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Experimental investigation of moist air condensation on hydrophilic, hydrophobic, superhydrophilic, and hybrid hydrophobic-hydrophilic surfaces

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ABSTRACT

This study experimentally investigates the condensation performance amid hydrophobic, hydrophilic, superhydrophilic and hydrophobic-hydrophilic hybrid patterned surfaces with air velocity ranging from 0.5 m/s to 4.0 m/s and relative humidity of 85%, 60% and 40%. The hybrid novel surface employs inverted V shape channels design with alternate hydrophilic and hydrophobic channel to direct condensate, and the accumulated condensate is gathered at vertical hydrophilic channel for further effective condensate removal. It is found that the heat transfer coefficient for hydrophobic surface is higher than that of hydrophilic surface irrespective of the operational velocity and relative humidity. Dropwise condensation prevails for the hydrophobic surface and a twig-like structure of condensate is seen for the hydrophilic surface, and this phenomenon becomes more pronounced when the relative humidity is increased. The superhydrophilic surface shows the worst heat transfer performance due to filmwise condensation. The hybrid surface shows superior heat transfer performance over other surfaces. The heat transfer coefficient obtained is around 3–9% higher than that of hydrophobic surface and is about 6–16% higher than hydrophilic one. The proposed novel design offers a shorter cyclic condensate removal time and better condensate drainage. It is found that the maximum diameter for the hybrid surface is about 80–90% smaller than the hydrophobic surface and the droplet size before falling off is relatively independent of operational velocity.

1. Introduction

Thermal energy conversion relied heavily on the heat transfer process. Hence ways of optimization and enhancement of heat transfer performance are quite imperative for thermal engineers. One of the important heat transport process is associated with condensation of humid air upon the cooler surface. Condensation occurs when the surface temperature is below the dew point of the moist air. In most cases, the condensation can be categorized as filmwise or dropwise depending on the surface wettability [1]. The condensate tends to be dropwise when the surface wettability decreases. By contrast, filmwise condensation (FWC) prevails when the wettability increases. In practice, condensation performance relies heavily on the distinct condensate mode subject to its corresponding surface wettability and structure [2,3].

So far there had been a number of studies aiming at the effect of surface wettability on condensation heat transfer. Many of them found that dropwise condensation (DWC) provides a higher rate of droplet removal on the plate surface, and revealed a better heat transfer performance. On the other hand, as the wettability increases to a certain degree, the condensate tends to be filmwise which deteriorates heat transfer performance [2] accordingly. DWC had attracted much more attention from researchers over the past few decades and numerous studies had dedicated to investigate and to clarify the phenomenon and mechanism behind DWC (e.g. [4–12]). A number of researches had discovered that the thermal performance of DWC is affected by the maximum radius of droplets on the surface. There exists a proportional relationship between the heat transfer coefficient (HTC) and maximum radius of droplets in which HTC starts to decline when exceed the maximum radius [2,10,12–18].

In addition, some of the aforementioned studies focused on the design of surface structure in attempts to augment the condensation performance. Many of them encompassed superhydrophobic,

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Nomenclature

A	surface area (m^2)
C_p	heat capacity (J/kg-K)
h	heat transfer rate (W/m^2-K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number (dimensionless)
Pr	Prandtl number (dimensionless)
Q	heat transfer rate (W)
Re	Reynolds number, dimensionless
RH	Relative humidity (%)
T	temperature (°C)

