Near Field Condensation

Xiao Yan

Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign

<https://orcid.org/0000-0001-9948-3468>

Feipeng Chen

University of Illinois at Urbana Champaign

Chongyan Zhao

Tsinghua University

Yimeng Qin

University of Illinois at Urbana Champaign

Xiong Wang

Tsinghua University

Kazi Fazle Rabbi

University of Illinois at Urbana Champaign <https://orcid.org/0000-0003-3630-1625>

Muhammad Jahidul Hoque

University of Illinois at Urbana Champaign

Hanyang Zhao

University of Illinois at Urbana-Champaign

Jiaqi Li

university of illinois <https://orcid.org/0000-0002-3218-5930>

Tarek Gebrael

University of Illinois at Urbana-Champaign

Feng Chen

Tsinghua University

Jie Feng

Princeton University

Nenad Miljkovic (✉ nmiljkov@illinois.edu)

University of Illinois at Urbana Champaign

Article

Keywords: dropwise condensation, heat transfer, near field condensation, hydrophilic surfaces, superhydrophobic surfaces, droplet population density

Posted Date: July 15th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-39896/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Near Field Condensation

*Xiao Yan¹, Feipeng Chen¹, Chongyan Zhao², Yimeng Qin¹, Xiong Wang¹, Kazi Fazle Rabbi¹,
Muhammad Jahidul Hoque¹, Hanyang Zhao¹, Jiaqi Li¹, Tarek Gebrael¹, Feng Chen², Jie Feng¹,
Nenad Miljkovic^{1,3,4,5*}*

¹Department of Mechanical Science and Engineering, University of Illinois at Urbana–
Champaign, Urbana, IL, 61801, USA

²Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing, 100084, China

³Department of Electrical and Computer Engineering, University of Illinois at Urbana–
Champaign, Urbana, IL, 61801, USA

⁴Materials Research Laboratory, University of Illinois at Urbana–Champaign, Urbana, Illinois
61801, USA

⁵International Institute for Carbon Neutral Energy Research (WPI-I2CNER), Kyushu University,
744 Moto-oka, Nishi-ku, Fukuoka, 819-0395, Japan

*Corresponding Author: Nenad Miljkovic: nmiljkov@illinois.edu

Abstract

Dropwise condensation represents the upper limit of condensation heat transfer. Promoting dropwise condensation relies on surface chemical functionalization, and is fundamentally limited by the maximum droplet departure size. A century of research has focused on active and passive methods to enable the removal of ever smaller droplets. However, fundamental contact line pinning limitations prevent gravitational and shear-based removal of droplets smaller than 250 μm . Here, we break this limitation through near field condensation. By de-coupling nucleation, droplet growth, and shedding *via* droplet transfer between parallel surfaces, we enable the control of droplet population density and removal of droplets as small as 20 μm without the need for chemical modification or surface structuring. We identify droplet bridging to develop a regime map, showing that rational wettability contrast propels spontaneous droplet transfer from condensing surfaces ranging from hydrophilic to hydrophobic. To demonstrate efficacy, we perform condensation experiments on surfaces ranging from hydrophilic to superhydrophobic. The results show that near field condensation with optimal gap spacing can limit the maximum droplet sizes and significantly increase the population density of sub-20 μm droplets. Theoretical analysis and direct numerical simulation confirm the breaking of classical condensation heat transfer paradigms through enhanced heat transfer. Our study not only pushes beyond century-old phase change limitations, it demonstrates a promising method to enhance the efficiency of applications where high, tunable, gravity-independent, and durable condensation heat transfer is required.

Introduction

Since James Watt's revolutionary decision to physically separate the condenser from the piston of the Newcomen engine in the 17th century, condensation has been a key process governing the progress of humanity. Of particular, dropwise condensation has been the main pursuit of the 20th century due to its potential to enhance the efficiency of thermoelectric power generation¹, water distillation², and high heat flux thermal management³. The efficient removal of condensate is the key to improving performance due to condensate becoming thermal-conduction-limited at larger length scales^{4,5}. Utilizing surface chemistry to transform the condensate morphology from a thin film (*i.e.*, filmwise condensation) to discrete droplets (*i.e.*, dropwise condensation) enhances heat transfer by up to 20X⁶. The enhancement arises from the presence of gravity-driven shedding and sweeping of droplets approaching capillary length scales (~ 1 mm for water)⁵. Further reduction of shedding droplet sizes *via* coalescence-induced droplet jumping^{6,7} leads to further enhancement ($\approx 2X$), with efforts to minimize the averaged droplet sizes ongoing^{8,9}.

To decrease shedding droplet size, enormous effort has been spent on tuning condensate-surface interactions *via* the use of hydrophobic^{10,11}, superhydrophobic¹²⁻¹⁴, hybrid¹⁵⁻¹⁸, and slippery surfaces¹⁹⁻²⁵. These approaches promote shedding with an increased population of small (~ 10 μm) droplets¹⁹⁻²⁵. In spite of the success of developed laboratory-scale functional surfaces, lack of durability is the primary barrier to dropwise condensation application²⁸. Weak adhesion, drainage of the lubricant layer²⁹, physical and chemical instability^{30,31}, and airborne volatile organic compound deposition³²⁻³⁴ all lead to significant deterioration of condensation performance within short timescales ($\sim$ weeks). Furthermore, although enhancing droplet shedding is a prevailing strategy to enhance condensation, nucleation site density and condensate morphology play a significant role in determining the overall heat transfer^{35,36}. Thus far, developed functional surfaces

remain incapable of addressing the conflicting need for enhanced nucleation and droplet growth (small droplet contact angle), and enhanced shedding (large contact angle and small hysteresis).

Capillary-driven droplet transfer between surfaces³⁷⁻³⁹ provides an alternate path to effectively shed condensate from unmodified smooth surfaces. As observed daily, droplet transfer occurs when a tissue approaches a spilled water droplet residing on a surface. The droplet is sucked into the tissue upon contact due to the capillary forces, forming a liquid bridge which breaks up (Fig. S1). Similar phenomena are present during condensation on superhydrophobic surfaces, where small ($\sim \mu\text{m}$) droplets nucleate and grow in micro-cavities beneath large ($\sim \text{mm}$) Cassie-Baxter state droplets (Fig. 1A)²⁷, consuming them upon coalescence.

To overcome fundamental dropwise condensation limits, we demonstrate ‘near field’ condensation as a method to control the maximum droplet size and population distribution on a wide variety of modified and unmodified surfaces. By confining the space between a hydrophilic surface and the condenser (Fig. 1B), passive removal is enabled with suppression of liquid bridge formation in the gap. This transfer mechanism enables droplet transition by rationally designing the wettability contrast of the surface pair. The dependence of the bridging states on wettability contrast is elucidated in the form of a regime map. To confirm the efficacy of near field condensation, we conduct experiments to show that droplet shedding can be achieved on surfaces having a wide range of apparent advancing contact angles, *i.e.*, $\theta_a = 45\text{-}170^\circ$. Furthermore, we experimentally demonstrate effective control of maximum droplet size (down to $\sim 10 \mu\text{m}$) and a significant increase in the population of sub-20- μm droplets by up to 450%. Using dropwise condensation theory and direct numerical simulations, we show that near field condensation using unmodified and durable smooth surfaces enables regulation of heat transfer *via* the tuning of the surface gap, and a 100% enhancement in heat flux over dropwise condensation. Our study presents

a method for decoupling nucleation, droplet growth, and shedding from surface functionality to achieve enhanced and controllable condensation heat transfer while removing the need for durability-limited functional coatings and surface finishes.

Figure 1. (A) Optical microscopy image showing shaded coalescence during hierarchical condensation. Small droplets growing underneath a large Cassie-Baxter droplet are sucked into the large droplet upon coalescence due to Laplace pressure contrast. (B) Schematic of near field condensation driven by wettability contrast between the condensing surface (bottom) and adsorbing surface (top). The surfaces are separated by a gap to allow condensate droplets to grow to their maximum size R_{max} determined by the bottom surface contact angle θ and gap spacing H .

