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ABSTRACT

Water collection via fiber-based coalescers shows promise in mitigating increasing water scarcity, and most studies usually focus on the water collection by accumulating water through successive coalescences of fog in the absence of condensation. Here, we report on non-uniform condensate morphologies observed during air-vapor mixture condensation on a cantilevered microfiber. Due to the competition between thermal conduction resistance within the fiber and condensation heat transfer resistance on the fiber surface, the vapor diffusive flux along the fiber varies accordingly, engendering three representative condensate morphologies. We systematically examine the effects of fiber length, diameter, and material (constantan, 316L steel, and alumel) on these condensate morphologies. Scaling analyses are also provided to reveal the underlying physics. Our experimental investigations and theoretical analyses reported in this work shed more light on air-vapor mixture condensation mechanisms that could pave the way to future condensation-associated applications.

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I. INTRODUCTION

Multiple natural systems have evolved thread-based structures capable of harvesting and transporting water directionally from fog or humid air, such as spider silks,¹ cactus spines,² and pine needles.^{3,4} Such water harvesting functionality is generally endowed by the gradients of surface-free energy^{5,6} and Laplace pressure.⁷ Furthermore, the groove structure^{3,8} parallel to the longitudinal axis is believed to serve as a guided slideway for the droplets. Fibrous water harvesters inspired by nature^{9–15} have been drawing scientists' attention due to their potential applications in alleviating global water shortages. In addition to being widely found in nature, fiber-based coalescers also underpin a variety of human activities ranging from food production, water purification to petroleum industry, and gas plants.^{16–21} Fine droplets accumulated on the fiber will merge into larger ones after successive coalescences, which are then typically removed either through external forces, such as gravitational force, hydrodynamic shear²⁰ or vibration-induced standing waves,²² or by self-propelling powered by surface energy released upon drop coalescence.^{23,24}

Numerous investigations have been carried out regarding fibrous coalescers, mainly aiming at unraveling and utilizing the intriguing phenomenon of directional liquid transport. However,

such water collection process in which phase change plays no role at all is fundamentally different from dew harvesting whose overall performance is profoundly affected by dew nucleation and growth. When subjected to cold and humid environments, condensation inevitably occurs on the surfaces.^{4,25,26} However, the underlying physics associated with air-vapor mixture condensation on a microfiber remain inadequately understood until this day. Moreover, conventional meshes capable of harvesting fog are mostly composed of individual fibers.^{27–29} From these perspectives, it will be of significant interest to investigate the characteristics of condensation on an individual microfiber as a system module.

In this work, we report our findings observed during air-vapor mixture condensation on a cantilevered microfiber with a constant cross section. The fiber is cooled below the dew point while remaining at a temperature higher than the heterogeneous ice nucleation temperature. The condensation on the hydrophilic microfiber starts from isolated liquid nuclei which swiftly grow large enough to merge with nearby counterparts. After a period of growth and coalescence, unlike the conventional breath figures occurring on flat substrates,^{30–32} the condensate exhibits three distinct distribution morphologies along the axis of the fiber. In specific, the heights of condensed droplets may increase, remain nearly unchanged, or

decrease from the fiber base toward its tip. The occurrence of such condensate morphologies can be explained based on the competition between two different heat transfer resistances: thermal conduction resistance within the fiber (R_{cond}) and condensation heat transfer resistance on the fiber surface (R_{conv}). Additionally, we provide scaling analyses to shed light upon the relation between condensate morphology and fiber thermophysical properties.

II. METHODOLOGY

A. Experimental details and observations

A visualization based experimental investigation is carried out to directly observe the condensate profile on a cantilevered microfiber. Figure 1 shows a schematic diagram of the experimental setup composed of a cooling bath, a customized cryostage with an acrylic screen, a data acquisition and recording system, and an imaging system. The customized cryostage consists of a Peltier element (Thermoelectric coolers, Ferrotec, 9500/127/060B) and an aluminum block embedded with a U shaped channel for circulating coolant to regulate the substrate temperature. The cooling bath (Julabo, FL1701) serves as heat sink to remove the heat generated by the Peltier element. The acrylic screen surrounding the cryostage is used to eliminate possible connective flow above the fiber during the condensation process. A humidity and temperature sensor (Omega, HX93BDC-RP1) is used to detect local temperature and relative humidity (RH) of ambient air with accuracies of $\pm 0.6^\circ\text{C}$ from 0 to 50°C and $\pm 2.5\%$ from 20% to 80% RH, respectively. The substrate temperature is measured by a T-type thermocouple (Omega) with an accuracy of $\pm 0.1^\circ\text{C}$. The imaging system includes a high quantum-efficiency camera (PCO, Edge 4.2) and a microscope (Nikon, 883240) with $10\times/20\times$ objective lens. The thermally conductive microfiber after treatment is cooled by

attaching it normally to the surface of the Pieter element. The enlarged insert sketches the condensate profile typically observed on short fibers with relatively high thermal conductivity ranging from $16.3\text{ W}/(\text{m K})$ to $28.5\text{ W}/(\text{m K})$.

