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Experimental investigation on steam condensation heat transfer enhancement with vertically patterned hydrophobic–hydrophilic hybrid surfaces

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ABSTRACT

The maximum droplet radius and droplet size distribution are significant for dropwise condensation heat transfer. Adjusting the maximum droplet radius and droplet size distribution with vertically patterned hydrophobic–hydrophilic hybrid surface is an effective method to enhance and optimize condensation heat transfer performance. The maximum droplet radius and droplet size distribution adjustment with hydrophobic–hydrophilic hybrid surface, and the resultant heat transfer performance are investigated experimentally in this paper. The results indicate that with the increase of hydrophobic region width, the maximum droplet radius on hydrophobic region increases while the droplet population density decreases. An optimum hydrophobic region width exists and the steam condensation heat transfer performance decreases with the increase of hydrophilic region width. And the performance can be larger than that of complete dropwise condensation for appropriate hybrid surfaces. The steam condensation heat transfer performance on the optimum hybrid surface is about 23% higher than that of complete dropwise condensation at surface subcooling of 2.0 K. Steam condensation heat transfer enhancement factor increases with the increase of hydrophobic region width first and then decreases with its further increase. The optimum hydrophobic region width is about 0.55 mm and the corresponding optimum maximum droplet radius is about 0.25 mm. Heat transfer enhancement factor decreases with the increase of surface subcooling and the optimum heat transfer enhancement factor is also significantly dependent on the surface subcooling. When the surface subcoolings are 2.0 K, 4.0 K and 6.0 K, the optimum heat transfer enhancement factors are about 1.23, 1.11 and 1.07, respectively. Steam condensation heat transfer can be enhanced with hydrophobic–hydrophilic hybrid surface more effectively at low surface subcooling. The experimental results and theoretical analysis agrees well to each other.

1. Introduction

Steam condensation can be classified as filmwise and dropwise condensation based on the interaction between condensate and condensing surface. Dropwise condensation heat transfer has drawn much more attention due to its much higher heat transfer performance than that of filmwise condensation [1–6]. During the past several decades, many attempts were conducted to clarify dropwise condensation heat transfer mechanism and its influencing factors because it is very significant to exploit effective method for dropwise condensation regulation and heat transfer enhancement.

It is well known that dropwise condensation heat transfer performance tremendously depends on maximum droplet radius. Both theoretical analysis and experimental investigation showed that dropwise condensation heat transfer coefficient decreased with the increase of the maximum droplet radius [7,8]. The maximum droplet radius, droplet rapid motion, droplet size distribution, and then condensation heat transfer performance could be adjusted with special condensing surfaces, such as gradient surfaces [9–11], superhydrophobic surfaces [12–17], grooved surfaces [18,19], hydrophobic–hydrophilic patterned surfaces [20–22] and hybrid surfaces [23–29].

Gradient surfaces could induce spontaneous and directional movement of condensate droplets due to variation of surface free energy difference between condensate and surface. Daniel et al. [9] found that droplet spontaneously moved from weak wettable region to strong one induced by coalescence for steam condensation on gradient surface. The velocity was hundred and thousand times higher than that induced by typical Marangoni effect, and

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Nomenclature

E	heat transfer enhancement factor
f_{DWC}	area fraction of dropwise region on hybrid surface
f_{FWC}	area fraction of filmwise region on hybrid surface
g	gravitational acceleration, m s^{-2}
h	heat transfer coefficient, W m^{-2} K^{-1}
h_i	interfacial heat transfer coefficient, W m^{-2} K^{-1}
H_{fg}	latent heat of evaporation, kJ kg^{-1}
n	population density of small droplet, m^{-3}
N	population density of large droplet, m^{-3}
q	heat flux of condensation, W m^{-2}
q_{CDWC}	heat flux of complete dropwise condensation, W m^{-2}
q_{DWC}	heat flux of dropwise region on hybrid surface, W m^{-2}
q_{exp}	heat flux of experiment, W m^{-2}
q_{FWC}	heat flux of filmwise region on hybrid surface, W m^{-2}
q_{h}	condensation heat flux on hybrid surface, W m^{-2}
q_{the}	heat flux of theoretical analysis, W m^{-2}
Q	heat transfer rate, W
r	droplet radius, m
r_{e}	critical droplet radius, m
r_{min}	minimum radius of a droplet can grow, m
r_{max}	maximum radius of droplet, m
R	radius of the condensing surface, m
t_1, t_2, t_3, t_4	temperatures measured by thermocouples in condensing block,°C
t_{b}	temperature of steam bulk, °C
t_{w}	temperature of condensing surface, °C
$\bar{t}$	average temperature, °C
ΔT	surface subcooling degree, K
x_1, x_2, x_3, x_4	distances between the thermocouples and condensing surface, m
$\bar{x}$	average distance, m
W_{DWC}	dropwise region width, m
W_{FWC}	filmwise region width, m

