

Recently, many researchers have investigated superhydrophobic condensers considering their efficient droplet removal process especially through spontaneous droplet jumping. When microscale droplets coalesce on suitably designed superhydrophobic surfaces, they jump away from the surface by converting the excess amount of the surface energy released during the coalescence to the kinetic energy [10–18]. Such droplet jumping process can further enhance condensation heat transfer coefficient by up to 30% compared to hydrophobic surfaces by increasing number density of small droplets and decreasing droplet size removed from the surfaces [19–24].

In order to predict the condensation heat transfer performance of water repellent surfaces and help to develop high efficiency condensers, the thermal network model has been applied. Previous studies have suggested the analytical 1D model considering all possible thermal resistances associated with the conduction through a droplet, liquid–vapor interfacial resistance, droplet curvature effect and the structures and coatings on hydrophobic and superhydrophobic surfaces [25–30].

Such models considered the static situation where droplets are sitting on a surface. Our previous work showed that the heat transfer rate through the base area of a single droplet decreases as a contact angle increases due to the rise of conduction resistance through the droplet. However, when the number density of droplets was multiplied together, the total heat transfer performance was higher on the surfaces with a high contact angle [30,31]. Recently, the 1D model was further refined by considering the 2D temperature distribution and local heat flux variation around the liquid–solid contact line [32]. The model demonstrated that the majority of heat transfer occurs at the three phase contact line of the individual droplet and such local heat transfer effects must be considered for more accurate estimation of heat transfer performance.

However, most of these previous studies have been focused on a static droplet and little attention has been paid to the dynamic heat transfer rate during the coalescence of droplets that plays a

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significant role for the droplet growth on non-wettable surfaces. In addition, the three dimensional temperature variations of the vapor and liquid phase have not been fully investigated due to the simplicity of the previous models.

In our previous works, we investigated the hydrodynamic behaviors and energy conversion mechanisms of coalescing droplets using a full 3D numerical model based on the level contour reconstruction method [33–35]. Our previous studies showed that 40–60% of the released surface energy was converted to the kinetic energy on the superhydrophobic surface, while only ~20% was converted on the hydrophobic. The relatively lower receding contact angle was responsible for the increase in the viscous dissipation loss and resulting lower conversion rate. Despite these numerical efforts, the previous numerical works were only focusing on the momentum transfer not the thermal energy transfer.

In this work, we extend our previous works and present dynamic heat transfer analysis of condensed droplets growing and coalescing on hydrophobic (HPo) and superhydrophobic (SHPo) surfaces using a full 3D numerical simulation. We applied two sets of dynamic contact angles obtained from the experimental characterization of HPo and SHPo samples and the numerical model was applied to the situation where two water droplets are growing through condensation until the coalescing occurs on a horizontal surface. We investigated the changes in the interfacial areas and heat transfer rate during the droplet growth and coalescence on the investigated surfaces. The effects of vapor phase temperature distribution, parasitic thermal resistance and surface flooding on the heat transfer rate are also quantified to analyze the heat transfer performance of the suggested SHPo and HPo.

2. Model

In this study, the dynamic heat transfer analysis of droplets during growth was investigated using a full 3D numerical model based on the level contour reconstruction method, a hybrid scheme that combines the advantage of the front tracking and level set methods [33–35]. Fig. 1 shows the schematic of the simulated domain with the boundary conditions. Periodical boundary condition has been used for the x and y direction. Bottom surface has been treated as non-slip wall boundary condition with the undercooling of 5 K and open boundary condition allowing phase change has been applied to the top surface. Since we applied the periodic boundary condition in horizontal direction to account for repetitive generation of multiple droplets over the wall, the effects of the top boundary condition was not significant. In our case, we chose the open (i.e. Adiabatic) condition to produce more stable solution with limiting computational resource.