We conduct thorough experiments to examine the effects of microfiber length L , sectional area A , and thermal conductivity k , and three types of fiber materials (constantan, 316L steel, and alumel) with various lengths were used. The thermal conductivities of constantan and alumel are $21.9\text{ W}/(\text{m K})$ and $28.5\text{ W}/(\text{m K})$, respectively.³³ The microfibers were ultrasonically cleaned (Branson 8510) in ethanol for 5 min and rinsed with de-ionized (DI) water subsequently and dried in N_2 gas flow finally. After such treatment, we used open source software ImageJ with plugin low-bond axisymmetric drop shaped analysis³⁴ to obtain the water contact angles on constantan, 316L steel, and alumel fibers as $72^\circ \pm 4^\circ$, $77^\circ \pm 4^\circ$, and $75^\circ \pm 4^\circ$, respectively. Using 316L stainless steel fibers with three different lengths (1.0 mm, 2.9 mm, and 5.7 mm) but the same diameter ($127\text{ }\mu\text{m}$) for illustration, Fig. 2 shows three characteristic condensate morphologies occurring at three different fiber lengths with the inserted shapes denoting the overall trend in the height changes of the condensed droplets. Of note, this work only focuses on the condensate profile during the self-similar stage³² and its underlying mechanism, but not the thermodynamic aspects of dew nucleation and growth, as well as the kinetic aspects of droplet coalescence. The experimental conditions are the fiber base temperature is -4.4°C , the ambient air temperature is 22.5°C , and the relative humidity is $\text{RH} = 55.3\%$. The effective length of microfiber in Fig. 2(a) is 5.7 mm which is beyond the boundary of the picture. When cooling starts from the fiber base, the temperature distribution along the microfiber can be evaluated by using one-dimensional fin theory³⁵ given a small Biot number. Here, $Bi = hd/4k$ for a cylindrical fiber, where

FIG. 1. Schematic illustration of the experimental setup used for the direct observation of condensate morphology on a cantilevered microfiber. The inset bounded by the green dotted line depicts a magnified plot of the condensate distribution along a short fiber showing an increasing amount of condensate toward the fiber tip.

FIG. 2. Three observed scenarios for condensate morphologies on 316L stainless steel fibers with the same diameter ($127\ \mu\text{m}$) but three different lengths: (a) 5.7 mm—the heights of condensed droplets decrease from the fiber base to its tip; (b) 2.9 mm—the heights of condensed droplets remain nearly uniform along the fiber; and (c) 1.0 mm—the heights of condensed droplets increase from the fiber base to its tip. The experimental conditions are $T_{\text{base}} = -4.4 \pm 0.1\ ^\circ\text{C}$, $T_{\text{air}} = 22.5 \pm 0.6\ ^\circ\text{C}$, and $RH = 55.3\% \pm 2.5\%$.

h is the convective heat transfer coefficient, while d and k denote the diameter and thermal conductivity of the fiber, respectively.³⁶ The condensation heat transfer coefficient for air–vapor mixture is of order about $10\text{--}100\ \text{W}/(\text{m}^2\ \text{K})$,^{37,38} which gives a value of Bi typically smaller than 2×10^{-4} . Once the fiber surface temperature is progressively cooled below a certain value, i.e., the dew point, and the heterogeneous nucleation energy barrier is surmounted simultaneously, water vapor nucleation initiates followed by dew growth and coalescence processes. Hydrophilic fibers were utilized in this work in order to reduce the condensation nucleation energy barrier according to classical nucleation theory.^{39,40} The dew point can be obtained from air temperature and relative humidity, with an uncertainty of $\pm 0.4\ ^\circ\text{C}$, by using the following equations based on the Magnus–Tetens approximation⁴¹ for the saturation vapor pressure of water in air,

$$T_{\text{dew}} = \frac{b \cdot \alpha(T_{\text{air}}, RH)}{a - \alpha(T_{\text{air}}, RH)}, \quad (1)$$

where $\alpha(T_{\text{air}}, RH) = (a \cdot T_{\text{air}})/(b + T_{\text{air}}) + \ln(RH)$, where T_{air} is ambient temperature in $^\circ\text{C}$. The constants are $a = 17.27$ and $b = 237.7\ ^\circ\text{C}$.⁴² The condensate profile with a decreasing droplet height distribution shown in Fig. 2(a) is anticipated, because the driving force for condensation, represented by the temperature difference between the dew point and the substrate temperature, gradually reduces along the fiber. However, the formation of condensate morphologies with nearly uniform and increasing droplet height distributions shown in Figs. 2(b) and 2(c), respectively, is quite intriguing. Therefore, we will further explore their underlying mechanisms in Sec. II B.