Greek symbols

ρ_{l}	density of condensate, kg m^{-3}
δ_{l}	thickness of condensate, m
λ_{l}	thermal conductivity of condensate, W m^{-1} K^{-1}
λ_{s}	thermal conductivity of copper, W m^{-1} K^{-1}
η_{l}	viscosity of condensate, Pa s

condensation heat transfer coefficient increased by 3–10 times compared with filmwise condensation. Chaudhury and Whitesides [10] visualized that droplet on gradient surfaces moved uphill to the wall spontaneously under surface free energy difference. Macner et al. [11] found that droplet size distribution was shift toward small droplets for gradient surface. The density of droplet with small radius was much larger than that with large radius. And it was beneficial to heat transfer performance.

Superhydrophobic surfaces were also effective methods to adjust droplet radius and control droplet motion during dropwise condensation. On superhydrophobic surface, droplet self-propelled jumping could be induced by droplet coalescence during condensation [13,14,30–32]. The radius of jumping droplet was only several decade micrometers. This spontaneous motion could significantly reduce the maximum droplet on condensing surface. The overall heat transfer coefficient on horizontal tube could be enhanced by 25% compared to that on smooth hydrophobic tube at low surface subcooling [13]. However, the mechanism of heat transfer enhancement only occurred at low surface subcooling was not very clear so far.

Miljkovic et al. [14] found that droplets jump much more regularly on smooth hydrophobic tube under electric field, and accordingly the droplet size distribution could be adjusted, subsequently the overall heat transfer coefficient could be enhanced by 50%. Miljkovic et al. [17] modified the droplet size distribution relationship in terms of the features on superhydrophobic surfaces during steam condensation. However, these results indicated that self-propelled droplet jumping phenomenon could be occurred just at low surface subcooling. Furthermore, Peng et al. [33] analyzed the mechanism of droplet spontaneous jumping phenomenon induced by coalescence on superhydrophobic surfaces by integrating the energy balance analysis and lattice Boltzmann method.

Although the superhydrophobic surfaces could induce droplet self-propelled jumping during dropwise condensation and enhance the dropwise condensation heat transfer at low surface subcooling, the droplet self-propelled jumping phenomenon could not occur at high surface subcooling. And the resultant dropwise condensation heat transfer was lower than that on hydrophobic surfaces as well [34].

As an alternative, the grooved surfaces and hydrophobic–hydrophilic hybrid surface were effectively used to enhance dropwise condensation heat transfer due to the fast droplet drainage and droplet size distribution adjustment by the special surface configurations. Izumi et al. [18] found that the droplet drainage and heat transfer coefficient strongly depended on the grooves width. The dropwise condensation heat transfer could be enhanced with appropriate grooves width. Narhe and Beysens [19] indicated that droplet size evolution at the early and intermediate stages was the same as that on flat surface. However, the instantaneous drying of the top surface of grooves was observed at the point in time due to the coalescence of droplet with a completely filled channel.

Derby et al. [20] investigated the flow condensation of steam in the hydrophobic–hydrophilic hybrid microchannels. The results indicated that the steam condensation heat transfer coefficient for the hydrophobic and hydrophobic–hydrophilic patterned channels could surpass that of the hydrophilic surface by an order of magnitude. Chatterjee et al. [21] indicated that steam condensation heat transfer coefficients on a surface with island patterns of hydrophilic and hydrophobic regions were higher than that of hydrophilic surface and lower than that of the hydrophobic surface. The influence of shape and feature size of pattern (island pattern and tree pattern) on steam condensation heat transfer coefficients was also experimentally measured [22].

The heat transfer performance was influenced by surface hybrid modes. The hybrid surface was designed more fine, the heat transfer performance was much higher. Experimental results indicated that the heat flux on the vertically divided hybrid surface may be higher than the weighted average heat flux of complete dropwise condensation and filmwise condensation [26]. However, Ma et al. [23,29] revealed that the condensate ring at the boundary of the upper filmwise condensation region and the dropwise region plays a very important role in condensation heat transfer enhancement. The overall heat transfer enhancement is dependent on the dividing numbers of dropwise and filmwise regions and the operating conditions, coordinately.

However, the heat transfer and its enhancement mechanism of dropwise–filmwise hybrid surface have not been clear yet. Therefore, Peng et al. [35] theoretically analyzed the mechanism by integrating dropwise and filmwise condensation heat transfer models in terms of the droplet size effects. The results revealed that there was an optimum maximum droplet radius on dropwise region.

In the present paper, the experiments of steam condensation on various vertically patterned hydrophobic–hydrophilic hybrid surfaces are carried out. The influence of hydrophobic region width