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Research Paper

Effects of geometry and dimension of micro/nano-structures on the heat transfer in dropwise condensation: A theoretical study

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HIGHLIGHTS

- Effect of roughness shape on dropwise condensation is investigated.
- Two roughness shapes including semi-pyramidal and semi-conical are considered.
- Effect of roughness shape is magnified at higher subcooling and nucleation sites.
- Roughness shape could change dropwise heat transfer by 2.5–4.5 times.

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ABSTRACT

Condensation is a phase change phenomenon which has many applications in the field of refrigeration, power plants and air-conditioning. It is well-known that dropwise condensation (DWC) has a considerably higher heat transfer than filmwise condensation. DWC occurs on hydrophobic and superhydrophobic surfaces (SHS). Research has shown that micro/nano structures are necessary for producing SHS. The geometry and dimensions of the structures could affect DWC heat transfer. In this research, a numerical study has been done to explore how much the configuration of these structures could change heat transfer in DWC. To attain this goal, two different structures, including semi-conical and semi-pyramidal and their limit states including prismatic and cylindrical structures have been considered. Effects of different parameters including the shape of the structures, roughness factor, and solid fraction on the single droplet and total heat transfer have been studied. Results show that the configuration of structures could significantly affect DWC heat transfer. For instance, at a constant roughness factor and solid fraction, semi-conical or pyramidal pillars have about 2.5–4.5 times higher total heat transfer than prismatic or cylindrical pillars. The shape of pillars could change the small droplet population by about 10%.

1. Introduction

Phase-change heat transfer mechanisms have very high heat exchanging capabilities. Condensation as a phase-change process has been used in many industrial applications including refrigeration, power plants, heating, ventilation and air conditioning (HVAC), and water desalination [1]. Condensation may appear on surfaces in the form of dropwise (DWC) or filmwise (FWC) condensation depending on the wettability of the surfaces. Research shows that DWC may give about one order of magnitude greater heat transfer rate than FWC [2,3]. Therefore, many efforts, both numerically and experimentally, have been done to discover the underlying mechanism or improve the heat transfer process of DWC [4–8]. For example, Kim et al. [9] presented an experimental study of FWC and DWC inside transparent circular tubes. The aim of their study was the observation of the formation and behavior of these two condensation regimes in internal flows. Mahapatra et al. [10] used hydrophilic-hydrophobic patterned surfaces to produce DWC and simultaneously drain the condensate. They optimized the parameters of the patterns and showed that the optimal pattern could enhance heat transfer over 30% as compared to pure DWC. Earlier studies of DWC mostly have focused on smooth surfaces covered with hydrophobic promoters [11]. From these studies, it has been revealed that the DWC heat transfer strongly depends on the droplet contact angle (CA) [12,13]. For example, Kim and Kim [14] numerically showed that by increasing CA from 90° to 150°, DWC heat transfer enhances by nearly 40%. However, studies in the materials science have shown that producing CA greater than 120° on smooth surfaces only by relying on chemical treating is difficult [15–17]. Instead, CA greater

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Nomenclature

a	a parameter defined in Fig. 3
A_a	cell cross section minus pillar at position x (m^2)
A_p	pillar cross section at position x (m^2)
A_1	a constant defined in Eq. (21)
A_2	a constant defined in Eq. (21)
A_3	a constant defined in Eq. (21)
A_4	a constant defined in Eq. (21)
B_1	a constant defined in Eq. (26)
B_2	A constant defined in Eq. (26)
b	a parameter defined in Fig. 3
CA	contact angle (°)
e	a parameter defined in Fig. 3
L	pillars center to center distance (m)
g	acceleration of gravity ($m\,s^{-2}$)
G	droplet growth rate ($m\,s^{-1}$)
H	pillars height (m)
h	a parameter defined in Fig. 3
h_{fg}	latent heat of condensation ($J\,kg^{-1}$)
h_i	liquid-vapor interface heat transfer coefficient ($W\,m^{-1}\,K^{-1}$)
k_a	vapor conductivity ($W\,m^{-1}\,K^{-1}$)
k_p	pillars conductivity ($W\,m^{-1}\,K^{-1}$)
k_w	water thermal conductivity ($W\,m^{-1}\,K^{-1}$)
N	population density of large droplets (m^3)
n	population density of small droplets (m^3)
N_s	number of nucleation sites per unit area (m^{-2})
q_d	heat transfer rate through a droplet (W)
q_x	heat transfer of a droplet base at position x (W)
q''	total heat flux ($W\,m^{-2}$)
r	droplet radius (m)
r_{min}	minimum droplet radius (m)
r_{max}	maximum droplet radius (m)
r_e	effective radius (m)
R_b	droplet base resistance ($k\,W^{-1}$)
R_c	droplet curvature thermal resistance ($k\,W^{-1}$)
R_d	droplet conduction thermal resistance ($K\,W^{-1}$)
R_i	vapor liquid interfacial resistance ($K\,W^{-1}$)
R_g	specific gas constant of vapor ($J\,kg^{-1}\,K^{-1}$)
T_s	surface temperature (K)
T_{sat}	saturation temperature (K)
ΔT	surface subcooling temperature (K)
ΔT_c	temperature drop of droplet curvature (K)
ΔT_d	temperature drop of conduction through droplet (K)
ΔT_i	interface temperature drop resistance (K)
x	distance from pillars top to pillar base (m)

