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Efficient Fog Harvesting Based on 1D Copper Wire Inspired by the Plant Pitaya

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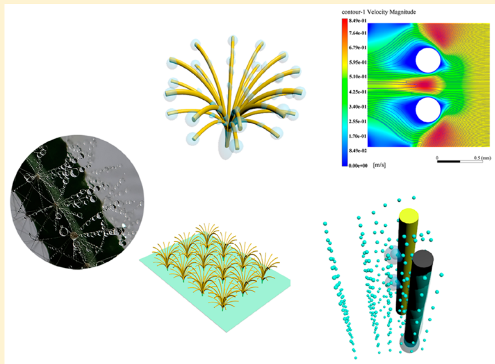
Supporting Information

ABSTRACT: The leaf of the plant pitaya shows excellent fog harvesting behavior through its 1D thorns with wire-like microstructures. The thorns of it cannot provide enough driving force for the droplet transportation by the special structure and chemistry gradient as the cactus thorns, but it showed efficient water supply which improved the fog harvesting greatly. The mechanism is studied based on 1D copper wire with similar 1D wire-like microstructure and wettability. This structure can significantly reduce the deviation of the fog-laden winds, and the surface intrinsic hydrophility makes water accumulate on it in the form of droplets, which endow it with an efficient water supply that is ∼100 times faster than that on a 2D-flat surface. In addition, it can also enhance the fog capture and water removal. The 3D fog collector composed of 1D microcopper wires has been fabricated which show a high fog harvesting efficiency of ∼13%. This work explains the role of 1D wire-like microstructure in efficient fog harvesting in a different view and provides new insight into the application of developing a more efficient fog collector.



■ INTRODUCTION

Fog, as a form of water source, is a normal meteorological phenomenon which is extremely important to those arid regions. There is a large amount of fogwater in the areas near the coast, forming the especial foggy climates.[1] The ecosystems on the arid regions near the coast, such as the Namib Desert, depend on the fog episodes in the form of persistent advection and orographic fog, since the amount of fogwater exceeds the rainfall water.[1−3] Many studies have been conducted to improve the understanding of the special climate and the fogwater collection in these regions.[4−7] The study of the water harvesting behavior of creatures, such as the Namib Desert beetle Stenocara,[8] cactus,[9] and spider silk[10] in the deserts, promoted the development of biomimetic fog harvesting materials and devices.[11−20] These studies made it possible to meet the freshwater demand in remote areas. According to the geometrical dimensions of fog harvesting surfaces, they can be classified into 1D, 2D, and 3D fog collectors. The role of the 3D structure was studied among special desert plants that can harvest fog, but the 3D biomimetic fog collector was rarely fabricated.[21,22] Biomimetic 2D flat surfaces and 1D wires have been studied widely for fog harvesting. Among them, the surface structure and surface chemistry of the fog collector are vital to the rate of fog harvesting. The special alternative hydrophobic/hydrophilic chemistry pattern of the desert beetle inspired the fabrication of a series of biomimetic 2D surfaces. The hydrophilic surface chemistry can promote the fog harvesting rate, and the hydrophobic pattern accelerates the water removal.[8,12,17] Besides this special alternative chemistry pattern, the design of the structure gradient endowed the 2D surface with directional wetting driving force[12,23] and Laplace pressure[24,25] which can also enhance the fog harvesting ability. The 1D fog collectors, enlightened by the cactus spines and spider silk,[15,18] possess a high water harvesting rate. Periodic roughness-gradient conical copper wire fabricated by Zheng et al.[15,26] can harvest fog and achieve long-range unidirectional droplets transportation by the drop coalescence released surface energy, gradients of geometric curve-induced Laplace pressure, and periodic roughness-induced surface energy difference. Tian et al.[18] fabricated a large-scale bioinspired spindle knot cavity microfiber which showed excellent fog harvesting ability due to the knot part that can enhance the water driving force of the directional water transport. On the basis of the fog harvesting experiment on woven meshes, Park et al.[27] developed a model to predict the overall fog-collection efficiency of the meshes (composed of 1D wires). This model took into consideration hydrodynamics and surface wettability which promote the under-

