Investigation of Dropwise Condensation Heat Transfer on Laser-Ablated Superhydrophobic/Hydrophilic Hybrid Copper Surfaces

Zitao Song, Mingxiang Lu, and Xuemei Chen*

ABSTRACT: Heterogeneous surfaces with wetting contrast have gained extensive attention in recent years because of their potential application in condensation heat transfer enhancement. In this work, we engineered superhydrophobic/hydrophilic hybrid (SHH) surfaces on copper substrates via a laser-ablation process. We demonstrated that the as-fabricated SHH surfaces present dropwise condensation behavior; the condensate droplet growth, departure, and heat transfer performance depend strongly on the spacing of the hydrophilic spot. The surface with the hydrophilic spot spacing of 100 μm (SHH100) exhibits the most efficient dropwise condensation in terms of fast droplet growth rate, efficient coalescence-induced droplet departure, as well as enhanced heat transfer coefficient (HTC) compared to the homogeneous superhydrophobic (SHPo) surface. The mechanism underlying the enhanced condensation heat transfer performance is analyzed. A 12% enhancement on condensation HTC was found on SHH100 surface compared with the SHPo surface. Our results provide important insights for the design of hybrid surfaces with wetting contrast for enhancing condensation heat transfer performance in many industrial applications.

INTRODUCTION

Condensation heat transfer plays an important role in various industrial applications, such as power generation, thermal management, water harvesting, and other fields.1-9 It has been demonstrated that dropwise condensation that typically happens on the hydrophobic or superhydrophobic (SHPo) surfaces4-9,10 enables heat transfer coefficient (HTC) an order of magnitude higher than filmwise condensation taking place on the hydrophilic or superhydrophilic (SHPi) surfaces. To promote dropwise condensation, extensive researches have been concentrated on engineering nano- or micro/nano-structured SHPi surfaces over the past decade.11,12,14-17 The condensate droplets on the SHPo surfaces can depart from the surfaces via coalescence-induced jumping or sweeping by the coalesced droplets in the way of rolling off the surface.18-26 The spontaneous departure of condensate droplets significantly accelerates the refreshing of the cold SHPo surfaces, which induces a huge potential for heat transfer enhancement.11,13,22 However, the large nucleation energy barrier and high thermal resistance underneath the Cassie-state condensate droplets on the SHPo surfaces would compromise the heat-transfer efficiency.27 Moreover, under high supersaturation conditions, the increased droplet nucleation density causes the droplets to stay in a highly pinned Wenzel state if the surfaces are not designed properly, which would result in the formation of undesirable flooding condensation.10,28 In recent years, approaches to achieve efficient sustained dropwise condensation have been focused on engineering hybrid surfaces with heterogeneous wettability.29-32 By judiciously designing surfaces with optimal geometry and wettability, the advantage of dropwise condensation and filmwise condensation can be integrated on the same surface. Peng et al. reported that the condensation heat-transfer performance on the dropwise-filmwise hybrid surface is dependent on the surface subcooling degree,31 filmwise region width, and surface contact angle. Subsequently, they experimentally indicated that the steam condensation heat transfer on the hydrophobic–hydrophilic hybrid surface is strongly related to the width of hydrophobic and hydrophilic regions, and the performance is more effectively enhanced at low surface subcooling.32 Hou et al. created an array of microscale hydrophilic pillars on the nanostructured SHPi substrate33 and demonstrated that on such a hybrid surface with high-contrast wettability, the synergistic cooperation in the recurrent dropwise and filmwise condensation modes led to improvements in the heat transfer properties including droplet nucleation density, growth rate, self-removal, as well as overall HTC. Ölçeroğlu and McCarthy engineered a hybrid surface by optimizing a rectangular array of SHPi
islands on the SHPo substrate to promote the self-organization of microscale droplets, which was shown to effectively delay flooding and promote transition from jumping-mode to shedding-mode removal at increased supersaturations. Ji et al. showed that the SHPi-hydrophobic hybrid surface can well-control condensate droplet diameters, and the condensation heat-transfer performance is better than that of smooth hydrophilic or hydrophobic surfaces.

