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Study on the wettability and condensation heat transfer of sine-shaped micro-grooved surfaces

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ABSTRACT

In this study, sine-shaped micro-grooved surfaces with depth of 12–24 μm and width of 30–60 μm were precisely and smoothly fabricated using dry etching technique on aluminium surfaces. After hydrophobic modification, the wettability and the heat transfer characteristics of dropwise condensation on the micro-grooved surfaces were investigated experimentally, and the coalescence and sweeping processes of droplets on micro-grooved surfaces were dynamically analyzed. As the results show, the wetting behavior and heat transfer characteristics on the micro-grooved surfaces presented anisotropic characteristics, the static contact angle in perpendicular direction $\theta_\perp$ was significantly larger than that in parallel direction $\theta_\parallel$, and same trends can also be observed for contact angle hysteresis. In heat transfer experiments, the plates were set vertically and the grooves were arranged in two positions, vertical and horizontal. For the vertically grooved surface, the sweeping effects of falling droplets were enhanced by the vertical grooves and the heat transfer during dropwise condensation was increased to 30–50%. Better heat transfer performance can be achieved when the ratio of height to pitch, A/P, increased. Different from vertical grooved surfaces, the experimental results obtained from horizontal grooved surfaces were similar to the results of smooth surface. Both net force and sliding velocity increased as droplets grew, and larger geometrical size was favorable to droplets falling for same ratio of A/P. The velocities of sliding down on horizontal grooved surface were only 60–70% of that on smooth surface, while the velocities of sliding down on vertical grooved surfaces can reach 1.2 times or higher than that on smooth surface.

1. Introduction

Condensation involves change of phase from the vapor state to the liquid. It is associated with heat and mass transfer, during which vapor migrates towards the liquid–vapor interface and is converted into liquid. Apart from natural phenomena, condensation is an essential part of energy conversion, water harvesting, and thermal management systems. When vapor comes in touch with a surface below the saturation temperature, dropwise condensation is preferred when surface is not wetted by the liquid. The heat transfer coefficient of dropwise condensation is an order of magnitude larger than for filmwise mode that occurs when the surface is wetted. This makes dropwise condensation a very attractive mechanism for industrial applications [1]. Dropwise condensation begins with drop formation at preferred nucleation sites at the atomic scale. The small droplets start to grow up through direct condensation of steam and then coalesce with adjacent droplets. When droplets become large enough, they are generally removed from the surface by the action of gravity or drag forces resulting from the motion of surrounding gas. As the drops roll or fall from the surface they merge with droplets in their path, effectively sweeping the surface clean of droplets. Droplets then begin to grow anew on the freshly exposed solid surface. Through the analysis of the heat transfer process of the dropwise condensation, it can be found that the heat transfer performances of dropwise condensation are significantly affected by the departure diameter and the sweeping cycle of the droplets. Tanasawa and coworkers' experiments [2] showed that the heat transfer coefficient, which was proportional to the scale of droplets, decreased with the increase of drop sizes. Their conclusions were supported by the research of Rose [3], Ma et al. [4,5] and Lee et al. [6]. Moreover, Yamali et al. [7] and Izumi et al. [8] investigated the effect of sweeping cycle on dropwise condensation heat transfer with theoretical analyses and experiments. They found that the sweeping frequency of droplets was a very important factor affecting the heat transfer process of the dropwise condensation. Lee et al. [6,9] fabricated pin structures and unique micro/nano-scale porous surfaces to promote dropwise condensation, their experimental results showed that higher heat transfer rate can be obtained from the modified surfaces. From visual observations, they found that micro/nano-scale porous surfaces can effectively initiate

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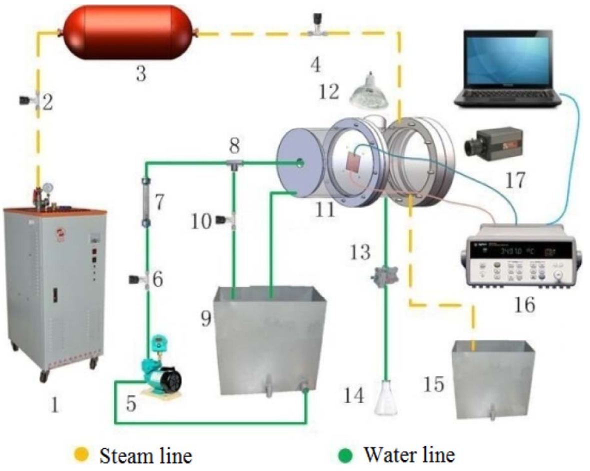
Nomenclature