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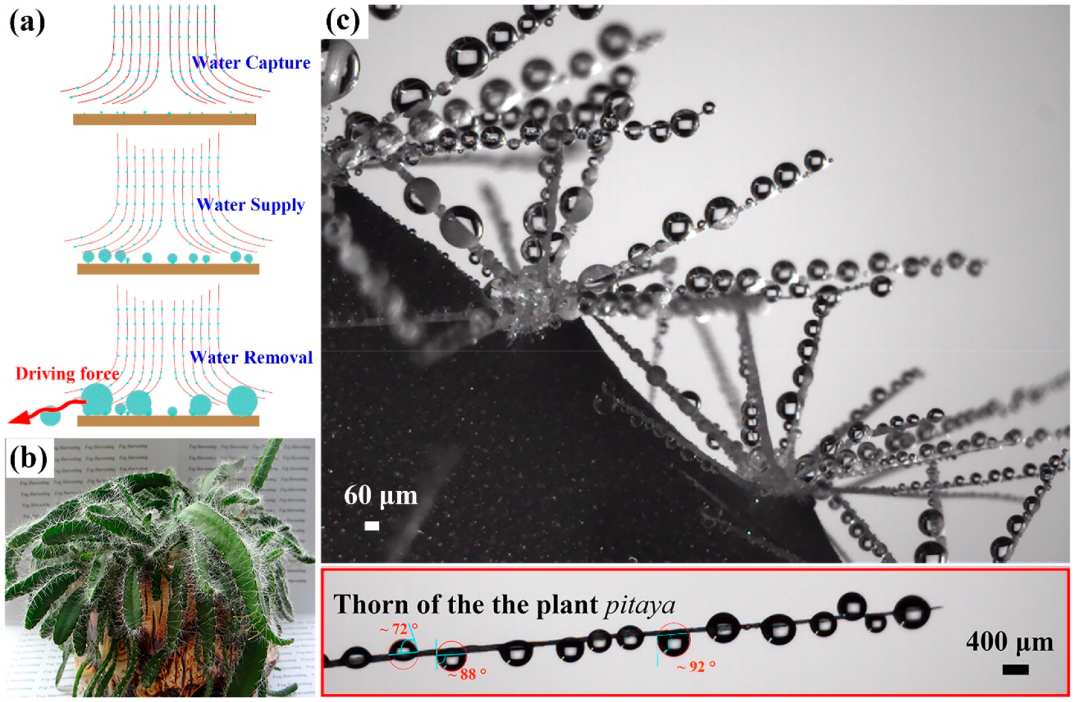

Figure 1. (a) Three processes of fog harvesting: water capture, water supply, and water removal. (b) Optical image of pitaya. (c) The pitaya covered with microthorns showed excellent fog harvesting in 20 s with a fog velocity of ∼60 cm/s. Inside the red box is shown the wettability of the thorn.

standing of the fog harvesting mechanism that is related to the structure of 1D wires. The high water collection rate, easy large-scale fabrication, and low cost of the 1D wire make it more promising to access freshwater from fog than the traditional 2D biomimetic surfaces, and the difference of fog harvesting behavior among different geometrical dimensions of fog harvesting surfaces is mainly due to the mechanism of fogwater supply, which was rarely studied.

Fog harvesting can be divided into three parts:[28−31] (a) water capture, the process of the capture of tiny droplets on the surface of the fog collector; (b) (fog)water supply, the process of the coalescence between the droplets in the fog episode and the water droplet (film) on the surface of collector; and (c) water removal (drainage), the process of drainage of harvested water (Figure 1a). Water capture and water removal are greatly affected by the surface chemistry and special structure as reviewed above, while the water supply is less related to it. The flowing air phase of fog has always been underestimated in the biomimetic fog harvesting studies, which can affect the water supply dramatically. Briefly, viscous forces drag the fog droplets moving forward by flowing air. Therefore, the flowing air has a significant effect on the movements of droplets, and it will be disturbed by different topographies. Aizenberg et al.[29] studied the condensation of water vapor on the slippery bulges and proved that the discontinuities can enhance vapor diffusion flux; thus, the water supply was enhanced. Boreyko et al.[32] presented a mechanistic understanding of how harps that were composed of 1D steel wires enhance the fog harvesting dynamics, which is also related to enhanced water supply. Our previous work demonstrated that the bulge on the biomimetic surface can influence the flowing fog; the bulges can "focus" more droplets and enhance the water supply.[30] Accordingly, the air phase is an intrinsic component of fog in all the biomimetic fog harvesting which is more related to water supply, and more efforts should be paid to the comprehensive understanding of the water supply dominated fog harvesting.

