Self-Sustained Cascading Coalescence in Surface Condensation

Chander Shekhar Sharma,‡ Cheuk Wing Edmond Lam, Athanasios Milionis, Hadi Eghlidi, and Dimos Poulikakos*†

Laboratory of Thermodynamics in Emerging Technologies, Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland

ABSTRACT: Sustained dropwise condensation of water requires rapid shedding of condensed droplets from the surface. Here, we elucidate a microfluidic mechanism that spontaneously sweeps condensed microscale droplets without the need for the traditional droplet removal pathways such as use of superhydrophobicity for droplet rolling and jumping and utilization of wettability gradients for directional droplet transport among others. The mechanism involves self-generated, directional, cascading coalescence sequences of condensed microscale droplets along standard hydrophobic microgrooves. Each sequence appears like a spontaneous zipping process, can sweep droplets along the microgroove at speeds of up to \( \sim 1 \text{ m/s} \), and can extend for lengths more than 100 times the microgroove width. We investigate this phenomenon through high-speed in situ microscale condensation observations and demonstrate that it is enabled by rapid oscillations of a condensate meniscus formed locally in a filled microgroove and pinned on its edges. Such oscillations are in turn spontaneously initiated by coalescence of an individual droplet growing on the ridge with the microgroove meniscus. We quantify the coalescence cascades by characterizing the size distribution of the swept droplets and propose a simple analytical model to explain the results. We also demonstrate that, as condensation proceeds on the hydrophobic microgrooved surface, the coalescence cascades recur spontaneously through repetitive dewetting of the microgrooves. Lastly, we identify surface design rules for consistent realization of the cascades. The hydrophobic microgrooved textures required for the activation of this mechanism can be realized through conventional, scalable surface fabrication methods on a broad range of materials (we demonstrate with aluminum and silicon), thus promising direct application in a host of phase-change processes.

KEYWORDS: condensation, hydrophobic, coalescence, cascade, microgrooves

1. INTRODUCTION

Electricity,¹ potable drinking water,² and information technology³ count as among the critical demands of modern human society. The diverse industrial activities that endeavor to meet these needs, thermal power generation,⁴ water desalination,⁵ water harvesting,⁶,⁷ and thermal management of electronic devices⁸ among others, involve heterogeneous condensation of water as a critical physical process. It is well known that hydrophobic and superhydrophobic surfaces cause water to condense as distinct droplets that are periodically shed to hydrophobic and superhydrophobic surfaces⁹–¹⁸ or by causing directional droplet movement with capillarity gradients.¹⁹,²⁰

In this work, we investigate a mechanism that spontaneously sweeps condensate droplets from hydrophobic surfaces without the need for the traditional droplet removal pathways mentioned above. It involves a self-generated cascading sequence of droplet coalescences along standard hydrophobic microgrooves, which can proceed at a speed of up to \( \sim 1 \text{ m/s} \) and can sweep droplets over large ridge areas between microgrooves. We explain the underlying physics for these coalescence cascades through careful high-speed in situ observations of condensation at a microscale and identify design rules for their consistent realization. Such droplet sweeps present an alternative approach for gravity-independent refreshment of the condensing surface while requiring only facile and scalable surface fabrication on a wide range of materials, including metals, thus avoiding a more elaborate

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2. RESULTS AND DISCUSSION

2.1. Hydrophobic Microgrooved Surface. We investigate the condensation of water on hydrophobic microgrooved surfaces as shown in Figure 1. We fabricate such microgrooves primarily on a metal (aluminum) due to the obvious importance of metals in energy applications. Figure 1A shows the morphology of such a microgroove as obtained through conventional milling in aluminum followed by adding a hydrophobic coating. Similar microgrooves can also be obtained from silicon through standard etching methods (see the Experimental Section and Section S1). Figure 1B shows the hydrophobicity of the surface at a microscale as observed through in situ condensation observation using ESEM.