Although a large amount of studies have been conducted on understanding and fabricating hybrid surfaces to enhance dropwise condensation heat transfer, the large-scale fabrication of these surfaces is tedious and costly. Moreover, the underlying physical mechanism of the enhanced heat transfer on the hybrid surface is not clearly understood. Therefore, in this work, we develop a facile, reproducible, and scalable technique to create tunable hydrophilic patterns on the SHPo copper substrates. To demonstrate the effectiveness of such SHPo/hydrophilic hybrid (SHH) surfaces, the role of hydrophilic pattern spacing on the dropwise condensation performance is experimentally and theoretically investigated.

# RESULTS AND DISCUSSION

## Characterization of the Hybrid Surfaces

In this work, the SHH surfaces were fabricated using a combined wet-etching and laser ablation technique. Figure 1a shows the scanning electron microscopy (SEM) image of a representative hybrid surface, the inset shows the schematic diagram of the hybrid surface; (b,c) SEM images of the nanostructured area and laser-ablated area; the insets show the water contact angles on the corresponding surfaces; (d) EDS spectra of the nanostructured background and laser-ablated area.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Characterizations of the as-fabricated SHH surface. (a) SEM image of a representative hybrid surface, the inset shows the schematic diagram of the hybrid surface; (b,c) SEM images of the nanostructured area and laser-ablated area; the insets show the water contact angles on the corresponding surfaces; (d) EDS spectra of the nanostructured background and laser-ablated area.

The diameter of the hydrophilic spot (D) is fixed to be ~18 μm (the smallest dimension that the laser system can create), and the spacing of the hydrophilic spot (L) is varied to be ~50, 75, and 100 μm (the surfaces are denoted as SHH50, SHH75, and SHH100), respectively, in order to exploit the effect of surface wettability on the heat-transfer performance. The circular dents in the SEM image represent the laser-ablated hydrophilic spot. Figure 1b,c are the zoomed-in SEM images of the SHPo background and laser-ablated area, respectively. The surface of the background is covered by a thin layer of knife-like CuO nanostructures; the large contact angle (~165°) and small tilt angle (<1°) demonstrate the CuO nanostructures and the silane coating impart the background to have SHPo property. In order to measure the wetting property of the laser-ablated area, we fully ablated the SHPo surface using the same laser-processing parameter that was used to create circular patterns on the SHPo background. It can be seen from Figure 1c that the laser inscribed most of the CuO nanostructures from the SHPo background, leaving behind melted rough structures. The contact angle on the laser-ablated surface is ~60°, indicating a hydrophilic property.

However, the silane coating was not fully removed from the SHPo background because the ratio of fluorne between the nanostructured SHPo background and the laser-ablated hydrophilic region is comparable (Figure 1d). The reason behind the hydrophilic wetting property on the laser-ablated areas is due to the fact that the laser irradiation rapidly increases the local temperature, which induces the formation of irreversibly disordered molecules that are desorbed from the silane coating, resulting in the increase of surface wettability.

## Visualization of Dropwise Condensation Dynamics

In order to illustrate the effect of hydrophilic spot spacing on the condensate droplet nucleation and growth behavior, we first use a digital microscope to visualize the condensation dynamics on different SHH surfaces under the ambient conditions. The ambient temperature was 25 ± 3 °C, and the relative humidity was 60 ± 4%. Samples were placed vertically on the cooling stage set at 2 °C. The record started when the first droplet was visibly observed in the camera. Each sample was recorded for 45 min. As shown in Figure 2a, the vapor preferentially nucleates on the hydrophilic spots and form liquid embryos because of the low nucleation energy barrier compared to the SHPo background. As condensation progresses, the embryos quickly grow and form big droplets either by direct condensation or by absorbing condensates from the SHPo background as a result of the surface energy gradient. When the droplets grow big enough, adjacent condensate droplets on the hydrophilic spots start to coalesce, the coalesced droplet can depart from the surface (Figure 2b–d) if the released surface energy overcomes the adhesion of the droplets to the surfaces; otherwise, the condensate droplets would form immobile droplets that stay still on the surfaces (Figure 2e–g).