The leaf of the plant pitaya was covered by 1D thorns, which was efficient for fog harvesting (Figure 1b,c; Figure S1 and Movie S1 in the Supporting Information). Tiny droplets in fog were harvested by the thorn effectively and then grew fast on the hydrophilic surface of the thorn. Interestingly, this plant did not show the special driving force for water compared with the cactus spines and spider silk, but it showed efficient water supply. During the long-term evolution, plants adopted an optimized structure to adapt to the complex environment. Special plant morphology assisted the ecological success. Take the thorn of plants for example; it has been reported to possess abilities such as grazing protection,[33] drag reduction,[34,35] light capture,[36] and the fog harvesting mentioned. That is to say, the role of the 1D structure is more significant than what was already known, and this 1D wire-like microstructure-dominated fog harvesting can provide new insight into the biomimetic fog harvesting. To figure it out, the fog harvesting experiment was studied based on a 1D copper wire that has similar 1D wire-like microstructure and wettability to the thorn (Figure 1), and the mechanisms of water capture, water removal, and especially the water supply were further studied with flow field analysis. The 1D wire-like microstructure and the growing form of droplets on the hydrophilic wires greatly affected water supply. The rate of water supply on copper wire is ∼100 times faster than that on the 2D flat surface, and the fog deposition efficiency of the wire is up to 90%. Such an efficient water supply can further enhance water capture and water removal. Based on this, the biomimetic 3D fog collector was fabricated and showed efficient fog harvesting with a high fog harvesting efficiency up to 13%, which is rarely reported. The significance of water supply in fog harvesting was presented, which promoted the understanding of biomimetic fog harvesting based on the 2D flat surface and 1D wire.

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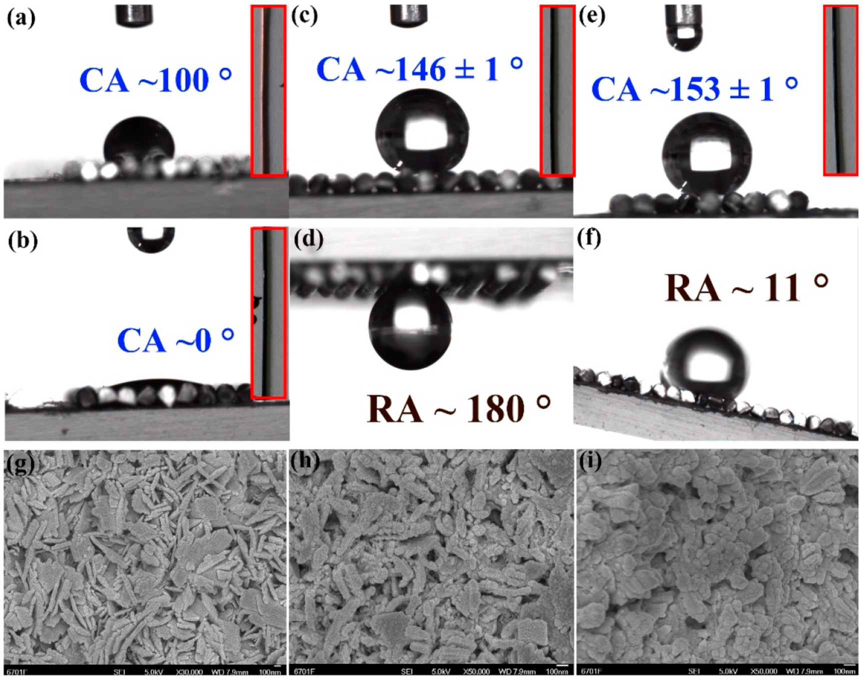