2.2. Coalescence Cascade. The mechanism manifests itself as a self-propagating, cascading sequence of droplet coalescence events advancing in a zipping manner during condensation of water on a standard hydrophobic microgrooved surface, as shown in Figure 2A. Condensation on such microgrooved surfaces proceeds through spatially uniform nucleation and growth of condensate droplets within and outside the microgrooves. The nucleation and growth of droplets inside and outside the microgrooves is likely to be similar due to similarity in curvature, chemistry, and roughness of surfaces inside and outside the microgrooves. Eventually, when a microgroove is filled with the condensate at any location, a droplet growing outside the microgroove on the ridge may coalesce with the condensate in the microgroove (Figure 2, panels i and ii). Unexpectedly, however, instead of such coalescence causing the removal of only this individual droplet from the ridge, we observe that such an individual coalescence event can trigger a rapid sequence of similar coalescence events along the length of the microgroove.

High-speed imaging reveals a cascading coalescence sequence that proceeds at speeds of up to 1 m/s while sweeping condensate droplets from a large area along the ridge in a zipping-like motion (see panels ii–ix in Figure 2A). As indicated by the gravity vector in the first panel, this effect can also proceed against gravity. The sequence eventually culminates with the microgroove filled with the condensed collected from the coalescing droplets and any excess condensate located in multiple bulges along the filled length of the microgroove (panels ix and x in Figure 2A). The small bulges eventually collapse into the microgroove (panel xi in Figure 2A) collecting the excess condensate in a single large bulge (not visible in the figure) at the completion of the coalescence sequence.

The propagation of this zipping-like coalescence sequence is achieved by the oscillations of the condensate meniscus inside the microgroove, as elucidated through high-speed snapshots in Figure 2B and corresponding schematics shown in Figure 2C. We observe that these oscillations are always initiated from
Figure 3. (A) Beeswarm distribution plots of swept droplet diameters ($D$, defined in inset) for microgrooves of widths of ~100 μm and depths of ~171 to 422 μm machined in aluminum and coated with PTFE. The grey zone demarcates the limit estimate $D_{\text{crit}}$. Each beeswarm plot is based on ~300 measurements and is shown in different colors for clarity. In the beeswarm distribution, the horizontal spread at any ordinate $D$ indicates the relative proportion of droplets of diameter $D$ swept by the cascading coalescence sequence. The yellow zone below the $D_{\text{crit}}$ limit represents the range of droplet sizes swept by the coalescence sequence progressing in a partially filled microgroove. The orange zone above $D_{\text{crit}}$ indicates droplet sizes swept by the coalescence sequence proceeding in a completely filled microgroove or in the presence of a large bulge. (B) Schematic illustrating that droplets with $D < D_{\text{crit}}$ (droplets 1, 2, and 3 in green) are readily absorbed by the advancing meniscus [panels (i) and (ii)] due to a favorable Laplace pressure difference with the microgroove meniscus ($P_1, P_2, P_3 > P_0$). A droplet with $D > D_{\text{crit}}$ (droplet 4 in red with $P_4 < P_0$) forms a bulge. The bulge causes the sweeping of subsequent droplets with $D > D_{\text{crit}}$ [e.g., droplet 5 in panels (iii) and (iv)]. $P_0$ represents Laplace pressures inside the bulge. The legend at the bottom defines the color scheme for droplets.