Results

Wettability-Contrast Induced Droplet Transfer

Though a liquid bridge usually forms to fill gaps between surfaces^{37,40-42}, we demonstrate here that liquid bridges can be suppressed when the droplet exists between surfaces having wetting contrast. To study droplet bridging, we visualized bridging dynamics between surfaces with differing wettabilities, defined as the difference between the apparent receding contact angle of the bottom surface $\theta_{b,r}$ and the apparent advancing contact angle of the top surface $\theta_{t,a}$ ($\theta_{b,r} - \theta_{t,a}$). Here, $\theta_{t,a}$ and $\theta_{b,r}$ are used since the top surface governs spreading, while the bottom surface governs receding during liquid bridging. To grow a target droplet, we used a frequency-controlled piezoelectric dispenser to dispense monodisperse droplets on the bottom surface^{43,44}. The accumulation of the dispensed microscale droplets allows for the continuous growth of a target droplet to a desired size until the dispenser is turned off. A top surface residing above the bottom surface is then moved downwards steadily at $\sim 10 \mu\text{m/s}$ to approach the target droplet by tuning an independent 3-axis stage until it touches the top interface of the target droplet. Bridging dynamics are captured with a high-speed camera at 25X magnification (see Methods and Section S3, Supplementary Information).

As wettability contrast ($\theta_{b,r} - \theta_{t,a}$) increases, the droplet state between the surfaces transitions from bridging to non-bridging (Fig. 2). Specifically, a stable liquid bridge is formed between the surface pair having low wettability contrast ($\theta_{t,a} = 71 \pm 1^\circ$, $\theta_{b,r} = 93 \pm 3^\circ$, Fig. 2A). Upon contacting the top surface, the droplet spreads, accompanied by the advancing of the contact line and decrease of the dynamic contact angle. Simultaneously, the dynamic contact angle, defined by the extent of the droplet base, starts to decrease followed by a slight receding of the contact line on the bottom surface. The balance between the upper advancing and bottom receding of the

droplet results in the formation of a liquid neck bridging the surfaces. However, the liquid neck is broken when wettability contrast is increased by decreasing the apparent advancing contact angle of the top surface ($\theta_{t,a} = 38 \pm 1^\circ$, $\theta_{b,r} = 93 \pm 3^\circ$, Fig. 2B). In contrast to bridging, the droplet spreads faster on the more hydrophilic top surface while the droplet base shrinks until the neck pinches off. After neck breakup, a small satellite droplet remains on the bottom surface while the droplet on the top surface continues to spread. To confirm that bridging is primarily governed by wettability contrast, we performed experiments with varying droplet sizes and surface gaps (H), showing that the bridging dynamics and final liquid states are independent of H in the range of 0.5 to 1.7 mm (Fig. S3). All experimental cases correspond to Bond numbers $Bo = \Delta\rho g D^2 / \gamma < 0.4$, where $\Delta\rho$ is the density difference across the liquid vapor interface, g is the acceleration due to gravity, D is the droplet diameter, and γ is the liquid-vapor surface tension of water, implying the negligible role of the gravitational forces in our experiments.

The wettability contrast not only determines the bridging state, it also affects the equilibrium shape of the bridge. As the wettability contrast increases, the liquid bridge shows differing morphologies ranging from convex (Inset I, Fig. S6A) to concave (Inset II-IV, Fig. S6A). Consistent with the observation of morphology development for non-bridging droplets, the concave shape of the bridge in the high-wettability-contrast case is necessary to achieve thinning of the liquid neck that leads to eventual neck breakup.

Although we show that large wettability contrast prevents bridging, incomplete droplet transfer or water retention may exist once the liquid neck breaks up. To study water retention, we examined the water retention ratio, defined as the remnant water volume on the bottom surface compared to the original droplet volume, as a function of wettability contrast. As shown in Figure S7A, the water retention ratio is $< 7\%$ and decreases with wettability contrast. In addition

to wettability contrast, the water retention ratio also shows dependence on the bottom surface contact angle hysteresis. Indeed, superhydrophobic and slippery bottom surfaces having small hysteresis ($\theta_{b,a} - \theta_{b,r} < 10^\circ$) result in negligible water retention when paired with a hydrophilic top surface (Fig. S7B).

Figure 2. Wettability-contrast-dependent droplet states between parallel surfaces. (A) Bridging state showing the formation of a stable liquid bridge between surfaces having low wettability contrast ($\theta_{t,a} / \theta_{b,r} = 71 \pm 1^\circ / 93 \pm 3^\circ$). **(B)** Non-bridging state showing liquid bridge breakup between parallel surfaces having large wettability contrast ($\theta_{t,a} / \theta_{b,r} = 38 \pm 1^\circ / 93 \pm 3^\circ$). Spreading, receding, and pinch-off are identified with red arrows. The gap between the parallel surfaces is $H = 850 \pm 70 \mu\text{m}$. Gravity points downwards towards the bottom surface. See video S1.

Bridging Dynamics

The final state of the droplet in the gap is governed by the interplay between droplet spreading on the top surface and receding on the bottom surface. To study droplet dynamics between the parallel surfaces, we captured the dynamic contact angles and contact radii for both bridging and non-bridging cases (Fig. 3A and 3B). To enable bridging, a small wettability contrast was achieved by pairing a hydrophilic top surface ($\theta_{t,a} = 33 \pm 1^\circ$) with a less hydrophilic bottom surface ($\theta_{b,r} = 72 \pm 1^\circ$). To achieve non-bridging, the same hydrophilic top surface ($\theta_{t,a} = 33 \pm 1^\circ$) was paired with

a hydrophobic bottom surface ($\theta_{b,r} = 93 \pm 3^\circ$). For the bridging case, as the droplet interface touches the top surface, the dynamic advancing contact angle on the top surface undergoes a sharp decrease followed by a gradual decline (Fig. 3A). Meanwhile, the droplet on the bottom surface shows a rapid decrease in the dynamic receding angle followed by a steady recession governed by a constant receding contact angle (Fig. 3A). Corresponding to the dynamic contact angle evolution, the spreading radius on the top surface shows a sharp increase during early stages followed by a slowed growth later on, while the receding radius on the bottom surface initially remains unchanged until the droplet base reaches the receding contact angle, after which it decreases steadily (Fig. 3B). Similar wetting dynamics were observed in the non-bridging case, with differences existing at and after initial pinch-off. Due to the larger wettability contrast, the spreading radius grows faster with an accelerated decrease of the receding radius as the droplet neck approaches pinch-off. Immediately after pinch-off, the released droplet on the top surface shows a sharp increase of the dynamic contact angle and spreading radius due to the rapid recoil of the broken liquid filament before it starts to freely spread on the top surface (Fig. 3A and 3B).

To determine the droplet transfer time scale, we analyzed the droplet receding behavior prior to pinch-off, which starts with an inertial stage followed by a steady receding stage (Fig. 2B and 3B). During the inertial stage, the droplet base remains unchanged until it senses the capillary wave initiated from the top interface. The duration of the inertial stage scales as $\Delta t_i \sim \tau H/R_s$, where $\tau = \sqrt{\rho R_s^3 \gamma^{-1}}$ is the inertial/capillary time, R_s is the radius of the spherical cap, and ρ is the liquid density. Following the inertial stage, the droplet base recedes with a nearly constant velocity v_r (Fig. 3B). The timescale of receding is $\Delta t_r \sim R_b/v_r$, which is a function of wettability contrast, *i.e.*, $\Delta t_r = f(\theta_{t,a}, \theta_{b,r})$ (Eq. S7, Section S4, Supplementary Information). The total time required for

droplet transfer prior to pinch-off, Δt_p , is expected to scale with the sum of Δt_i and Δt_r , which is consistent with our experimental results as demonstrated in Fig. 3C.

Figure 3. Wetting dynamics of bridging and non-bridging droplets. (A) Apparent contact angle on the top (θ_t^D) and bottom (θ_b^D) surface as a function of dimensionless time (t/τ). (B) Dimensionless spreading radius on the top surface (R_t^*) and receding radius on the bottom surface (R_b^*) as a function of dimensionless time (t/τ). Wettability contrast of the bridging case: $\theta_{t,a} / \theta_{b,r} = 33 \pm 1^\circ / 72 \pm 1^\circ$. Wettability contrast of the non-bridging case: $\theta_{t,a} / \theta_{b,r} = 33 \pm 1^\circ / 93 \pm 3^\circ$. The inertial stages prior to droplet base recession are shaded. The pinch-off moment for the non-bridging cases is identified with arrows. (C) Experimental pinch-off time (Δt_p) as a function of the semi-analytical pinch-off time $\Delta t_i + \Delta t_r$ defined as the sum of the inertial time Δt_i and receding time Δt_r .