Figure 3 shows the long-term dropwise condensation dynamics on the SHPo and SHH surfaces (the field-of-view is 1600 μm × 1200 μm). We can see an ordered droplet nucleation and growth on the hydrophilic spots for the SHH surfaces, in comparison with the random droplet growth on the uniform SHPo surface. On the SHH surfaces, the droplet growth rate on the single hydrophilic spot before coalescence happens is plotted in Figure 4a. It can be seen that the droplet growth rate increases with the increase of hydrophilic spot spacing. This may be because when the spacing of hydrophilic spot increases, a large portion of the SHPo area is exposed and more condensate droplets nucleate and grow in this area. The local wettability difference at the boundaries between the hydrophilic region and the nanostructured SHPo area might accelerate droplet movement and coalescence toward the hydrophilic region, contributing to a larger droplet growth rate on the single hydrophilic spot; whereas on the hybrid surface with smaller hydrophilic spot spacing, the droplet coalescence occurs frequency on the hydrophilic spots, limiting the droplet size on the single hydrophilic spot. As a matter of fact, the droplets on the surfaces with smaller hydrophilic spot spacing experience more severe hysteresis.
after coalescence with neighboring droplets because the hydrophilic patterns act as pinning points; therefore, the coalesced droplet would not depart from the surface after coalescence, resulting in the formation of bigger maximum droplet on the SHH50 surface (Figure 4b). The larger the hydrophilic spot spacing is, the smaller the maximum droplet that anchored on the hybrid surfaces; the maximum droplet diameter on the SHPo surface is the smallest compared to the SHH surfaces because of the lack of hydrophilic pinning points (Figure 4b).

Theoretical Analysis of Maximum Droplet Size Variations on the Hybrid Surfaces. In order to explain the differences of maximum droplet size observed on various SHH surfaces, we carried out the theoretical analysis by considering the system energies that govern coalescence-induced droplet departure, that is, the released surface energy $\Delta E_s$ ($\Delta E_s = E_s - E_s'$, where $E_s$ and $E_s'$ are the surface energy before and after droplet coalescence), kinetic energy $E_k$, and energies dissipated by viscous $E_{vis}$ and surface-adhesion effects $E_{adh}$.21,29,31,37 For simplicity, we only considered the coalescence of two equally sized droplets on the SHH surfaces.

The surface energy of the droplet before coalescence is given by

$$E_s = 2\pi \gamma _l r^2 \left[1 - \cos \theta \right] + \frac{\sin^2 \theta (1 - \phi_{HPi} - \phi_{SHPo} + \phi_{HPi} \phi_{SHPo})}{2}$$

(1)

where $\gamma_l$ is the water liquid–vapor surface tension, $r$ is the droplet radius, $\theta$ is the apparent contact angle, and $\phi_{HPi}$ and $\phi_{SHPo}$ are the area fraction of hydrophilic and SHPo regions on the SHH surface, respectively.

The surface energy of a coalesced droplet ($E'_s$) is expressed as

$$E'_s = 4\pi R^2 \gamma _l = 4^{2/3} \pi r^2 \gamma _l (2 - 3 \cos \theta + \cos^3 \theta)^{2/3}$$

(2)

The viscous energy for each droplet can be estimated as

$$E_{vis} = \frac{r^{3/2} \cdot 144 \mu_w \gamma _l^{1/2} r_w^{-1/2} (\theta - \sin \theta \cos \theta)^2}{\pi (2 - 3 \cos \theta + \cos^3 \theta)}$$

(3)

where $\mu_w$ is the liquid water dynamic viscosity, and $r_w$ is the liquid water density.

The droplet coalescence must overcome the interfacial adhesion between the droplet and the surface, and the adhesion-induced energy dissipation $E_{adh}$ is expressed as

$$E_{adh} = \frac{\gamma _l r^2}{2}$$

(4)

Figure 4. (a) Average droplet growth rate on the single hydrophilic spot for different SHH surfaces. (b) Maximum diameters of droplets overtime on different SHH surfaces.
\[ E_{ad} = \gamma_f A \left( 1 + \cos \theta_{y,SHF} \right) \phi_{SHF} + \left( 1 + \cos \theta_{y,SHP} \right) \phi_{SHP} \]

where \( A \) is the projected contact area of the droplet, and \( \theta_{y,SHF} \) and \( \theta_{y,SHP} \) are the Young’s contact angle on the hydrophilic and SHF-Po regions, respectively.