a completely filled part of microgroove wherein a meniscus pinned at the edges of the microgroove exists. When a droplet growing in the ridge area and near the microgroove edge, for instance droplet 1 in Figure 2B, coalesces with the pinned meniscus, this otherwise stable meniscus gets perturbed. The droplet has higher Laplace pressure due to the condensate within the microgroove due to the much higher curvature of the droplet. This causes the droplet to drain into the condensate within the microgroove, and the associated fluid inertia drives the meniscus beyond its equilibrium position. The resulting competition between fluid inertia and surface tension results in a perturbation with an amplitude of the order of ~10 μm (defined by $h$ in Figure 2, panel iii; see Section S3 for details) that rapidly travels as a capillary ripple across the width of the microgroove. The phase velocity $u$ of the capillary-gravity waves created at any interface is given by $u = \sqrt{\sigma k / \rho} + g/k$ where $\sigma$ and $\rho$ are the surface tension and density of water, respectively, and $k = 2\pi / \lambda$ is the wavenumber with $\lambda$ as the wavelength of the capillary ripple. However, surface tension dominates at small length scales relevant here, and thus the meniscus perturbation is a pure capillary ripple traveling across the pinned meniscus at a phase velocity of $u = \sqrt{2 \sigma \rho / \lambda \rho}$. While the coalescence continues, the capillary ripple reflects from the pinned edge of the meniscus and triggers transverse oscillations similar to those of a sessile droplet with a pinned contact line. Due to the small length scales involved, these meniscus oscillations proceed with a short characteristic time period $\tau_i = \sqrt{\rho \lambda^3 / 2 \sigma \rho} \approx 10 \mu s$ thus necessitating high-speed imaging to capture them (Section S4). This time period reflects the fact that these meniscus oscillations are governed by a competition between fluid inertial and capillary forces, similar to the time scale of liquid droplet coalescence. These meniscus oscillations persist due to the relatively long relaxation time inherent in sessile droplet coalescence and catch further droplets along the edge of the microgroove, as shown in Figure 2B,C, even before the original droplet coalescence event is completed. This is evident from the initiation of coalescence of droplets 2 and 3, much before the coalescence of droplet 1 is completed. This process repeats, and the coalescence sequence propagates along the microgroove. We observed that the overall speed of this propagation depends upon the amount of condensate present in the microgroove immediately prior to the initiation of the coalescence sequence. A microgroove that is fully filled with condensate causes the sequence to proceed at speeds as high as 1 m/s. The propagation speed is lower if the microgroove is only partially filled with the condensate because, in this case, the microgroove needs to be progressively filled by advancing the meniscus within the microgroove in order to catch the downstream droplets on the ridge. (See Section S5 for further details.)

Irrespective of the state of the microgroove before the initiation of the cascading coalescence sequence, once initiated, the sequence propagates as long as droplets are available within and outside the microgroove to feed the meniscus advancing within the microgroove. This results in coalescence sequences that can propagate for lengths more than 100 times the microgroove width. Any coalescence event between the advancing meniscus and an individual droplet induces oscillations that are essentially local. These oscillations need to de-pin the meniscus within the microgroove and advance it sufficiently to catch the next downstream droplet. In the absence of such droplets, the oscillations are exponentially attenuated by the bulk viscous dissipation within the liquid with a characteristic time of $\tau_s = \eta / \rho W^2$, which is of the order of ~0.01 μs ≪ $\tau_c$ (Section S6). Here, $\eta$ is the fluid viscosity, and $W$ is the microgroove width. However, the resulting termination of the coalescence sequence is only temporary, and the phenomenon self-initiates again when droplets become available through continuous condensation.

2.3. Modeling and Swept-Droplet Distribution. The coalescence sequence sweeps droplets of a range of sizes from the ridge area as it propagates along the microgroove. We investigate this aspect for varying microgroove geometries by analyzing the size distribution of droplets swept during the coalescence cascades. Figure 3A shows such distributions for four microgrooves with the same widths but increasing depths from 171 to 422 μm. The swept-droplet size is defined by droplet diameter $D$ as shown in inset of Figure 3A. The
Further, this upper bound increases as the depth of the size distribution for the microgroove geometries tested. As depicted in Figure 3A, this value bounds most of the droplet coalescence with more droplets. Eventually, the resulting large drops [encircled in panel (iii)] are shed under gravity as indicated by yellow arrows. Drop 1 also moves under gravity initially but is eventually absorbed into the microgroove when it gets connected to a large drop pinned at the edge of the sample via a filled microgroove (panels vii and viii). Scale bar: 2 mm. Substrate: aluminum. Coating: PTFE. Images are captured at 1000 fps.