Droplet Bridging Regime Map

Figure 4 shows the regime map demarking conditions for droplet bridging as a function of surface wettability contrast. Top surfaces having smaller apparent advancing contact angles with bottom surfaces having larger apparent receding contact angles suppress liquid bridging. In particular, superhydrophilic top surfaces ($\theta_{t,a} \approx 0^\circ$) efficiently transfer droplets from almost all bottom surfaces regardless of the apparent receding angle of the bottom surface. In addition,

superhydrophobic bottom surfaces ($\theta_{b,r} > 150^\circ$) efficiently transfer droplets for almost all top surfaces regardless of the apparent advancing contact angle of the top surface ($\theta_{t,a} < 150^\circ$).

To show the effects of wettability contrast and to predict final droplet states (bridging or non-bridging), we performed an energy analysis of the droplet-surface system. We begin by considering the case where the droplet on the bottom surface transfers to the top surface, with a fraction (ε) of volume retained on the bottom surface. By examining the interfacial energy associated with the initial state where the spherical cap droplet rests on the bottom surface and the final state where the droplet resides on the top surface, we obtained the surface energy difference ΔE_s (Eq. S9-S21, Section S5, Supplementary Information) that is eventually dissipated by viscous dissipation δE_d . The total dissipation associates with viscous dissipation in the bulk liquid, contact line, and boundary layer⁴⁵. To estimate the viscous dissipation components during bridging and breakup, we first performed finite element method (FEM) fluid dynamics simulations, showing a large velocity gradient near the advancing and receding contact lines with small velocity gradients in the liquid bulk (Fig. S10B, Section S6, Supplementary Information). The FEM simulations imply that significant viscous dissipation occurs at the contact lines. Viscous dissipation at the contact line, δE_{cl} , which accounts for the dominant portion of the total viscous dissipation⁴⁵ can be estimated by:

$$\delta E_{cl} \approx 2\pi \sum_{i=1,2} \lambda_i \int r_i v_i dr_i , \quad (1)$$

where the subscript $i = 1$ denotes the case where the droplet spreads on the top surface and $i = 2$ denotes droplet receding on the bottom surface. λ_i is the friction coefficient depending on the specific surface and surrounding phase⁴⁵. r_i and v_i are the radius and velocity of the contact line, respectively (Eq. S1-S4, Section S4, Supplementary Information).

The droplet bridging regime was estimated by comparing the excess surface energy with total viscous dissipation. Bridging is preferred when $\Delta E_s \leq \delta E_d \approx \delta E_{cl}$, implying that excess surface energy exceeds the viscous dissipation energy barrier. To account for the variation of λ_i (0.03-0.105 Pa·s)^{46,47} and ε (0-7%, Fig.S7) for varying surface pairs, we calculated the envelope lines corresponding to the most favorable ($\lambda_i = 0.03$, $\varepsilon = 0\%$) and unfavorable ($\lambda_i = 0.105$, $\varepsilon = 7\%$) cases for non-bridging. The predicted bridging bound agrees well with our experimental data despite the neglected bulk viscous dissipation associated with bridge pinch-off (Fig.S10B).

Figure 4. Droplet bridging regime map as a function of top surface apparent advancing contact angle $\theta_{t,a}$ and bottom surface apparent receding contact angle $\theta_{b,r}$. The light green region represents the predicted bridging bound accounting for the variation of friction coefficient λ_i (0.03-0.105) and water retention ratio ε (0-7%).

Condensate Shedding and Heat Transfer Performance

To characterize the efficacy of droplet transfer during condensation as a means to enhance heat transfer, we performed condensation experiments on hydrophobic ($\theta_a^{\text{app}} / \theta_r^{\text{app}} = 106 \pm 1^\circ / 97 \pm 1^\circ$) and hydrophilic ($\theta_a^{\text{app}} / \theta_r^{\text{app}} = 87 \pm 2^\circ / 43 \pm 4^\circ$) copper (Cu) surfaces. A superhydrophilic nanostructured copper oxide (CuO) mesh ($\theta_a^{\text{app}} \approx 0^\circ$) was used as a receptor surface and was stacked on top of the Cu substrates using two fine metal wires to form a gap (diameter $D = 50$ - $200 \mu\text{m}$) (see Methods for fabrication details). The formed gap allowed droplets condensing on the Cu substrate to grow until they contact the CuO mesh. A CuO mesh was used due to its good wickability arising from the highly roughened CuO nanostructures (roughness factor, $r \approx 10$)⁶. Furthermore, the microscale openings⁶ enabled optical access for observation to study bridging, and high vapor permeability to access the condensing Cu surface. The bottom Cu substrates were placed horizontally on a Peltier cold plate having a surface temperature $T_s = 1 \pm 0.5^\circ\text{C}$ and the condensation process was captured *via* top-view optical microscopy (see Methods).

In contrast to a regular dropwise condensing hydrophobic Cu surface, where spherical condensate droplets grow and coalesce to form large droplets that occupy the entire field of view (Fig. 5A), near field condensation in the presence of the CuO mesh effectively confined the maximum droplet size. This was shown by the sudden disappearance of droplets followed by re-nucleation of sub- $10\text{-}\mu\text{m}$ droplets in the cleared areas ($t > 10 \text{ min}$, Fig. 5B). Differing from single-droplet transfer, droplet-mesh contact was triggered by the coalescence of two or multiple droplets, followed by a wave-like propagation of droplet transfer ($t = 12 \text{ min}$, Fig. 5B). The multiple droplet transfer results from the liquid spreading on the CuO mesh, similar to cascading coalescence of condensate in grooves⁵⁰.

Condensate droplet transfer was also observed on CuO mesh-covered hydrophilic Cu surfaces, regardless of the irregular film-like droplet shape (Fig. 5C-D). The results were consistent with the regime map in Figure 4, further confirming the robustness of droplet transfer enabled by wettability contrast. Unlike the hydrophobic Cu surface (Fig. 5B), condensation on the hydrophilic Cu showed higher nucleation site density, as observed on the cleared Cu area immediately after droplet transfer ($t = 50$ min, Fig. 5E). The enhanced nucleation density and reduced thermal conduction resistance³⁶ due to the low contact angle result in rapid condensation cycling starting from nucleation, droplet growth, coalescence, transfer, and re-nucleation again (Fig. 5E, Video S2).

To further probe the extremes of substrate wettability enabling near field condensation, we performed experiments on a smooth hydrophilic mirror-finished Si wafer ($\theta_a^{\text{app}} / \theta_r^{\text{app}} = 45 \pm 3^\circ / 27 \pm 5^\circ$), and a superhydrophobic nanostructured CuO surface ($\theta_a^{\text{app}} / \theta_r^{\text{app}} = 170 \pm 6^\circ / 167 \pm 8^\circ$). Consistent with the regime map (Fig. 4), wettability-contrast-induced condensate transfer was observed in both surfaces (Section S7, Supplementary Information). Specifically, similar to condensation on hydrophilic Cu surfaces, rapid droplet growth, cascading droplet transfer, and enhanced re-nucleation were observed on the hydrophilic Si surface (Fig. S11A, Video S2). On the superhydrophobic surface, while small droplets (10-50 μm) spontaneously jumped out of plane *via* surface to kinetic energy transfer⁶, larger droplets (~ 100 μm) progressively accumulated on the horizontal surface due to droplet size mismatch⁴³, after which droplets transferred upon contact with the superhydrophilic CuO top mesh (Fig. S11B).

Figure 5. Wettability-contrast-induced droplet shedding during near field condensation on hydrophobic and hydrophilic surfaces. Time-lapse optical microscopy images of condensation on a hydrophobic ($\theta_a^{\text{app}}/\theta_r^{\text{app}} = 106 \pm 1^\circ / 97 \pm 1^\circ$) Cu surface **(A)** without and **(B)** with a superhydrophilic CuO mesh ($\theta_a^{\text{app}} \approx 0^\circ$) placed on top. Time-lapse images of condensation on a hydrophilic Cu surface ($\theta_a^{\text{app}}/\theta_r^{\text{app}} = 87 \pm 2^\circ / 43 \pm 4^\circ$) **(C)** without and **(D, E)** with a superhydrophilic CuO mesh placed on top. The nucleation-growth-coalescence-shedding-re-nucleation cycle is shown with a higher magnification (50X) in **(E)**. Droplet shedding with multi-coalescence is identified in dotted enclosed regions. Insets in **(B)** and **(E)** show the zoomed-in view of re-nucleation after droplet transfer from the hydrophobic and hydrophilic surfaces, respectively. See Video S2. Condensation experiments performed with air temperature $T_a = 25 \pm 1^\circ\text{C}$, relative humidity $\Phi = 40 \pm 5\%$, and surface temperature $T_s = 1^\circ\text{C}$. See Methods.