A_{lv}	liquid–vapor interface [m^2]
A_{sl}	solid-liquid interface [m^2]
C_{pl}	specific volume [kJ/kg·K^{-1}]
C_f	coefficient of friction [–]
F_r	retention force [N]
F_s	viscous force [N]
G	gravity [N]
h	heat transfer coefficient [W/m^2·K^{-1}]
h_{fg}	latent heat of vaporization [J/kg]
M	mass flow rate [kg/s]
M_g	gravity moment [N·M]
n	number of micro-grooves [–]
q	heat flux [W/m^2]
r_b	base radius [mm]
r_d	departure radius [mm]
T_s	surface temperature [°C]
T_w	wall temperature [°C]
U	sliding velocity [mm/s]
V	volume of the deformed drop [mm^3]
W_a	adhesive work [N/m]
α	initial point of the crest [mm]
Δa	wetting width on crest [mm]
ΔT	subcooling temperature [°C]
η	surface wetting ratio [–]
θ	contact angle [degree]
θ_{adv}	advancing contact angle [degree]
θ_{avg}	average contact angle [degree]
θ_{rcd}	receding contact angle [degree]
λ	thermal conductivity [W/m^2·K^{-1}]
ξ	azimuthal angle [rad]
ρ	density [kg/m^3]
σ	liquid–vapor interfacial tension [N/m]

dropwise condensation by generating smaller condensates and limiting the growth of 'large' condensate drops and by improving surface renewal rate [9]. They also indicated that a thinner nano- or sub microscale pins surfaces was required to increase condensation heat fluxes [6].

The adoption of microscale grooves on surface could reduce the resistance and adhesion work of droplets sliding, and therefore was recognized as an effective method for enhancing the heat transfer of dropwise condensation. Watanabe et al. [10] firstly proposed that the departure diameter and sweeping cycle of droplets can be significantly decreased by utilizing micro-grooves with special geometry on superhydrophobic surface. Sommers and Jacobi [11,12] described photolithographic techniques to obtain micropatterns on aluminum surfaces with parallel grooves, 30 μm wide and tens of microns in depth. The experimental results showed that critical droplet size was nearly 50% smaller on micro-grooved surfaces than on the same surface without micro-grooves. Droplets movement in superhydrophobic grooves were performed by Xu and co-workers [13] experimentally. They found that droplets on V-shaped grooves translated from the immersed state to the suspended state as the cross sectional angle of the groove decreased and the suspended droplet departed from the groove bottom as the droplet volume increased. Li et al. [14] also investigated the sliding process of droplets on micro-V-grooves with different pitches. Their experimental results indicated that the contact angle increased with the increasing of groove depth and V-angle. The increase of the groove pitch was conducive to droplets sliding, and wetting behavior was also anisotropic obviously. Zamuruyev et al. [15] designed microscale trapezoid grooves on hydrophobic surface to enhance its dropwise condensation heat transfer. Their experimental results indicated that micro-grooved geometry can enhance droplets transfer from the Wenzel to the Cassie state and directional transport over long distances, and these trapezoidal grooves created a capillary pressure gradient which enabled droplet transfer, right after nucleation, from the "pinned" state, inside the groove, to the upper surface of the crest. A theoretical model was developed by Lu and co-workers [16] to predict the heat transfer efficiency of dropwise condensation for surface with tiny sizes of triangular grooves (2, 5 and 10 μm), and the calculations agreed well with their experiment results. Both experiments and simulations were employed by Zhong et al. [17] to study the wettability of homogeneous and heterogeneous surfaces with rectangular microgrooves 20–40 μm in spacing and 20–180 μm in depth. They found that groove geometry had a profound impact on the drainage behavior of condensed droplets, and the sliding of droplets on micro-grooved surface presented obvious anisotropy. Ma et al. [18] studied the anisotropic wettability of droplets during the sliding process on rectangular microgrooves experimentally. Their results showed that the contact angle in the parallel direction was



1- steam generator; 2, 4, 6, 10- trim valve; 3- superheater; 5- diaphragm pump; 7- rotor flow meter;

8-three direct links; 9, 15- tank; 11- condensation cavity; 12-LED light source; 13-stem trap valve;

14- meter tank; 16- data acquisition instrument; 17- high speed camera

Fig. 1. Schematic diagram of the experimental apparatus. 1-steam generator; 2, 4, 6, 10-trim valve; 3-superheater; 5-diaphragm pump; 7-rotor flow meter; 8-three direct links; 9, 15-tank; 11-condensation cavity; 12-LED light source; 13-stem trap valve; 14-meter tank; 16-data acquisition instrument; 17-high speed camera.