The microgroove geometry, however, affects the largest droplets that can be swept by the coalescence cascade as evident from the distributions extending to larger D values for larger depths. A droplet is swept from the ridge by the advancing meniscus within the microgroove when the Laplace pressure of the meniscus inside the microgroove, $P_M$, is higher than that for the advancing condensate meniscus inside the microgroove, $P_{M'}$. This condition allows us to estimate an upper bound $D_{cut}$ for $D$ as $D < D_{cut} = [(1/2W + 1/4H) \sin (\theta - \pi/2) + 1/4H]^{-1}$ where $H$ is the microgroove depth and $\theta$ is the advancing contact angle of the meniscus inside the microgroove. $D_{cut}(H, W, \theta)$ signifies the maximum droplet size that can be swept by a coalescence cascade occurring in a partially filled hydrophobic microgroove of depth $H$, width $W$, and contact angle $\theta$. This limit is estimated based on the Laplace pressure difference between the advancing meniscus within the microgroove and the droplet on the ridge area at the microgroove edge that is about to coalesce with it (see Section S7 for details). As depicted in Figure 3A, this value bounds most of the droplet size distribution for the microgroove geometries tested. Further, this upper bound increases as the depth of the microgroove increases due to reduction in the relative Laplace pressure of the meniscus inside the microgroove.

Figure 4. Periodicity of the zipping-like cascading coalescence sequence: (A) a single bulge and filled microgroove are formed after the conclusion of the coalescence sequence (panel i). Subsequently, the bulge induces dewetting of the microgroove through condensate withdrawal as indicated by yellow arrows. Scale bar: 200 µm. Images are captured at 1000 fps. (B) Schematic showing the condensate withdrawal process along with an overall pressure difference driving this process. (C) Zoomed-out view of the sample wherein the coalescence cascades are visible as intermittent dark ridge areas. Three bulges formed due to such events are encircled in panel (ii). These bulges grow due to repeated occurrences of the effect and coalescence with more droplets. Eventually, the resulting large drops are shed under gravity as indicated by yellow arrows. Drop 1 also moves under gravity initially but is eventually absorbed into the microgroove when it gets connected to a large drop pinned at the edge of the sample via a filled microgroove (panels vii and viii). Scale bar: 2 mm. Substrate: aluminum. Coating: PTFE. Images are captured at 50 fps.
surface under gravity (Movie S4). Due to the multiple coalescences required to grow these drops to the eventual departure size, these drops are larger than the $D_{\text{crit}}$ limit for droplet sweeping from the ridge area for an individual coalescence cascade. In essence, a body force is required only once every few occurrences of the coalescence sequence—condensate withdrawal cycle to shed the large drops. This periodic cycle can sweep a large surface area over time compared to conventional dropwise condensation on planar hydrophobic samples (see Section S9). Although the zipping-like coalescence cascades cause wetting of the microgroove, it is unlike the wetting of microtextures observed in the case of droplets much larger in size than surface microfeatures and involving a change of the wetting state from Cassie–Baxter to the Wenzel state. 36 In our work, the condensate droplets under consideration are of the same or smaller length scale than that of the microgrooves and always have the same wetting state as that on a planar hydrophobic surface. Additionally, unlike the irreversible change of the large-drop wetting state from Cassie–Baxter to Wenzel, the wetting of microgrooves described here is reversible as the morphology of the microgrooves causes its spontaneous dewetting due to the withdrawal of condensate as elucidated above.