To characterize near field condensation heat transfer, we examined the droplet growth rate and droplet size distribution on a hydrophobic Cu surface covered with a superhydrophilic CuO mesh (Fig. 5B). As droplets grow to a height ($H \approx 60 \mu\text{m}$) or radius ($R_{\text{max}} \approx 50 \mu\text{m}$) *via* direct condensation or coalescence, they are transferred to the top CuO mesh upon contact, resulting in a sharp decrease in droplet radii, after which the droplets grow again (Fig. 6A). When the surface gap is decreased further ($H \approx 20 \mu\text{m}$), the maximum droplet radius is constrained to $R_{\text{max}} \approx 15 \mu\text{m}$ (Fig. 6A), approaching the jumping droplet size on superhydrophobic surfaces⁶. In contrast, droplets on the mesh-free hydrophobic Cu surface grew steadily to reach much larger sizes ($\approx 120 \mu\text{m}$) during the same period. Compared to the mesh-free hydrophobic Cu surface (dropwise condensation, $H \approx \infty$), near field condensation with $H \approx 60 \mu\text{m}$ and $H \approx 20 \mu\text{m}$ results in a $\approx 100\%$ and $\approx 450\%$ larger number density of sub-20- μm droplets (Fig. 6B), respectively, which contribute $\approx 80\%$ to the overall heat transfer of classical dropwise condensation (Fig. S12, Section S8, Supplementary Information)²⁶.

To quantify the near field condensation heat transfer, we calculated the overall surface heat flux as a function of the gap distance, H . The overall heat flux is obtained by integrating the heat transfer through individual droplets over the droplet size range⁵¹⁻⁵³:

$$q'' = \int_{R_{\text{min}}}^{R_e} q(R, \theta) n(R, \theta) dR + \int_{R_e}^{R_{\text{max}}} q(R, \theta) N(R, \theta) dR, \quad (2)$$

where $q(R, \theta)$ is the heat transfer through a single droplet with a radius R on a surface having an apparent advancing contact angle θ (Section S8, Supplementary Information). The nucleation radius R_{min} is determined using classical nucleation theory and R_{max} is dependent on the droplet shedding mechanisms⁵¹⁻⁵³. The radius when droplets start to coalesce, R_e , is determined by the nucleation site density N_s *via* $R_e \approx 1/\sqrt{4N_s}$ ⁵¹. The functions $n(R, \theta)$ and $N(R, \theta)$ are the droplet

size distributions for small droplets ($R < R_e$) and large droplets ($R \geq R_e$), respectively^{51,54}. For dropwise condensation on a vertically-oriented surface, $R_{\max}$ is governed by surface wettability⁵¹, typically approaching the capillary length scale of the working fluid ($\sim$ mm, Section S8, Supplementary Information). For near field condensation, $R_{\max}$ is determined geometrically by (Fig. 1B):

$$R_{\max} = \frac{H}{1 - \cos \theta}. \quad (3)$$

To enable a fair comparison, the nucleation site density N_s for all surfaces were identical in our analysis. As shown in Figure 6D, as H decreases, q'' increases regardless of the surface wettability. Compared to dropwise condensation, a 200% enhancement in q'' can be achieved when $H \approx 100$ μ m. The substrate contact angle plays an important role in heat transfer. A hydrophobic surface having $\theta = 110^\circ$ outperforms surfaces having $\theta = 70^\circ$ and 90° for a constant nucleation site density and identical gap. It should be noted that lower apparent advancing contact angle reduces the thermodynamic energy barrier to heterogeneous nucleation, thus leading to higher nucleation site density⁵⁵ (Insets in Fig. 5B and 5E), which is not incorporated in the current analytical calculations, and stands to only enhance the efficacy of near field condensation.

To enhance the fidelity of the theoretical calculations, and to enable better insights into near field condensation mechanisms, we developed a numerical simulation by incorporating condensation multi-scale physics and simulating the entire process^{56,57}. A superhydrophilic top surface was employed to adsorb condensate from the condensing surface once the droplets reached the top surface. As shown in Figure 6D, droplet nucleation, growth, coalescence, and shedding dynamics were successfully captured, reproducing the near field condensation observations shown in Figure 5. The dependence of condensation heat fluxes on surface gap was obtained, and was shown to be consistent with the theoretical results (Fig. 6C).

Figure 6. Characterization of near field condensation. (A) Near field condensation droplet radius R as a function of time t on the hydrophobic Cu surface ($\theta_a^{\text{app}} / \theta_r^{\text{app}} = 106 \pm 1^\circ / 97 \pm 1^\circ$) for differing surface gaps H . The $H = \infty$ represents the case of dropwise condensation (no mesh). (B) Near field condensation droplet number density N as a function of droplet radius R on the hydrophobic Cu surface with differing surface gaps H . Bars are stacked to facilitate comparison. See Methods for condensation experiment details. (C) Theoretically (solid lines) and numerically simulated (data points) overall heat fluxes q'' as a function of surface gap H for near field condensing substrates having varying apparent advancing contact angles θ . The star symbols represent classical dropwise condensation. Inset: schematic showing near field condensation. For theory and simulation parameters, see Sections S8 and S9 of the Supplementary Information. (D) Time-lapse images of the numerical simulation results for near field condensation. The top surface (black) is partially removed to facilitate visualization of condensation on the bottom (white) surface. Droplet shedding is shaded in red. See Video S3.

Discussion

Near field condensation uses wettability-contrast induced droplet transfer between parallel surfaces as a means to break the fundamental heat transfer limitations of dropwise condensation. Liquid dewetting and spreading dynamics along with thermodynamic analysis illuminates the importance of wettability contrast on droplet bridging. Although we experimentally demonstrate that capillary forces dominate droplet transfer for droplet sizes ranging from $\sim 10\text{ }\mu\text{m}$ to 1 mm , viscous forces can alter bridging dynamics and resist liquid bridge pinch-off, hindering transfer for highly-viscous liquids or nanoscale water droplets having Ohnesorge numbers $Oh > 0.1$, where $Oh = \mu/\sqrt{\gamma\rho D}$ where μ is the dynamic viscosity of the condensing fluid⁵⁸. Furthermore, due to the negligible role of gravitational forces on the droplets studied here ($R < 1.7\text{ mm}$ and $Bo < 0.4$), droplet transfer is independent of orientation. For larger droplets ($Bo > 0.4$), gravitational forces may begin to affect droplet transfer. Future theoretical, simulation, and experimental work is needed to examine the effects of liquid viscosity and gravitational forces and explore droplet size limitation beyond which the demonstrated droplet transfer mechanism fails.

The droplet length scales studied here are significantly ($> 100\times$) larger than the surface roughness length scale ($< 1\text{ }\mu\text{m}$). For surface structures comparable to droplet sizes, contact line spreading and receding differs from smooth or nanostructured surfaces⁵⁹⁻⁶¹. Thus, structure-dependent viscous dissipation needs to be incorporated when predicting bridging behavior (Eq. 1). For instance, structures on the bottom surface may affect droplet receding, liquid neck development, and water retention due to the enlarged surface area, structure-induced pinning, and altered local flow fields. Incorporation of rationally designed diverging microstructures such as V-grooves or conical-channels on the condensing surface to enable droplet self-transport²⁷ is likely to further promote droplet transfer during near field condensation. In addition to condensing

surface structures, spreading and pinch-off of the liquid bridge on the receptor surface can be altered with structures. For a surface pair having a superhydrophilic droplet receptor (top), the effects of surface wickability governed by intrinsic wettability, structure length scale, and porosity need further investigation. Highly-wicking surfaces are preferred to enhance capillary action during droplet spreading^{62,63}, thus promoting pinch-off of formed liquid bridges.