The kinetic energy \( E_k \) of the droplet after coalescence must balance the release of surface energy \( \Delta E_s \) and dissipation energies \( (E_{vis} + E_{adh}) \)

\[ E_k = \Delta E_s - E_{vis} - E_{adh} \]

The coalescence-induced droplet departure occurs only if \( E_k > 0 \). According to the equations above, the radius of two equally sized droplets on the SHH50 surface has to reach at least \( \sim 31 \mu m \) in order to propel coalescence-induced departure (Figure S1), indicating that the droplets have to coalesce at least once to propel departure because the radius of the first coalescing droplets on the SHH50 surface is \( \sim 25 \mu m \). When droplets coalesce at a small scale, the adhesion energy \( E_{adh} \) consumes a large portion of the released surface energy; thus, it is not easy to trigger coalescence-induced droplet departure on the SHH50 surface, leading to the formation of larger maximum droplets compared to the SHH surfaces with larger hydrophilic spot spacing.

On the SHH75 and SHH100 surfaces, the coalescing droplets are also calculated to reach a radius of \( \sim 31 \mu m \) in order to depart from the surface (Figure S1). This indicates that the droplet can depart from the surface as soon as coalescence with the neighboring droplet on the hydrophilic spot. However, on the hybrid surface with larger hydrophilic spot spacing, the droplets coalescence may not always occur among hydrophilic spots, but involve the coalescence of droplets condensed on the SHF-Po background. When the droplets on the SHF-Po area (relatively small) coalesce with the droplets on the hydrophilic region, the released surface energy \( \Delta E_s \) cannot overcome the dissipation energies because of the severe adhesion of the droplet on the hydrophilic region (large \( E_{adh} \)), which would result in the kinetic energy \( E_k < 0 \), and the droplet becomes immobile after coalescence. This phenomenon happens frequently on the SHH75 surface but not on the SHH100 surface. Because the larger hydrophilic spot spacing enables the formation of larger droplets on the hydrophilic region (Figure 4a), the coalescence of these large droplets would convert more extra surface energy to the kinetic energy, which contributes more frequent coalescence-induced droplet departure behaviors, resulting in the distribution of smaller droplets on the SHH100 surface compared to the SHH75 surface (Figure 4b).

**Measurement and Modeling of Condensation HTC.**

Heat-transfer performance experiments are conducted on the pure SHF-Po surface and SHH surfaces with different hydrophilic spot spacing using the experimental setup shown in Figure 5. In the custom chamber, a copper block (Figure S2) wrapped by PTFE was settled between the condensation chamber and cooling water, and the tested samples were attached on the top of the copper block by thermal paste to minimize the thermal resistance between the samples and copper block. During the experiment, cooling water filled the chamber and chilled the copper block, making droplets condense on the samples that were pasted on the other side of the copper block. A thin film resistance temperature detector was settled between the samples and copper block to measure the temperature of samples. Four T-type thermocouples were inserted into four holes on the copper. As the HTC of PTFE is low and the holes are located far away from the condensing surface, the effect of heterogeneous heat transfer can be neglected and the heat transfer in the middle of the copper can be treated as one-dimensional steady-state heat conduction. Thus, by measuring the temperature of the holes, as well as the distance between each hole and the top surface of copper block, we can get the heat flux \( q \) of the copper block according to following equation

\[ q = -\lambda \left( \sum_{i=1}^{4} (x_i - \bar{x})(T_i - T) \right) / \sum_{i=1}^{4} (x_i - \bar{x})^2 \]

where \( T \) is the temperature of each hole, \( x_i \) is the distance between each hole and the top surface of the copper block, and \( \lambda \) is the thermal conductivity of the copper block. With the heat flux, we can get the condensation HTC \( h \) according to the equation

\[ h = q / (T_{sat} - T_w) \]

where \( T_{sat} \) is saturation temperature, and \( T_w \) is the temperature of the sample, which can be measured directly through the resistance-temperature-detector located between the copper block and the sample. The vapor was set to 120 °C, and the subcooling was set to 12 °C.