### 2.5. Surface Design.
To inspire rational design of surfaces for achieving this coalescence sequence, we investigated water condensation on hydrophobic microgrooves with aspect ratios (defined as $H/W$) spanning from 0.1 to nearly 4 with the ridge width kept constant. We observed that long coalescence sequences are consistently exhibited when $(H/W)$ is larger than $\sim 1.6$ and $D_{\text{crit}}$ is large enough such that $[D_{\text{crit}} \cos (\theta - \pi/2)]/L > 0.3$ as illustrated in the regime map shown in Figure 5A. Here, $D_{\text{crit}} \cos (\theta - \pi/2)$ represents the droplet base diameter corresponding to $D_{\text{crit}}$ and $L$ is the ridge width. At smaller aspect ratios or smaller $D_{\text{crit}} \cos (\theta - \pi/2)$ values, the microgrooves cannot sustain a progressive meniscus movement necessary for the emergence of the cascading coalescence sequence, and the overall condensation process approaches the case of planar hydrophobic surfaces wherein such rapid droplet sweeping is absent (Section S10). Additionally, we observed that the maximum size of droplets swept by the liquid zipping effect could be controlled by reducing the ridge width between the microgrooves as shown in Figure 5B. As the ridge width is reduced below the $D_{\text{crit}} \cos (\theta - \pi/2)$ limit, the maximum size that the droplets can grow before they are swept reduces, resulting in direct control over the swept droplet distribution.

### 3. CONCLUSIONS
We have elucidated a mechanism for passive removal of condensed droplets involving self-generated coalescence cascades of droplets along hydrophobic microgrooves. Such coalescence cascades offer an unexplored pathway for enhanced dropwise condensation without requiring traditional surface modification routes of passive condensate shedding adopted to date, involving either the fabrication of super-hydrophobic textures, lubricant-impregnated textures, or surfaces with wettability gradients. We have quantified the droplet sweeping size as a function of microgroove geometry and have also proposed simple design rules for consistent realization of these coalescence cascades. Lastly, we have demonstrated control over the droplet removal size through modification of geometrical parameters of the texture. This control over the swept droplet size, and the fact that the periodic coalescence sequence and condensate removal cycle can sweep large areas of surfaces without the need for conventional droplet shedding modes (see Section S10) signals toward a potential to achieve significant enhancement in efficiency of industrial processes involving condensation. Additionally, we have noticed that droplets even as small as $\sim 10 \text{ \mu m}$ can sustain this sequential coalescence sequence (see Movie S5), indicating that it may be possible to realize this mechanism at even smaller scales by further downscaling the overall microgroove dimensions with suitable aspect ratios. This would be advantageous in miniaturized phase-change applications such as micro heat pipes and thermal diodes. Moreover, since this mechanism requires only standard hydrophobic (and not superhydrophobic) microgrooves, it accords significant flexibility regarding the choice of base material and coating for implementation in industrially relevant operating conditions.

Figure 5. (A) Regime map of the liquid zipping-like coalescence sequence with varying aspect ratios ($H/W$) and a fixed ridge width for hydrophobic microgrooves in aluminum. The numbers in green and red indicate aspect ratios for the various microgroove geometries. The green data points correspond to microgrooves for which the coalescence sequence is realized and red data points represent microgrooves where the coalescence sequence is absent. The contour lines correspond to the ratio $[D_{\text{crit}} \cos (\theta - \pi/2)]/L$. Ridge width $L$ is defined in the inset of (B). Based on data points and contours, the microgrooves need to be designed such that $(H/W) > 1.6$ and $[D_{\text{crit}} \cos (\theta - \pi/2)]/L > 0.3$. (B) Control of swept droplet size through reduction in microgroove ridge width $L$. Beeswarm distributions of swept droplet diameters are shown in terms of base diameter $D \cos (\theta - \pi/2)$ for $\sim 100 \text{ \mu m}$ wide and $\sim 200 \text{ \mu m}$ deep microgrooves for ridge widths $L \approx 480$ and $\sim 240 \text{ \mu m}$ (in blue), $\sim 180 \text{ \mu m}$ (in black), and $\sim 90 \text{ \mu m}$ (in orange). $D_{\text{crit}} \cos (\theta - \pi/2)$ for this microgroove geometry lies in the range of $\sim 164$–$216 \text{ \mu m}$ as indicated by the grey zone. For $L > D_{\text{crit}} \cos (\theta - \pi/2)$, swept droplet distributions (in blue) are unaffected by $L$. However as $L$ is reduced, the swept droplet distribution first becomes more uniform (see distribution in black for $L \approx D_{\text{crit}} \cos (\theta - \pi/2)$), and subsequently, the maximum droplet swept size is reduced when $L < D_{\text{crit}} \cos (\theta - \pi/2)$ (see distribution in orange).
4. EXPERIMENTAL SECTION