B. Our proposed mechanisms and numerical simulations of mass diffusion flux

Recently, millimetric convex structures^{43,44} have demonstrated superior performance in promoting condensation. Also, geometrical (edges, corners grooves, and scratches) or thermal discontinuities (temperature) were earlier reported to impose significant influences upon vapor mass diffusion around droplets.⁴⁵ Droplets near the outer edges or corners could attract more water vapor than those near the inner edges, leading to a much faster growth speed. Moreover, the effects of vapor conditions (pure vapor vs an air–vapor mixture) on dropwise condensation on millimetric surface structures were investigated.³⁸ Specifically, for our experimental results, the condensate profiles intrinsically represent the diffusive flux magnitude of water vapor condensing along the microfiber under natural convection condition. Inspired by these works,^{38,43–45} we propose that our observed condensate morphologies are due to the competing effects between two thermal resistances: the thermal conduction resistance R_{cond} being dependent primarily on the thermophysical properties of the fiber and the condensation heat transfer resistance R_{conv} being largely related to the ambient condition. Such competing effects result in three scenarios: when $R_{\text{cond}} \gg R_{\text{conv}}$ which is the case for long, thin fibers with relatively low thermal conductivity, the overall condensation is dominated by the heat conduction rate through the fiber, giving rise to the decreasing droplet height condensate morphology [Fig. 2(a)]. Conversely, when $R_{\text{cond}} \ll R_{\text{conv}}$ which is the case for short, thick fibers with relatively high thermal conductivity, the total condensation is mainly due to the focusing vapor diffusion flux at the fiber apex, leading to an increasing droplet height condensate profile [Fig. 2(c)]. When $R_{\text{cond}} \approx R_{\text{conv}}$, the more balanced competition between the two thermal resistances leads to a relatively uniform condensate morphology except for the fiber tip that is subjective to the edge effect [Fig. 2(b)]. To better understand the experimental results, numerical simulations using COMSOL Multiphysics 5.3 were carried out to compute vapor diffusion flux along the fiber based on the following assumptions:

- (1) The water vapor concentration field is governed by the steady-state, mass diffusion equation without convection, i.e., $D\nabla^2 c = 0$.
- (2) Vapor concentration variation in the θ direction is negligible (2D axisymmetric model).
- (3) Water vapor is considered as an ideal gas, and its concentration on domain bottom and fiber surfaces is at the saturation vapor pressure corresponding to their respective temperatures.
- (4) The condensation heat transfer coefficient, h , is uniform over the fiber surface.

The diffusive flux of water vapor (J) can be readily determined by Fick's law,

$$J = -D\nabla c, \quad (2)$$

where D is the diffusion coefficient of vapor in air. The temperature distribution along the cantilevered fiber length L can be obtained using fin theory,

$$\frac{T(x)}{T_0} = \frac{\cosh(m(L-x)) + \frac{h}{mk} \sinh(m(L-x))}{\cosh(mL) + \frac{h}{mk} \sinh(mL)}, \quad (3)$$

where $T(x) = T - T_{\text{air}}$ is the excess temperature and $m = \sqrt{hP/(kA)}$ with $P = \pi d$ and A denoting the perimeter and cross-sectional area of the fiber, respectively. For our work involving water vapor condensation on microfibers with varying parameters, the condensation heat transfer coefficient h was determined by using an optical microscopic image-based method to directly measure the thickness change of condensate during the initial stage of dropwise condensation on microfiber.⁴⁶ It was reported that a fiber with a smaller diameter has a higher condensation heat transfer coefficient as the diffusive flux is proportional to the -0.25 power of the fiber diameter.⁴⁷

2D axisymmetric simulation domain for the steady vapor mass diffusion problem is shown in Fig. 3, and the *transport of diluted species (tds)* module was exploited with a vapor diffusion coefficient (D) of $2.2 \times 10^{-5} \text{ m}^2/\text{s}$. The width and height of the simulation domain are set as 2 mm and 10 mm, respectively. T_{base} and T_{air} are kept being -4.4°C and 22.5°C , respectively. The fiber thermal conductivity for 316L stainless steel is 16.3 W/(m K) , while the value for the condensation heat transfer coefficient is set as $51 \text{ W/(m}^2 \text{ K)}$. The diameter of the microfiber is fixed at $127 \mu\text{m}$. The water vapor concentrations on the top and right sides of the domain are kept at 0.65 mol/m^3 , serving as the vapor reservoir, and the value on the domain bottom and the fiber surface is constrained to be the saturation vapor pressure of water corresponding to respective temperatures. Here, the temperature distribution along the cantilevered fiber is evaluated via the fin theory, and the saturation vapor pressure is obtained from Engineering ToolBox.