For comparison purpose, the HTCs on the SHH surfaces were theoretically calculated as well, the implementation details of the calculations are as follows. The dropwise condensation heat transfer rate of the condensing SHH surface can be obtained by multiplying the heat transfer rate through an individual droplet \( q_{ind} \) with the droplet number density

\[ q_{total} = \int_{r_{min}}^{r_{sat}} q_{ind}(r)n(r)dr + \int_{r_{min}}^{r_{max}} q_{ind}(r)N_z(r)dr \]

where \( r_{min} \) is the smallest stable droplet radius written as \( r_{min} = 2T_{sat}n/(h_f \rho \Delta T)^{1/2} \) where \( T_{sat} \) is the saturated temperature, and \( h_f \) is the latent heat of vaporization. \( r_{max} = (4N_z)^{-1/2} \) is the effective radius obtained with the nucleation density \( N_z \).
surface is given as \( 40 \) nanostructures \( (33 \text{ W/m}^2\text{K}) \), superhydrophobic background, droplet size distribution equation is written as \( 40 \)

\[
q_{\text{ind}} = \frac{(T_{\text{sat}} - T_0)\pi r^2(1 - r_{\text{min}}/r)}{R_1 + R_d + \left(\frac{R_{\text{HPT}}}{R_{\text{HPT}} + R_1} + \frac{R_{\text{SHPo}}}{R_{\text{SHPo}} + R_1} + \frac{R_{\text{HPi}}}{R_{\text{HPi}} + R_1}\right)}
\]

where \( R_{\text{SHPo}}, R_{\text{SHPo}}, \) and \( R_{\text{HPi}} \) are the thermal resistance of low surface energy coating, superhydrophobic background, and hydrophilic spots, and air, respectively. \( R_1 \) is the liquid–vapor interfacial thermal resistance, and \( R_d \) is the thermal resistance through the droplet, which can be expressed as

\[
R_1 = \frac{1}{2h_1(1 - \cos \theta)}
\]

\[
R_d = \frac{\theta r}{4k_1 \sin \theta}
\]

where \( h_1 \) is the interfacial HTC \( (15.7 \times 10^6 \text{ W/m}^2\text{K}); \) and \( k_1 \) is the thermal conductivity of liquid water. By combining all the resistances to the equation, the heat flux of a single droplet can be written as

\[
q_{\text{ind}} = \frac{\Delta T \pi r^2(1 - r_{\text{min}}/r)}{2h_1(1 - \cos \theta) + \frac{\theta r}{4k_1 \sin \theta} + \frac{1}{\sin^2 \theta} \left(\frac{k_{\text{HPT}}}{\delta_{\text{HPT}} + \delta_{\text{SHPo}}} \right)^2 + \frac{k_{\text{SHPo}}}{\delta_{\text{SHPo}} + \delta_{\text{HPi}}} + \frac{k_{\text{HPi}}}{\delta_{\text{HPi}} + \delta_{\text{SHPo}}} + \frac{k_{\text{air}}}{\delta_{\text{air}} + \delta_{\text{SHPo}}} + \frac{k_{\text{HPT}}}{\delta_{\text{HPT}} + \delta_{\text{SHPo}}} - 1}
\]

Because of the narrow visual field and limited observation time of the visualization experiment, \( N_i(r) \) is calculated manually through the visualization experiment with a field-of-view \( 1600 \mu\text{m} \times 1200 \mu\text{m} \), and the result of observed distribution is then extended to the whole sample.

The measured and calculated HTC of various surfaces are shown in Figure 6. Note that the overall measured values of HTC for the surfaces are slightly lower compared to the reported values \( 20,31,43 \) due to the fact that a thick layer of thermal paste is used to connect the condensing surface to the copper block, and the thermal conductivity of the thermal paste \( (~9 \text{ W/m}^2\text{K}) \) is much lower than the copper block \( (~390 \text{ W/m}^2\text{K}) \); whereas the previous works were carried out on the textured surfaces fabricated directly on pure copper block without extra thermal resistance like thermal paste. We can see from Figure 6 that both the measured and calculated HTC increase with the increase of the hydrophilic spot spacing.