Near field condensation offers significant advantages when compared to conventional dropwise or jumping droplet condensation. Rather than optimizing for a single process on a single substrate, near field condensation enables enhanced nucleation and droplet growth on hydrophilic substrates, while simultaneously allowing dropwise-like shedding with extreme control of the droplet distribution. Dropwise condensation on hydrophobic substrates trades low nucleation density for efficient droplet shedding. Superhydrophobic surfaces enable even more efficient droplet shedding at the cost of even lower nucleation density and droplet growth rate^{36,55}. In addition to nucleation limitations, hydrophobic and superhydrophobic surfaces suffer from flooding and poor durability due to the need for chemical modification. Near field condensation does not rely on condensing surface chemistry, and hence can overcome the barriers associated with longevity. Unlike the functional surfaces which rely on the ultra-thin and physically^{31,64} and chemically^{30,32} unstable coatings with complex coating procedures, wettability contrast can be achieved by pairing raw materials such as metals and metal oxides. The elimination of coatings enables the long-term durability and fabrication-simplicity of near field condensation. In addition to optimizing heat transfer and enabling durability, near field condensation enables continuous regulation of the heat transfer rate (> 2) *via* tuning of the surface gap (Fig. 6C). Along with directionally independent performance, tunable heat transfer is promising for thermal diode⁶⁵, vapor chamber^{66,67}, and thermal regulator applications⁶⁸.

Efficient shedding of condensate from a variety of surfaces (Fig. 5 and Fig. S11) demonstrates robustness and versatility of near field condensation. However, to ensure the long-term efficacy, the adsorbed liquid on the receptor surface needs to be drained. For atmospheric condensation where the heat transfer rate is low ($< 0.1 \text{ W/cm}^2$)⁶⁹ due to gas diffusion effects⁷⁰, the absorbed water spreads rapidly on the wicking receptor surface, leading to a high evaporation rate due to increased contact line area. Thus, water accumulation or flooding was not observed during condensation experiments lasting multiple hours in our study (Fig. 5). For pure-fluid condensation having higher heat fluxes ($> 10 \text{ W/cm}^2$, for steam), surface area, surface spatial arrangement, and micro/nanostructures need to be rationally designed to facilitate liquid transport and drainage *via* gravitational forces, pressure forces, or evaporation. This is particularly important when considering thermal management applications such as thermal diodes, vapor chambers, and thermal spreaders, where thin-film evaporation or boiling on the high-temperature top side presents an efficient way of returning the adsorbed condensate to the condenser and spreading the heat.

Our study provides new insights into the governing mechanisms of dropwise and filmwise condensation. Previous studies have shown that gravitational-shedding based dropwise condensation is governed by the surface wettability⁵ and contact angle hysteresis²⁰. Near field condensation breaks these paradigms by enabling the equivalent of dropwise condensation on hydrophilic substrates not requiring extremely low hysteresis. Differing from liquid transport *via* capillary flows⁷¹ or droplet jumping^{65,67} in existing thermal management devices, near field condensation provides a method for direct and rapid liquid return to the evaporator, reducing condensation thermal resistance due to elimination of porous wicking structures or functional chemical coatings on the condensing surface.

Methods

Surface Fabrication

The superhydrophobic CuO surface (Fig. 1A and S11B) was fabricated with chemical oxidation followed by hydrophobic silane deposition⁶. Specifically, mirror-finish Cu plates (99.9% purity, McMaster) were first ultrasonically cleaned with acetone (Sigma, CAS # 67-64-1) for 5 min and rinsed with ethanol (Sigma, CAS # 64-17-5), isopropanol (Sigma, CAS # 67-63-0), and deionized (DI) water (Sigma, CAS # 7732-18-5) and dried with a clean nitrogen stream. To remove the native oxide, the samples were then immersed in a hydrochloric acid solution (HCl, 2M, Sigma, CAS # 7647-01-0) for 30 s, and then rinsed with DI water and dried with a clean nitrogen stream. To synthesize the CuO nanoblade structures, the cleaned samples were immersed into a hot (96 ± 3 °C) alkaline solution composed of NaClO₂ (Sigma, CAS # 7758-19-2), NaOH (Sigma, CAS # 1310-73-2), Na₃PO₄·12H₂O (Sigma, CAS # 10101-89-0), and DI water (3.75:5:10:100 wt %). The oxidation process lasted ≈ 10 min, after which the samples were removed from the solution, rinsed immediately with DI water, and dried with a clean nitrogen stream. The oxidized CuO surfaces were then functionalized with heptadecafluorodecyltrimethoxy-silane (HTMS) (TCI America, CAS #: 83048-65-1) *via* vapor phase deposition⁶. The surface samples were placed in a beaker with a vial of 1 mL HTMS toluene (Sigma, CAS # 108-88-3) solution (5% v/v). A lid was placed on top to seal the container, followed by heating in an atmospheric pressure oven (Thermo Scientific, Lindberg Blue M) at 90 ± 5 °C for 3 hours.

The superhydrophilic CuO meshes (Fig. 5) were fabricated *via* the same chemical oxidation method (without HTMS deposition) described above using commercially available Cu meshes (TWP Inc.). The wire diameter, opening, and spacing of the meshes are 50, 75, and 125 μ m,

respectively. Before chemical oxidation, the CuO meshes were cut into $\approx 10 \times 10 \text{ mm}^2$ pieces and pressed to be flat using a compressor (MTS1-DFS, Nextech).

The mirror-finished Cu (Fig. 5C-E) and Si (Fig. S11A) surfaces are commercially available and were cleaned with acetone, isopropanol, ethanol, and DI water, then dried with clean nitrogen before used in the experiments. The hydrophobic Cu surface (Fig. 5A and 5B) was fabricated by coating the cleaned mirror-finished Cu plate with HTMS *via* chemical vapor deposition as described above.

To control the wettability of the top and bottom surfaces (Fig. 2, 3, and 4), various materials with or without coatings including Cu, Al, Si, stainless steel, Teflon, Si with slippery omniphobic covalently attached liquids (SOCAL)⁶, and lubricant-infused CuO surfaces (SLIPS) were used. All surfaces were smooth with negligible wettability heterogeneity induced by roughness. To achieve highly hydrophilicity, the smooth surfaces were cleaned using air plasma (PDC-001-HP, Harrick Plasma) at a medium power setting for 5-10 min. For all surfaces, the contact angles remained almost unchanged and the effects of adsorption of volatile organic compounds (VOCs) on the surface could be neglected given the short duration of surface atmospheric exposure before and during experiments^{32,34}. Table S1 and Section S3 of the Supplementary Information contains detailed characterization of the surfaces.

Surface Characterization

Water contact angles of the surfaces were measured using a piezoelectric micro-goniometer (MCA-3, Kyowa Interface Science) with voltage and frequency control. To measure the advancing contact angle, monodisperse water droplets with radii of $\approx 18 \text{ }\mu\text{m}$ were dispensed by the piezoelectric nozzle operating at 7 V and 30-60 Hz. The droplet on the surface was grown to

≈ 100 nL by accumulating the dispensed droplets and the advancing of the droplet contact line was recorded at 1 fps by an integrated camera and custom optics. For droplets smaller than 100 nL, potential droplet resonance due to the addition of small dispensed droplets, which may introduce a water hammer-type pressure and cause droplet wetting transition, was not present, thus allowing for accurate measurements of contact angle during droplet dispensing. The receding contact angle was measured by stopping dispensing droplets and letting the droplet shrink *via* evaporation. The advancing and receding contact angles were extracted by commercial software (FAMAS, Interface Measurements & Analysis System, Kyowa) *via* the ellipse fit method. Measurements were repeated on 3 - 5 different locations on the surface to obtain the averaged advancing or receding contact angles.

Visualization of Liquid Bridging Dynamics

To grow a droplet and visualize liquid bridging dynamics between parallel surfaces (Fig. 2, 3, and 4), we interfaced a high-speed camera (Phantom v711, Vision Research) with the microgoniometer (MCA-3, Kyowa Interface Science) (Fig. S2). The piezoelectric dispenser was placed above a surface (referred to as bottom surface herein) with a spacing of 5-10 mm, and turned on to dispense monodisperse microscale droplets having radii of $\approx 18 \mu\text{m}^{43}$. The target droplet grew in size due to the addition of the dispensed monodisperse microscale droplets until it reached a desired size and the dispenser was removed. Droplet dispensing was carried out at 6-7 V and 10-500 Hz, depending on the required growth rate of the droplets. A top surface parallel to the bottom surface was then slowly approached to the target droplet by tuning a 3-axis stage until it contacted the topmost interface of the droplet. Droplet bridging dynamics between the top and bottom surfaces were captured with the high-speed camera. Imaging was performed with a $\approx 25\times$

magnification lens with a capture rate of up to 13,000 fps. Illumination was supplied by an LED source (TSPA22x8, Aitecsystem). All experiments were performed in ambient conditions with a temperature of 24 ± 1 °C and a relative humidity of $40 \pm 5\%$.