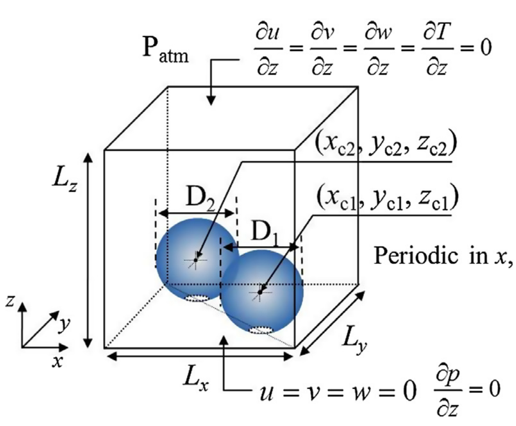

Fig. 1. The schematic showing the configurations, domain and boundary conditions applied to the present study.

The properties of liquid and vapor water at 1 atm have been chosen for the current simulation. Density of liquid and vapor water is $\rho_L = 958\ \text{kg/m}^3$ and $\rho_G = 0.596\ \text{kg/m}^3$. Viscosity of liquid water has been set to 0.279×10^{-3} kg/m·s and 1.2×10^{-5} kg/m·s for the water vapor. Conductivity of liquid and vapor is 0.68 W/m·K and 0.025 W/m·K. Specific heat was set to 4217 J/kg·K for liquid water and 2029 J/kg·K for vapor. Latent heat of 2.26×10^3 kJ/kg was used. Surface tension coefficient was 0.0589 N/m. Properties used in the simulation were summarized in Table 1. The box size of $0.06 \times 0.06 \times 0.06\ \mu\text{m}^3$ has been used with 128^3 grid resolution. In the model, near-spherical droplets start growing at two different positions ($x_{c1} = 19.4$, $y_{c1} = 19.4$, $z_{c1} = 13$) and ($x_{c2} = 40.6$, $y_{c2} = 40.6$, $z_{c2} = 13$) so that the droplets merge at the center of the box when their diameter reach ~30 μm (see Fig. 1).

Full description of the phase temperature can be derived using entropy balance across the interface but still an unresolved issue [29]. Thus, in most numerical simulation with phase change, the interface temperature T_s between droplets and vapors was customarily assumed to be constant equilibrium temperature for the simplicity of the computation. Previous thermal-network-based condensation heat transfer models also assumed the constant interface temperature [26–31]. Recently, 2D axisymmetric model was suggested with applying the constant heat transfer coefficient at the liquid–vapor interface [32], which clarified the importance of capturing the temperature distribution at the interface and within the droplet.

In the present work, we are interested in the behavior of the vapor phase induced from fluid motion associated with phase change considering the convective nature of the vapor as well as the liquid phase. For that purpose, we solved full energy equations for both liquid and vapor phase with describing the temperature condition to provide more stable numerical solution. We note that we did not fix the interface temperature constant. In our model, the interface temperature is modified by considering the effect of the interfacial resistance to the mass transfer across the interface [36] as in Eq. (1). Condensation rate at the bottom wall is the highest, therefore the interface temperature smoothly changes from the subcooled wall temperature to the saturation temperature.

$$T_s = T_{sat} - \frac{\dot{m}''}{\varphi}, \tag{1}$$

where T_{sat} is the saturation temperature of the system, $\dot{m}''$ is the mass transfer rate across the interface, φ represents kinetic mobility describing the resistance to mass transfer across the interface. The kinetic mobility φ can be described in detailed as follows:

$$\varphi = \frac{2\alpha}{(2-\alpha)} \frac{h_{fg}}{\sqrt{2\pi R T_{sat}}} \frac{1}{(1/\rho_G - 1/\rho_L) T_{sat}} \tag{2}$$

Here, R is the gas constant, h_{fg} is the latent heat of vaporization and α is the constant which range from ~0.04 to 1 depending on the fluid. In our condensation simulation, α is set to 1 as recommended by previous studies [37]. The ρ is the density of the fluid and subscript G and L stand for gas and liquid, respectively. By considering the effect from mass transfer across the interface, interface temperature can have smooth transition to the wall temperature where large mass flux can be anticipated thus providing converged solution. More complete liquid–vapor phase temperature condition

Table 1
Liquid and vapor properties incorporated to the present model.

Properties	Liquid	Vapor
Density [kg/m^3]	958	0.596
Dynamic viscosity [kg/m·s]	0.279×10^{-3}	1.2×10^{-5}
Thermal conductivity [W/m·K]	0.68	0.025
Specific heat [J/kg·K]	4217	2029