4.1. Materials and Fabrication. Aluminum samples were cut from 1 mm thick sheets (99.5% aluminum sheets, AW1085, Metal Service Menziken AG, Switzerland), and the microgrooves of various aspect ratios were milled into the sample. Subsequently, the samples were thoroughly cleaned by ultrasonication first in acetone and isopropanol (Sigma-Aldrich) and finally in DI water. The microgrooves were hydrophobized by a coating of either polytetrafluoroethylene (PTFE) or trichloro-1H,1H,2H,2H-perfluorodecylsilane (FDTS) (Sigma-Aldrich). For PTFE coating, the cleaned samples were first activated with oxygen plasma and then spray-coated with PTFE dispersed in dichloromethane (1 wt %) (Sigma-Aldrich). The PTFE dispersion (10 mL) was sprayed over a sample area of approximately 30 cm². The samples were kept immersed in this solution for 120 min and subsequently baked at 120 °C for 45 min.

Similar microgrooves were also fabricated in silicon by etching silicon wafers through a Bosch process using the PlasmaPro Estrellas 100 deep Si etcher (Oxford Instruments). Prior to that, a sacrificial layer was applied by spin-coating and patterned with a UV mask aligner Karl Suss MA6. It consisted of a positive photoresist (Microposit S1813). The unexposed parts were washed away using a solution containing 80 wt % water and 20 wt % Microposit 351 developer. The photoresist residues left under the etching process were subsequently removed by O₂ plasma exposure at 600 W for 16 min (Q235 Microwave Plasma Etcher, Omni Technologies, U.S.A.). The etched samples were made hydrophobic by coating the sample with a thin layer of FDTS. The coating procedure was same as that for the aluminum samples except that the immersion time was chosen as 2 min and the subsequent baking time was set as 10 min.

The PTFE-coated planar aluminum surface showed an advancing contact angle of 119.7° ± 8.2° and a contact angle hysteresis of 31.1° ± 4.8°. The FDTS-coated aluminum surface showed an advancing contact angle of 111.3° ± 8.0° and a contact angle hysteresis of 37.8° ± 8.1°, and the FDTS-coated silicon surface had an advancing contact angle of 119.8° ± 4° and contact angle hysteresis of 43° ± 7.5°. The zipper-like coalescence cascades were observed on all three types of samples, which indicated that the occurrence of this effect is independent of the substrate material as long as the microgroove aspect ratio is correctly selected and all the surfaces of the microgroove are hydrophobic.

4.2. Experimental Setup. Figure 6A shows details of the custom-built experimental setup. It consists of a boiler, a pressure-reducing valve, a Plexiglas test chamber, a chiller, and a vacuum pump. Deionized (DI) water is used as the working fluid. The boiler generates steam at 100 °C and 1 bar by heating the DI water with two 2 kW electrical heaters. The generated steam is supplied to the pressure-reducing valve through an insulated steam line (shown in red). The pressure-reducing valve (bellow valve, Swagelok) reduces the pressure of the steam, which is then supplied to the test chamber. The test chamber is evacuated using the vacuum pump prior to the supply of steam. This fluid circuit is designed to be an open loop such that the condensate is drained from the bottom of the test chamber.

The sample is mounted in a vertical orientation with the microgrooves also aligned vertically, that is, parallel to gravity. During the experiment, the test chamber is maintained at a constant steam saturation pressure of ~50 mbar, the chiller is set to a temperature of 10 °C, and the resulting sample temperature is ~29 °C, indicating a surface subcooling of 4 °C (i.e., ~1.25).