Condensation Experiments

Droplet behavior during near field condensation (Fig. 5, 6A-B, and S11) was observed using a customized top-view microscopy setup consisting of an upright optical microscope (Eclipse LV100, Nikon) interfaced with a high-resolution camera (Qi2, Nikon). Samples were mounted horizontally on a Peltier cold stage (TP104SC-mk2000A, Instec) which was cooled to 1 ± 0.5 °C to condense water vapor from the laboratory ambient air. To construct the near field condensation system, a square piece of superhydrophilic CuO nanostructured mesh was placed on top of the condensing surface with a gap between the two surfaces, which was controlled by two straight Cu wires having diameters ($D = 50 - 200$ μm, McMaster). Condensation behavior was recorded at 1-10 fps with 5-50X objectives (TU Plan Fluor EPI, Nikon). Illumination was supplied by an LED light source (SOLA SM II Light Engine, Lumencor). The LED light source was specifically chosen for its high intensity and low power consumption (2.5 W) to minimize heat generation due to light absorption. Furthermore, by manually reducing the condenser aperture diaphragm opening size and increasing the camera exposure time, we were able to minimize the amount of light energy needed for illumination and hence minimize local heating effects during condensation experiments⁸. The condensation experiments were performed in laboratory ambient air having a temperature of 24 ± 1 °C and relative humidity of $40 \pm 5\%$ (RO120, Roscid Technologies). To measure the droplet size distributions (Fig. 6B), we allowed the condensation to proceed for 15 minutes to reach a quasi-steady state, and measured droplet sizes using ImageJ (NIH Image) in a

field of view of $1440 \times 957 \mu\text{m}$. Due to spatial resolution limits, droplets having $2R < 1.5 \mu\text{m}$ were not counted.

Numerical Simulations of Near Field Condensation

To optimize the design of the near field condensation system, we performed direct numerical simulations of the condensation process starting from nucleation to droplet growth, coalescence, and departure (Fig. 6C-D)^{56,57}. The nucleation sites were randomly assigned to the condensing surface, using a Poisson distribution⁷³. Droplet growth rate was determined by calculating the thermal resistance and implementing an energy balance. To simulate droplet shedding *via* transfer to the top surface, droplets growing beyond a height limit due to direct condensation or coalescence were immediately cleared from the condensing surface. Complete droplet transfer was assumed given the small liquid retention ratio (Fig. S7). Immediately after droplet shedding, a new round of nucleation sites was initiated on the refreshed areas. Time-dependent droplet size distributions were monitored to ensure that steady-state was reached when the data analysis was performed. To ensure the time step and condensing surface area independence of the simulation results, we conducted multiple simulations with varying time steps and surface length scales. Simulations were performed with pure steam at a temperature $T_v = 25^\circ\text{C}$ and a surface temperature $T_s = 20^\circ\text{C}$. See Section S9 of Supplementary Information for additional simulation details. For a freely available Matlab version of the numerical code, please see the Supplementary Information of Ref. 56.

541 **Data availability**

542 All data needed to evaluate the conclusions in the paper are present in the paper and/or the
543 Supplementary Information. Additional data related to this paper may be requested from the
544 authors.

545

546

References

1. Beér, J. M. High efficiency electric power generation: The environmental role. *Prog. Energ. Combust.* **33**, 107-134 (2007).
2. Al-Karaghoul, A. & Kazmerski, L. L. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable Sustainable Energy Rev.* **24**, 343-356 (2013).
3. Wiedenheft, K. F. et al. Hotspot cooling with jumping-drop vapor chambers. *Appl. Phys. Lett.* **110**, 141601 (2017).
4. Rose, J. On the mechanism of dropwise condensation. *Int. J. Heat Mass Tran.* **6**, 755-756 (1967).
5. Rose, J. W. Dropwise condensation theory and experiment: a review. *J. Power Energy.* **216**, 115-128 (2002).
6. Miljkovic, N. et al. Jumping-Droplet-Enhanced Condensation on Scalable Superhydrophobic Nanostructured Surfaces. *Nano Lett.* **13**, 179-187 (2013).
7. Boreyko, J. B. & Chen, C. H. Self-propelled dropwise condensate on superhydrophobic surfaces. *Phys. Rev. Lett.* **103**, 184501 (2009).
8. Cha, H. et al. Coalescence-induced nanodroplet jumping. *Phys. Rev. Fluids.* **6**, 64102 (2016).
9. Mulroe, M. D., Srijanto, B. R., Ahmadi, S. F., Collier, C. P. & Boreyko, J. B. Tuning Superhydrophobic Nanostructures To Enhance Jumping-Droplet Condensation. *ACS Nano.* **8**, 8499-8510 (2017).
10. Preston, D. J., Mafra, D. L., Miljkovic, N., Kong, J. & Wang, E. N. Scalable Graphene Coatings for Enhanced Condensation Heat Transfer. *Nano Lett.* **15**, 2902-2909 (2015).
11. Kim, G., Gim, S., Cho, S., Koratkar, N. & Oh, I. Wetting-Transparent Graphene Films for Hydrophobic Water-Harvesting Surfaces. *Adv. Mater.* **26**, 5166-5172 (2014).
12. Enright, R., Miljkovic, N., Alvarado, J., Kwang, K. & Rose, J. Dropwise Condensation on Micro-and Nanostructured Surfaces. *Nanoscale Microsc. Therm.* **3**, 223-250 (2014).
13. Chen, X. et al. Nanograssed Micropyramidal Architectures for Continuous Dropwise Condensation. *Adv. Funct. Mater.* **21**, 4617-4623 (2011).
14. Peng, Q. et al. Influence of groove orientation on dropwise condensation on hydrophobic and hierarchical superhydrophobic surfaces with microgroove arrays. *Int. Commun. Heat Mass.* **112**, 104492 (2020).
15. Hou, Y., Yu, M., Chen, X., Wang, Z. & Yao, S. Recurrent Filmwise and Dropwise Condensation on a Beetle Mimetic Surface. *ACS Nano.* **9**, 71-81 (2015).
16. Ölçeroğlu, E. & McCarthy, M. Self-Organization of Microscale Condensate for Delayed Flooding of Nanostructured Superhydrophobic Surfaces. *ACS Appl. Mater. Inter.* **8**, 5729-5736 (2016).
17. Wen, R. et al. Sustaining enhanced condensation on hierarchical mesh-covered surfaces. *Natl. Sci. Rev.* **5**, 878-887 (2018).
18. Peng, B., Ma, X., Lan, Z., Xu, W. & Wen, R. Analysis of condensation heat transfer enhancement with dropwise-filmwise hybrid surface: Droplet sizes effect. *Int. J. Heat Mass Tran.*, **77**, 785-794 (2014).
19. Dai, X. et al. Hydrophilic directional slippery rough surfaces for water harvesting. *Sci Adv.* **4**, q919 (2018).
20. Cha, H. et al. Dropwise condensation on solid hydrophilic surfaces. *Sci Adv.* **6**, x746 (2020).