For the measured data, the values of HTC on the SHH75 and SHH100 surfaces have an enhancement of 10 and 12% compared to that on pure SHPo surface, respectively. This may arise from the fast droplet nucleation/growth on the hydrophilic regions because of the low nucleation energy barrier; \( 42 \) the droplets on the SHPo region can be readily absorbed by the hydrophilic patterns as a result of the surface energy gradient between the SHPo background and the hydrophilic regions, facilitating the continuous growth of droplets. The droplet size distribution is then extended to the whole sample. This is achieved by using the droplet size distribution function should be considered in two cases. When \( r < r_o \), droplets grow by direct condensation, the droplet size distribution equation is written as

\[
n(r) = \frac{1}{3\pi r_c^3 r_c^2} r_c^{-2/3} r(r - r_{\text{min}}) \frac{A_2 r + A_1}{A_2 r + A_3} \exp(B_1 + B_2)
\]

\[
A_1 = \frac{\Delta T}{2\rho H_f \phi}
\]

\[
A_2 = \frac{\theta(1 - \cos \theta)}{4k_1 \sin \theta}
\]

\[
A_3 = \frac{1}{2h_1} + \frac{\delta(1 - \cos \theta)}{k_2 \sin^2 \theta}
\]
droplets on the hydrophilic spots. The fast droplet nucleation and growth on the hydrophilic regions increases the probability of droplet coalescence-induced departure. Moreover, the condensate droplets on the hydrophilic regions have a lower thermal resistance because there is no air pocket underneath the droplets, which enhances the heat transfer rate. It is worth noting that the HTC on the SHH75 surface is slightly lower than the SHH100 surface, even though the former surface has denser hydrophilic regions that would result in faster droplet nucleation/growth and more frequent droplet coalescence. This may be because of the fact that the droplet-coalescences on the SHH75 surface do not always induce departure, the immobile coalesced droplets formed on the surface would act as a thermal barrier and inhibit the heat transfer rate. This might also be the reason why the HTCs on the SHH50 surface is ~7% lower than that on pure SHPo surface, which enables frequent removal of droplets to replenish more surfaces available for the vapor to condense on. As a result, the distribution of droplets on the SHPo surface is shifted to smaller sizes that contribute to the majority of heat transfer in dropwise condensation. The theoretical calculated HTC values resemble the same trend with experimental results. However, the calculated values are slightly lower, this may be because of the noncondensable gas in air and error when adapting the experimentally values of \( N_s(\tau) \) in the modeling process. Although the enhancement of the heat-transfer performance in the current work is limited, the surfaces are very durable after the condensation test (Table S1); this work provides important insights for the surfaces are very durable after the condensation test (Table S1); this work provides important insights for the condensation performance on the as-fabricated surfaces. We fabricated superhydrophobic/hydrophilic hybrid (SHH) surfaces on copper substrates and systematically investigated the effect of hydrophilic spot spacing on the dropwise condensation performance on the as-fabricated surfaces. We found that, the condensation behavior exhibits dependence on the hydrophilic spot spacing; the coalescence-induced droplet departure frequency as well as HTC increases with the increase of hydrophilic spot spacing. To explain the mechanisms underlying the droplet departure behavior and heat-transfer performance observed/measured in the experiments, an energy-based model and mathematical heat-transfer model were employed. The insights provided by this study offer an avenue for designing optimal surfaces for higher-performance condensers.

## CONCLUSIONS

In summary, we developed a simple and facile technique to fabricate superhydrophobic/hydrophilic hybrid (SHH) surfaces on copper substrates and systematically investigated the effect of hydrophilic spot spacing on the dropwise condensation performance on the as-fabricated surfaces. We found that, the condensation behavior exhibits dependence on the hydrophilic spot spacing; the coalescence-induced droplet departure frequency as well as HTC increases with the increase of hydrophilic spot spacing. To explain the mechanisms underlying the droplet departure behavior and heat-transfer performance observed/measured in the experiments, an energy-based model and mathematical heat-transfer model were employed. The insights provided by this study offer an avenue for designing optimal surfaces for higher-performance condensers.