Figure 6B shows a schematic of the optical microscope setup. A white LED is used as the light source that is collimated by an objective. The collimated light is used to illuminate the sample using a beam splitter and through a long working distance objective (Olympus UPlanFl 4X/0.13). The signal from the sample is recorded by a high-speed camera (Photron Fastcam SA 1.1). The frame rate of the camera was adjusted according to the temporal information required from optical observations. For each frame rate setting, the maximum available image size setting was used. For observations of condensation on the entire sample, frame rates up to 250 fps were used. On the other hand, to temporally resolve the high-speed capillary ripples on the meniscus pinned at the microgroove, a frame rate of 250,000 fps was used. All images were captured with a spatial resolution of ~5.5 microns/pixel. Refer to Section S2 for details of the test chamber and experimental protocol.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.9b07673.

Further details on materials, fabrication, and the experimental setup; experimental details on determination of perturbation amplitude; capillary ripple velocity; effect of the initial state of the microgroove on propagation speed of the cascading coalescence sequence; ESEM observations; long coalescence sequences and termination of the coalescence cascade; measurements of swept droplet distributions, analysis of meniscus morphology, and Laplace pressure differences during the coalescence sequence; mechanism of spontaneous condensate withdrawal from the microgroove; increase in the sweep area due to the coalescence sequence—condensate withdrawal cycle; role of the microgroove aspect ratio and ridge width in triggering the cascading coalescence sequence (PDF)

Cascading coalescence sequence along a hydrophobic microgroove that proceeds in a zipping-like motion to sweep droplets from the ridge area. Excess condensate is collected in two bulges that also eventually get absorbed into the microgroove due to the possible location of a larger bulge outside the field of view (AVI)

Initiation of the coalescence cascade captured through high-speed imaging at 250,000 fps. The movie shows...
that coalescence of a droplet outside the microgroove with the meniscus pinned at microgroove edges causes meniscus oscillations that trigger sequential coalescences of more droplets located along the microgroove edges (AVI).

The coalescence sequence ends with the microgroove completely filled with the condensate over the propagation length of the coalescence sequence, and excess condensate is collected in one large bulge. Subsequently, this bulge triggers spontaneous withdrawal of condensate from the microgroove, and condensation restarts in the cleared area of the microgroove (AVI).

Overall view of condensation on a 20 mm × 20 mm microgrooved hydrophobic aluminum sample. Multiple occurrences of the cascading coalescence sequence and the shedding of resulting droplets are visible (AVI).

Coalescence sequence triggered and sustained by small droplets on a microgroove filled with condensate (AVI).

Comparison of propagation speed of the cascading coalescence sequence as a function of the state of the microgroove prior to initiation of condensation (AVI).

## AUTHOR INFORMATION

### Corresponding Authors
E-mail: chander.sharma@iitrpr.ac.in. Phone: +91 1881 230108 (C.S.S.). E-mail: dpoulikakos@ethz.ch. Phone: +41 44 632 27 38. Fax: +41 44 632 11 76 (D.P.).

### ORCID
Chander Shekhar Sharma: 0000-0002-6193-6457
Dimos Poulikakos: 0000-0001-5733-6478

### Present Address
‡Department of Mechanical Engineering, Indian Institute of Technology Ropar, 140001 Rupnagar, India

### Author Contributions
C.S.S. and D.P. conceived the research and provided scientific guidance in all of its aspects. C.S.S. designed the samples and experiments. A.M. developed the coating protocol and fabricated samples. H.E. designed the optical observation setup. C.W.E.L. and C.S.S. performed the experiments. C.S.S. and C.W.E.L. processed and analyzed the experimental results. C.S.S., C.W.E.L., and D.P. discussed the theoretical and data analyses, and C.S.S. wrote the first draft manuscript with subsequent inputs from all other coauthors leading to the final manuscript.

### Notes
The authors declare no competing financial interest.

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