Subscripts

i	inlet
L	plate length
o	outlet
s	surface
v	vapor
w	water
∞	ambient

superhydrophilic, gradient variations, hydrophilic-hydrophobic hybrid patterned surfaces for enhancement of heat transfer through droplet movements, distributions and controlling maximum radius of droplets. The successful hybrid pattern normally entails easier droplets movement by tailoring both high and low wettability characteristics along the surface. There had been a plenty of studies associated with the hybrid design. Yamauchi et al. [19] concluded that the heat flux of hybrid surface tends to be higher than that of hydrophobic or hydrophilic alone. Kumagai et al. [20] experimentally discovered that the hybrid pattern could result in higher maximum heat flux over the entire surface when compared to that of mono-hydrophobic one. Ma et al. [21] observed the heat flux of a hybrid one exceeds those of the hydrophilic or hydrophobic vertical plate. Grooten et al. [22] found that the heat flux of a hybrid surface is almost equal, or even better than the mono-hydrophobic one due to the droplets on the hydrophobic region of the hybrid surface were able to move toward the hydrophilic region, thereby leading to more efficient droplets removal. Chatterjee et al. [23,24] tested a hybrid surface with combinations of hydrophilic and superhydrophobic structure and reported an improvement of heat transfer performance of 7.6% over mono-hydrophobic surface. Ghosh et al. [25] designed a bio-mimic structure having banana trees onto a hydrophilic-superhydrophilic hybrid surface which results in smaller droplet's maximum radius and accordingly a higher rate of droplet removal. Their experiment showed this biomimetic design improved the heat transfer performance by 19% over mono-hydrophilic case when non-condensable gas is in presence. The design also indicated a decrease of droplet removal rate resulted from a stagnant loss phenomenon caused by the coherence of the droplets coming simultaneously from the left and right side channel of the center trunk. For steam condensation, Peng et al. [26] adjusted the ratio of hydrophilic and hydrophobic region on the surface and reported a 23% improvement of heat transfer relative to mono-hydrophobic surface. Based on the research by Ghosh et al. [25], Mahapatra et al. [27] developed a novel design in which the left and right side channel of the center trunk were changed to be dis-aligned along the center trunk in order to avoid the stagnant effect and thus accelerated the condensate removal rate. The design offered a better heat transfer performance with 30% enhancement than the previous mono-hydrophilic surface. In essence, the designs of hybrid surface showed potential in enhancement of condensation heat transfer for offering better condensate removal when comparing to mono-structure surface. However, the heat transfer performance is not only influenced by the surface structure but is also related to the ambient conditions like velocity and humidity. Yet the presence of non-condensable gas also casts huge effect on heat transfer performance (e.g. [28,29]), and the heat transfer performance is appreciably impaired when the non-condensable gas exists. For typical dehumidification with moist air, the majority of air contents are non-condensable, yet the operational conditions like velocity and humidity may vary considerably, thereby influencing the condensation significantly. Hence, the objectives of this study are therefore twofold. Firstly, a novel hybrid design is proposed that manipulates hydrophilic/hydrophobic arrangement to facilitate effectively condensate removal, and improve the heat transfer performance in dehumidification relative to pure hydrophilic and hydrophobic designs. Secondly, the influence of operational conditions on the dehumidification subject to a variety of surface wettability and structure, including hydrophobic, hydrophilic, superhydrophilic, hydrophobic-hydrophilic hybrid pattern and a reverse-placed hydrophobic-hydrophilic hybrid pattern had been thoroughly compared and discussed. In addition, the condensate flow patterns for the studied surfaces are also compared in detail.

2. Manufacturing of test samples and experiment apparatus

2.1. Sample preparation

The size of all copper plates in this study is 350, 250 and 3 mm in length, width and thickness, respectively. Four kinds of surface wettability treatment on copper surface had been fabricated for observing the water condensing phenomenon and comparing the heat transfer ability, including hydrophobic, hydrophilic, superhydrophilic surface, and hybrid hydrophobic-hydrophilic surface with a regular pattern. The hybrid surface features aligned V shape hydrophilic-hydrophobic channel to direct condensate toward some vertically hydrophilic channel for condensate drainage. Before the wettability treatment, each copper plate was sequentially polished with 240, 600, 800, 1200 grit sandpapers and cleaned by alcohol to remove the oxidized layer and contaminations on the surface. The hydrophobic surface is carried out by spraying an organic solution containing 0.2 wt% of ethyl nonafluorobutyl ether on fresh cleaned copper plate, and then the organic solvent is evaporated at 150 °C for 30 min. Since the water contact angle on a smooth copper surface showed a hydrophilic property, the as-prepared copper plate can be regarded as a hydrophilic one. The superhydrophilic one was modified with copper oxide by immersing copper plate in an aqueous solution with 1.5 M of sodium hydroxide and 0.05 M of potassium persulfate at 60 °C for 15 min. Then the copper plate was taken out of the reaction solution, rinsed thoroughly with water, and dried in air. Fig. 1 shows the SEM image of the noddle-like microstructure of copper oxide on the copper plate after hydrophilic treatment. The manufacture process of hydrophobic-hydrophilic surface is represented in Fig. 2(a). The hybrid surface features aligned V shape hydrophilic/hydrophobic channel to direct condensate toward some vertical hydrophilic channel for condensate drainage. The detailed dimension of the hybrid surface is schematically shown in Fig. 2(b).