## EXPERIMENTAL METHOD

**Fabrication of SHH Surfaces.** Commercially available Cu foils with a diameter of 26.4 mm and a thickness of 1 mm were used in the experiments. The Cu foils were first sanded successively with sandpapers of grit size from 320 to 2000, so as to remove the grease and impurities as well as polish the Cu surfaces. The samples were then cleaned in an ultrasonic bath with deionized (DI) water for 10 min, and rinsed with ethanol, isopropyl alcohol, and DI water, respectively. After drying on the hot plate, the samples were immersed into a hot alkaline solution (85 ± 3 °C) composed of NaClO₂, NaOH, Na₃PO₄·12H₂O, and DI water (3.75:5:10:100 wt %) for 30 min, then rinsed with DI water, and dried in air. Thus, the SHPi Cu surfaces were formed. In order to render the surface SHPo, the as-fabricated SHPi Cu samples were silanized by immersing in 1 mM n-hexane solution of 1H,1H,2H,2H-perfluoroctyl-trichlorosilane for 30 min, followed by heat treatment at 150 °C on a hotplate.

The SHH surfaces were fabricated via a laser-ablation process. An array of dots was selectively inscribed on the SHPo substrates using a commercial fiber laser-engraving system (PLS6MW, Universal Laser Systems, Inc., Scottsdale, AZ; 40 W, laser wavelength = 1.06 μm, 2.0° MW lens). The laser beam was raster-scanned across the surface at an output laser power of 9 W, speed of 0.254 m/s, and frequency of 30 kHz.

**Characterizations.** The morphologies of the SHH surfaces were observed by SEM (FEI Quant 250FEG) and chemical elemental composition on the surfaces were detected by the energy dispersive spectroscopy (EDS) equipped with SEM instrumentation. The static water contact angles were measured with a Ramé-Hart goniometer (model 290-U1). Droplets of ~10 μL volume were gently deposited on the samples, the contact angles were measured using the goniometer optics, and the tilt angles were measured by tilting the stage until the ~10 μL droplet rolled off from the surfaces.

**Visualization of Dropwise Condensation Dynamics.** The samples were placed vertically on the cooling stage (Cole-Parmer Standard Benchtop Chilling Block) using carbon adhesive tape to stick to the cooling stage and provide thermal contact. The temperature of the cooling stage was set at 2 °C. A digital microscope (Keyence VHX-6000, VH-Z100R wide-range zoom lens) was used to record the condensation processes.

**Experimental Setup for Condensation Heat Transfer Measurement.** The experiment setup mainly consists of a custom condensation chamber, a boiler, a vacuum pump, a cooling bath, and a data acquisition system. Before the experiment, the water in the boiler was boiled for 10 min to remove the gas in water. Then, the condensation chamber was evacuated to vacuum to remove all the noncondensable gas. The vapor was set to 120 °C, and the chamber was sealed to ensure a saturation status inside the chamber. The subcooling was maintained to 12 °C by controlling the temperature of cooling water. The temperature and pressure data was collected by an Agilent 34902A data acquisition system. The data for each sample was recorded for 100 times with a time interval of 5 s. The thermocouples have an accuracy of ±0.1 °C, and the resistance-temperature-detectors have an accuracy of 0.1%. The thermal paste could have an error of ±0.15 °C according to our test. The maximum uncertainty of the heat flux is 7.2%.

## ASSOCIATED CONTENT

**Supporting Information**

The Supporting Information is available free of charge at https://dx.doi.org/10.1021/acsomega.0c01995.

Regime map of the released surface energy \( \Delta E_s \), viscous energy \( E_v \), adhesion-induced energy \( E_{ad} \), and kinetic energy \( E_k \) when droplet coalescence occurs; sketch map of copper block; surface durability; and contact angles...
of the samples before and after the condensation experiment (PDF)

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes
The authors declare no competing financial interest.

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