- 593 21. Preston, D. J. et al. Heat Transfer Enhancement During Water and Hydrocarbon
594 Condensation on Lubricant Infused Surfaces. *Sci. Rep.-Uk.* **8**, 540 (2018).
- 595 22. Sett, S., Yan, X., Barac, G., Bolton, L. W. & Miljkovic, N. Lubricant-Infused Surfaces for
596 Low-Surface-Tension Fluids: Promise versus Reality. *ACS Appl. Mater. Inter.* **9**, 36400-
597 36408 (2017).
- 598 23. Sett, S. et al. Stable Dropwise Condensation of Ethanol and Hexane on Rationally
599 Designed Ultrascable Nanostructured Lubricant-Infused Surfaces. *Nano Lett.* **19**, 5287-
600 5296 (2019).
- 601 24. Zhang, L., Guo, Z., Sarma, J. & Dai, X. Passive Removal of Highly Wetting Liquids and
602 Ice on Quasi-Liquid Surfaces. *ACS Appl. Mater. Inter.* **12**, 20084-20095 (2020).
- 603 25. Zhao, H. et al. Extreme Antiscaling Performance of Slippery Omniphobic Covalently
604 Attached Liquids. *ACS Appl. Mater. Inter.* **12**, 12054-12067 (2020).
- 605 26. Graham, C. & Griffith, P. Drop size distributions and heat transfer in dropwise
606 condensation. *Int. J. Heat Mass Tran.* **16**, 337-346 (1973).
- 607 27. Yan, X. et al. Hierarchical Condensation. *ACS Nano.* **13**, 8169-8184 (2019).
- 608 28. Ma, J., Sett, S., Cha, H., Yan, X. & Miljkovic, N. Recent developments, challenges, and
609 pathways to stable dropwise condensation: A perspective. *Appl. Phys. Lett.* **116**, 260501
610 (2020).
- 611 29. Wong, T. S. et al. Bioinspired self-repairing slippery surfaces with pressure-stable
612 omniphobicity. *Nature.* **477**, 443-447 (2011).
- 613 30. Paxson, A. T., Yagüe, J. L., Gleason, K. K. & Varanasi, K. K. Stable Dropwise
614 Condensation for Enhancing Heat Transfer via the Initiated Chemical Vapor Deposition
615 (iCVD) of Grafted Polymer Films. *Adv. Mater.* **26**, 418-423 (2014).
- 616 31. Ma, J., Cha, H., Kim, M. K., Cahill, D. G. & Miljkovic, N. Condensation Induced
617 Delamination of Nanoscale Hydrophobic Films. *Adv. Funct. Mater.* **29**, 1905222 (2019).
- 618 32. Yan, X. et al. Atmosphere-Mediated Superhydrophobicity of Rationally Designed
619 Micro/Nanostructured Surfaces. *ACS Nano.* **13**, 4160-4173 (2019).
- 620 33. Cha, H. et al. Nanoscale-Agglomerate-Mediated Heterogeneous Nucleation. *Nano Lett.* **17**,
621 7544-7551 (2017).
- 622 34. Yan, X. et al. Atmosphere - Mediated Scalable and Durable Biphilicity on Rationally
623 Designed Structured Surfaces. *Adv. Mater. Interfaces*, 2000475 (2020).
- 624 35. Miljkovic, N., Enright, R. & Wang, E. N. Effect of Droplet Morphology on Growth
625 Dynamics and Heat Transfer during Condensation on Superhydrophobic Nanostructured
626 Surfaces. *ACS Nano.* **6**, 1776-1785 (2012).
- 627 36. Xiao, R., Miljkovic, N., Enright, R. & Wang, E. N. Immersion Condensation on Oil-
628 Infused Heterogeneous Surfaces for Enhanced Heat Transfer. *Sci. Rep.-Uk.* **3**, (2013).
- 629 37. Prakash, M., Quere, D. & Bush, J. W. M. Surface Tension Transport of Prey by Feeding
630 Shorebirds: The Capillary Ratchet. *Science.* **320**, 931-934 (2008).
- 631 38. Reis, P. M., Jung, S., Aristoff, J. M. & Stocker, R. How Cats Lap: Water Uptake by *Felis*
632 *catus*. *Science.* **330**, 1231-1234 (2010).
- 633 39. Powell, C. A., Savage & Guthrie, J. T. Computational simulation of the printing of
634 Newtonian liquid from a trapezoidal cavity. *Int. J. Numer. Method. H.* **12**, 338-355 (2002).
- 635 40. Chen, H., Tang, T. & Amirfazli, A. Effects of surface wettability on fast liquid transfer.
636 *Phys. Fluids.* **27**, 112102 (2015).
- 637 41. Vogel, M. J. & Steen, P. H. Capillarity-based switchable adhesion. *Proc. Natl. Acad. Sci.*
638 *U.S.A.* **107**, 3377-3381 (2010).

- 639 42. Qian, B., Loureiro, M., Gagnon, D. A., Tripathi, A. & Breuer, K. S. Micron-scale droplet
640 deposition on a hydrophobic surface using a retreating syringe. *Phys. Rev. Lett.* **102**,
641 164502 (2009).
- 642 43. Yan, X. et al. Droplet Jumping: Effects of Droplet Size, Surface Structure, Pinning, and
643 Liquid Properties. *ACS Nano*. **13**, 1309-1323 (2019).
- 644 44. Yan, X. et al. "Swimming Jellyfish": Visualizing Jet-Like Internal Flow in Coalescing
645 Droplets. *J. Heat Transfer*. **141**, 100901 (2019).
- 646 45. Vo, Q. & Tran, T. Critical Conditions for Jumping Droplets. *Phys. Rev. Lett.* **123**, 24502
647 (2019).
- 648 46. Vo, Q., Su, H. & Tran, T. Universal Transient Dynamics of Electrowetting Droplets. *Sci.*
649 *Rep.-Uk.* **8**, (2018).
- 650 47. Carlson, A., Bellani, G. & Amberg, G. Contact line dissipation in short-time dynamic
651 wetting. *EPL (Europhysics Letters)*. **97**, 44004 (2012).
- 652 48. Wen, R., Xu, S., Lee, Y. & Yang, R. Capillary-driven liquid film boiling heat transfer on
653 hybrid mesh wicking structures. *Nano Energy*. **51**, 373-382 (2018).
- 654 49. Weibel, J. A., Kim, S. S., Fisher, T. S. & Garimella, S. V. Carbon Nanotube Coatings for
655 Enhanced Capillary-Fed Boiling from Porous Microstructures. *Nanoscale Microsc. Therm.*
656 **16**, 1-17 (2012).
- 657 50. Sharma, C. S., Lam, C. W. E., Milionis, A., Eghlidi, H. & Poulikakos, D. Self-Sustained
658 Cascading Coalescence in Surface Condensation. *ACS Appl. Mater. Inter.* **11**, 27435-
659 27442 (2019).
- 660 51. Kim, S. & Kim, K. J. Dropwise condensation modeling suitable for superhydrophobic
661 surfaces. *J. Heat Transfer*. **133**, 81502 (2011).
- 662 52. Miljkovic, N., Enright, R. & Wang, E. N. Modeling and optimization of superhydrophobic
663 condensation. *Journal of Heat Transfer*. **11**, 111004 (2013).
- 664 53. Shang, Y., Hou, Y., Yu, M. & Yao, S. Modeling and optimization of condensation heat
665 transfer at biphilic interface. *Int. J. Heat Mass Tran.* **122**, 117-127 (2018).
- 666 54. Rose, J. W. & Glicksman, L. R. Dropwise condensation—the distribution of drop sizes.
667 *Int. J. Heat Mass Tran.* **2**, 411-425 (1973).
- 668 55. Fisher, J. C., Hollomon, J. H. & Turnbull, D. Nucleation. *J. Appl. Phys.* **19**, 775 (1948).
- 669 56. Birbarah, P., Chavan, S. & Miljkovic, N. Numerical Simulation of Jumping Droplet
670 Condensation. *Langmuir*. **35**, 10309-10321 (2019).
- 671 57. Xu, W., Lan, Z., Liu, Q., Du, B. & Ma, X. Droplet size distributions in dropwise
672 condensation heat transfer: Consideration of droplet overlapping and multiple re-
673 nucleation. *Int. J. Heat Mass Tran.* **127**, 44-54 (2018).
- 674 58. Brulin, S., Tropea, C. & Roisman, I. V. Pinch-off of a viscous liquid bridge stretched with
675 high Reynolds numbers. *Colloids Surf., A* **587**, 124271 (2020).
- 676 59. QIAN, B. & BREUER, K. S. The motion, stability and breakup of a stretching liquid bridge
677 with a receding contact line. *J. Fluid Mech.* **666**, 554-572 (2011).
- 678 60. Raj, R., Enright, R., Zhu, Y., Adera, S. & Wang, E. N. Unified Model for Contact Angle
679 Hysteresis on Heterogeneous and Superhydrophobic Surfaces. *Langmuir*. **28**, 15777-15788
680 (2012).
- 681 61. Forsberg, P. S. H., Priest, C., Brinkmann, M., Sedev, R. & Ralston, J. Contact Line Pinning
682 on Microstructured Surfaces for Liquids in the Wenzel State. *Langmuir*. **26**, 860-865
683 (2010).
- 684 62. Kissa, E. Wetting and Wicking. *Text. Res. J.* **66**, 660-668 (1996).