Greek symbols

α	condensation coefficient
ρ	density ($kg\,m^{-3}$)
θ	contact angle (°)
τ	sweeping period (s)
σ	surface tension ($N\,m^{-1}$)
δ	thickness (m)
ε	condensation coefficient
φ	solid fraction
υ	specific volume ($m^3\,kg^{-1}$)
υ	specific volume ($m^3\,kg^{-1}$)

Subscripts

a	advancing
b	base
c	curvature
co	related to conical roughness
d	drop
e	effective
g	gas
hc	hydrophobic coating
i	vapor-liquid interface
max	maximum
min	minimum
p	pillar
py	related to pyramidal roughness
r	receding
sat	saturated
s	surface
w	water

than 120° could easily be produced on micro/nano-structured surfaces covered with a hydrophobic promoter layer. Therefore, many methods for fabricating of superhydrophobic surfaces (CA > 150°) have been presented by investigators [18–20]. Similarly, some researchers have studied the effects of micro/nano structures on the DWC occurring on micro/nano-structured superhydrophobic surfaces. For instance, Miljkovic et al. [21] numerically modeled and optimized DWC on micro/nano-structured surfaces. They considered micro/nano structures as cylindrical pillars with known dimensions and center to center distances. Their results show that micro/nano structures have strong effects on the heat transfer so that by proper adjusting of the geometrical parameters of the pillars, heat transfer enhances by 190%. Lee et al. [22] presented a model for DWC on a nano-scale, pin structured surface. They defined an effective thermal conductivity for the combination of pillars and the in between trapped water/vapor based on the porosity of the substrate. Their results show that by reducing the height of pillars from 1 μm to 10 nm the heat transfer increases by nearly 60%. Chen et al. [23] produced surfaces which contain hydrophobic micro-pyramidal architectures covered with hydrophilic nano-structures. The surfaces were globally superhydrophobic. They showed that these surfaces could increase droplet density by 65% and droplet elimination by 450% as compared to a superhydrophobic surface with nanostructures alone. The thermal performance of the surfaces is not reported in this reference.

As the literature shows, the geometry and distribution of micro/nano structures could substantially affect the heat transfer process in DWC on a micro/nano-structured surface. Nevertheless, the effects of the configuration of micro/nano structures on the heat transfer process have not been examined extensively. Some micro/nano-structured superhydrophobic surfaces have been fabricated but they have not been implemented in DWC experiments. On the other hand, numerical investigations of DWC have also their own difficulties and every arbitrary micro/nano-structure cannot be simulated. In the current investigation, a numerical study is conducted based on the method of Kim and Kim [14] to investigate the effects of the configuration of micro/nano-structures on DWC. For this purpose, two different micro/nano-structured surfaces consisting semi-pyramidal, and semi-conical and their limit states including prismatic and cylindrical structures are considered. Effects of different parameters including the shape of structures, roughness factor, height of structures, and solid fraction on the single droplet and total heat transfer have been studied.

2. Heat transfer model

Unlike FWC, DWC is a discrete phase change phenomenon where single droplets appear on the distinct nucleation sites and grow solely as