The numerically calculated contours of water vapor diffusive flux on the lower part of the fiber surface for three scenarios are presented in Fig. 3, corresponding to the three scenarios shown in Fig. 2. The distributions of water vapor diffusive flux signify the condensate morphology. Of note, the only difference among these three simulation cases lies in the fiber length.

III. FURTHER DISCUSSION

A direct thermal resistance analysis gives

$$R_{\text{cond}} \sim \frac{4L}{\pi k d^2} \quad (4)$$

while

$$R_{\text{conv}} \sim \frac{1}{\pi h d L} \quad (5)$$

with L being the fiber length. By changing the fiber length, the relative magnitude of R_{cond} and R_{conv} can be tuned; this will alter the distribution of water vapor diffusive flux, thereby giving rise to the three condensate morphologies.

Figure 4(a) depicts a phase diagram that exhibits the dependence of three condensate morphology scenarios (indicated by right triangle, empty square and left triangle symbols) on L and kA . For a microfiber with given diameter and thermal conductivity

FIG. 3. Numerically simulated contours of diffusive flux, J ($\text{mol/m}^2\text{s}$) on the lower part of microfiber surface along the axial direction, corresponding to the three scenarios shown in Fig. 2: (a) $R_{\text{cond}} \gg R_{\text{conv}}$; (b) $R_{\text{cond}} \approx R_{\text{conv}}$; and (c) $R_{\text{cond}} \ll R_{\text{conv}}$. R_{cond} is the thermal conduction resistance within the fiber, and R_{conv} is the condensation heat transfer resistance on the fiber surface.

FIG. 4. Characterization of condensate morphology on a cantilevered microfiber. (a) Phase diagram showing the dependence of condensate distribution morphology on the length, thermal conductivity, and cross-sectional area of the fiber with right triangle, square, and left triangle symbols denoting the three condensation scenarios presented in (c), (b), and (a) in Fig. 2, respectively. (b) The slope of the top-side condensate as a function of the ratio of $T_{dew} - T_{tip}$ to $T_{tip} - T_{base}$. The error bars indicate the maximum deviation from three parallel measurements.

(i.e., fixed kA), the critical length giving $R_{cond} \approx R_{conv}$ featured by a uniform condensate distribution (i.e., scenario 2) can be evaluated with the scaling, $L_c \sim (kd/4h)^{0.5}$. This scaling shows that L_c increases when the value of kA increases (see empty squares). Specifically, the critical lengths for constantan, 316L steel, and

alumel microfibers predicted by this scaling are, respectively, 5.0 mm, 3.2 mm, and 1.8 mm which are quite closer to the experimental counterparts (4.2 mm, 2.9 mm, and 1.6 mm). Moreover, given the same heat flux density at the fiber tip, we have $\frac{R_{conv}}{R_{cond}} \sim \frac{T_{dew} - T_{tip}}{T_{tip} - T_{base}}$, showing that the condensate profile (morphology) is associated with the ratio of $T_{dew} - T_{tip}$ to $T_{tip} - T_{base}$. Hence, we quantitatively characterized the condensate profile in terms of its slope indicating the change of condensed droplet height on the top side of the fiber vs the ratio of $T_{dew} - T_{tip}$ to $T_{tip} - T_{base}$, and the results are depicted in Fig. 4(b) in which negative and positive slope values denote scenario 1 and scenario 3, respectively (see respective insert images). Point (1,0) together with its nearby area shows $\frac{T_{dew} - T_{tip}}{T_{tip} - T_{base}} \sim 1$, indicating comparable two thermal resistances for scenario 2. Of note, the characterizations were done by measuring condensate along the middle section, neglecting the left-most and right-most ones so as to reduce the uncertainty that primarily comes from the edge effects. Nonetheless, from both Figs. 4(a) and 4(b), the experimental results demonstrate that the occurring of scenarios can be explained by the competing effects of two thermal resistances R_{cond} and R_{conv} .

IV. CONCLUDING REMARKS

In summary, we observed the three different condensate morphologies formed during air-vapor mixture condensation on a cantilevered microfiber. We have shown both experimentally and numerically that the different condensate distributions arise from the competition between the thermal conduction resistance within the fiber and the condensation heat transfer resistance on the fiber surface. In addition, based on our systematic experiments, we have presented a phase diagram showing the dependence of the condensate morphology on the fiber length, cross-sectional area, and thermal conductivity. From a broader viewpoint, this work enriches our understanding of air-vapor mixture condensation, especially on fiber-based structures. We envision that such an intriguing condensate phenomenon would stimulate a range of condensation-associated applications.

AUTHORS' CONTRIBUTIONS

F.Z. and W.Z.F. contributed equally to this work.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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