63. Li, J., Fu, W., Zhang, B., Zhu, G. & Miljkovic, N. Ultrascalable Three-Tier Hierarchical Nanoengineered Surfaces for Optimized Boiling. *ACS Nano*. **13**, 14080-14093 (2019).
64. Wexler, J. S., Jacobi, I. & Stone, H. A. Shear-driven failure of liquid-infused surfaces. *Phys. Rev. Lett.* **114**, 168301 (2015).
65. Boreyko, J. B., Zhao, Y. & Chen, C. Planar jumping-drop thermal diodes. *Appl. Phys. Lett.* **99**, 234105 (2011).
66. Boreyko, J. B. & Chen, C. Vapor chambers with jumping-drop liquid return from superhydrophobic condensers. *Int. J. Heat Mass Tran.* **61**, 409-418 (2013).
67. Oh, J. et al. Jumping-droplet electronics hot-spot cooling. *Appl. Phys. Lett.* **110**, 123107 (2017).
68. Liu, T. et al. Tunable, passive thermal regulation through liquid to vapor phase change. *Appl. Phys. Lett.* **115**, 254102 (2019).
69. Enright, R. et al. How Coalescing Droplets Jump. *ACS Nano*. **8**, 10352-10362 (2014).
70. Huang, J., Zhang, J. & Wang, L. Review of vapor condensation heat and mass transfer in the presence of non-condensable gas. *Appl. Therm. Eng.* **89**, 469-484 (2015).
71. Peters, T. B. et al. Design of an Integrated Loop Heat Pipe Air-Cooled Heat Exchanger for High Performance Electronics. *IEEE Trans. Compon., Packag., Manuf. Technol.* **2**, 1637-1648 (2012).
72. Wang, L. & McCarthy, T. J. Covalently Attached Liquids: Instant Omniphobic Surfaces with Unprecedented Repellency. *Angew. Chem., Int. Ed.* **55**, 244-248 (2016).
73. Enright, R. M. N. D. Condensation on Superhydrophobic Copper Oxide Nanostructures. *J. of Heat Transfer*. **9**, 419-425 (2013).

Acknowledgements

N. M. gratefully acknowledges fruitful discussion with Professor Jonathan Boreyko of the Virginia Polytechnic Institute and State University during a visit in April 2019. Dr. Boreyko is independently pursuing liquid bridging studies for enhanced thermal management. The authors gratefully acknowledge funding support from the National Science Foundation under Award No. 1554249. Scanning Electron Microscopy was carried out in the Materials Research Laboratory Central Facilities, University of Illinois. N.M. gratefully acknowledges funding support from the International Institute for Carbon Neutral Energy Research (WPI-I2CNER), sponsored by the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

Author contributions

X.Y. and N.M. conceived the initial idea for this research. N.M guided the work. X.Y., F.C., Q.W., Y.Q., and K.R. fabricated and characterized the experimental samples. H.Z. and J.L. fabricated and characterized the SOCAL surfaces. F.C. and X.Y. carried out the liquid bridge experiments. X.Y., F.C., C.Z., J.F., and T.G. analyzed the data and performed the modeling. J.F. guided the energy analysis. X.Y. and M.H. carried out the condensation experiments and performed theoretical analysis. C.Z. and X.Y. conducted numerical simulations. X.Y., F.C., and C.Z. contributed equally. The authors appreciate the help from Qiyuan Wu with surface fabrication. All the authors were responsible for writing the paper and have given approval to the final version of the manuscript.

Competing interests

The authors declare that they have no competing financial interests

733

734

735 **Materials & Correspondence**

736 Correspondence and requests for materials should be addressed to N.M.

737

738 **Supplementary information**

739 Supplementary information for this paper is available at ××××××

740

741

Figures

Figure 1

(A) Optical microscopy image showing shaded coalescence during hierarchical condensation. Small droplets growing underneath a large Cassie-Baxter droplet are sucked into the large droplet upon coalescence due to Laplace pressure contrast. (B) Schematic of near field condensation driven by wettability contrast between the condensing surface (bottom) and adsorbing surface (top). The surfaces are separated by a gap to allow condensate droplets to grow to their maximum size $\propto$ determined by the bottom surface contact angle θ and gap spacing H .

Figure 2

Wettability-contrast-dependent droplet states between parallel surfaces. (A) Bridging state showing the formation of a stable liquid bridge between surfaces having low wettability contrast ($\theta_t / \theta_b = 71 \pm 1^\circ / 93 \pm 3^\circ$). (B) Non-bridging state showing liquid bridge breakup between parallel surfaces having large wettability contrast ($\theta_t / \theta_b = 38 \pm 1^\circ / 93 \pm 3^\circ$). Spreading, receding, and pinch-off are identified with red arrows. The gap between the parallel surfaces is $h = 850 \pm 70 \mu\text{m}$. Gravity points downwards towards the bottom surface. See video S1.

Figure 3

Wetting dynamics of bridging and non-bridging droplets. (A) Apparent contact angle on the top (θ_t) and bottom (θ_b) surface as a function of dimensionless time (t/τ). (B) Dimensionless spreading radius on the top surface (R_t^*) and receding radius on the bottom surface (R_b^*) as a function of dimensionless time (t/τ). Wettability contrast of the bridging case: $\theta_t / \theta_b = 33 \pm 1^\circ / 72 \pm 1^\circ$. Wettability contrast of the non-bridging case: $\theta_t / \theta_b = 33 \pm 1^\circ / 93 \pm 3^\circ$. The inertial stages prior to droplet base recession are shaded. The pinch-off moment for the non-bridging cases is identified with arrows. (C) Experimental pinch-off time (Δt_p) as a function of the semi-analytical pinch-off time $\Delta t_t + \Delta t_r$ defined as the sum of the inertial time Δt_t and receding time Δt_r .

Figure 4

Droplet bridging regime map as a function of top surface apparent advancing contact angle $\theta_{t,a}$ and bottom surface apparent receding contact angle $\theta_{b,r}$. The light green region represents the predicted bridging bound accounting for the variation of friction coefficient λ (0.03-0.105) and water retention ratio ε (0-7%).

Figure 5

Wettability-contrast-induced droplet shedding during near field condensation on hydrophobic and hydrophilic surfaces. Time-lapse optical microscopy images of condensation on a hydrophobic ($\theta / \theta = 106 \pm 1^\circ / 97 \pm 1^\circ$) Cu surface (A) without and (B) with a superhydrophilic CuO mesh ($\theta \approx 0^\circ$) placed on top. Time-lapse images of condensation on a hydrophilic Cu surface ($\theta / \theta = 87 \pm 2^\circ / 43 \pm 4^\circ$) (C) without and (D, E) with a superhydrophilic CuO mesh placed on top. The nucleation-growth-coalescence-shedding-renucleation cycle is shown with a higher magnification (50X) in (E). Droplet shedding with

multicoalescence is identified in dotted enclosed regions. Insets in (B) and (E) show the zoomed-in view of re-nucleation after droplet transfer from the hydrophobic and hydrophilic surfaces, respectively. See Video S2. Condensation experiments performed with air temperature $T = 25 \pm 1^\circ\text{C}$, relative humidity $\Phi = 40 \pm 5\%$, and surface temperature $T_s = 1^\circ\text{C}$. See Methods.

Figure 6

Characterization of near field condensation. (A) Near field condensation droplet radius r as a function of time t on the hydrophobic Cu surface ($\theta / \theta^* = 106 \pm 1^\circ / 97 \pm 1^\circ$) for differing surface gaps g . The $g = \infty$ represents the case of dropwise condensation (no mesh). (B) Near field condensation droplet number density n as a function of droplet radius r on the hydrophobic Cu surface with differing surface gaps g . Bars are stacked to facilitate comparison. See Methods for condensation experiment details. (C) Theoretically (solid lines) and numerically simulated (data points) overall heat fluxes q as a function of surface gap g for near field condensing substrates having varying apparent advancing contact angles θ . The star symbols represent classical dropwise condensation. Inset: schematic showing near field condensation. For theory and simulation parameters, see Sections S8 and S9 of the Supplementary Information. (D) Time-lapse images of the numerical simulation results for near field condensation. The top surface (black) is partially removed to facilitate visualization of condensation on the bottom (white) surface. Droplet shedding is shaded in red. See Video S3.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [NFCSI.pdf](#)