Figure 2. (a) Water contact angle on the original copper wires. (b) Water contact angle on the CuO wires. (c, d) Water contact angle and roll-off angle on the copper wires whose surfaces are covered by CuO and *n*-octadecanethiol (ODT) modified CuO. (e, f) Water contact angle and roll-off angle on the ODT-modified copper wires. (g), (h), and (i) are the SEM images of CuO surface, combinational CuO and ODT modified CuO surface, and totally ODT modified copper surface. The diameter of copper wires is 400 μm, and the length is 2 cm. Note that CA in (a) is greatly affected by the arrangement of copper wire.

Besides, it provided novel insights into designing a fog collector that is more efficient, more economic, and easily fabricated.

■ EXPERIMENTAL SECTION

Materials. The fresh leaf of the plant pitaya. Copper wires (50, 100, 400, and 1000 μm, purity ~99.5%) were purchased from Baoxin Copper Co., Ltd. Ethanol, acetone, sodium hydroxide (96%, NaOH), silicon oil, and ammonium persulfate (98%, $(NH_4)_2S_2O_8$) were obtained from Tianjin Rionlon Pharmaceutical Science & Technology Development Co., Ltd. *n*-Octadecanethiol (96%, $C_{18}H_{38}S$) was obtained from Sinopharm Chemical Reagent Co. Ltd. Sylgard 184 was purchased from The Dow Chemical Company.

Fabrication of Copper Wires with Different Wettability. *Superhydrophilic Copper Wire.* Copper wires (2 cm in length) with different diameters were ultrasonically washed in acetone and deionized water for 20 min, immersed in 0.1 M HCl for 1 min to remove the oxide layer, and then dried in N_2. Next, copper wires are etched in the aqueous solution of 2 M NaOH and 0.15 M $(NH_4)_2S_2O_8$ for 1 h.[37]

Superhydrophilic Copper Wire. After the ammonia corrosion, superhydrophilic copper wires were immersed in 10 mM *n*-octadecanethiol (96%)/ethanol for 12 h.

Copper Wire with Combinatorial Hydrophobicity/Hydrophilicity. After the ammonia corrosion, superhydrophilic copper wires were immersed in 0.2 mM *n*-octadecanethiol (96%)/ethanol for 12 h.

Fabrication of 3D Fog Collector Based on 1D Copper Wire. Eight to nine copper wires (1.5 cm in length and 100 μm in diameter) were tied together to form a "grass"-like structure. Then, these "grasses" were embedded in PDMS (length × width × height = 5 cm × 2.5 cm × 2 mm) substrate. To equip the copper wires with superhydrophility, the collector was immersed in the aqueous solution of 2 M NaOH and 0.15 M $(NH_4)_2S_2O_8$ for 1 h. To equip the copper wires with superhydrophobicity, superhydrophilic copper wires were immersed in 10 mM *n*-octadecanethiol (96%)/ethanol for 12 h after the ammonia corrosion.

Through the ammonia corrosion,[37] copper wires covered with standing and dense $CuO/Cu(OH)_2$ flakes have been fabricated successfully (Figure S2). Then, modified with *n*-octadecanethiol (ODT), the copper wire showed great superhydrophobicity (Figure 2 and Movie S2). An alternative hydrophobic/hydrophilic pattern on copper wires was fabricated through the fractional modification reported in our recent work.[38] As shown in Figure 2, Figure S3, and Movie S3, the copper wire with the combinational wettability has also been fabricated successfully.

Fog Harvesting Experiments. Fog-laden wind was generated by a humidifier, and 67 ± 3 g of water was transferred to fog within 30 min. The single copper wire for fog harvesting was settled perpendicular to the horizontal in front of the outlet of fog, with a spacing of 1 cm and fog speeds of 60 and 15 cm/s. The leaf of the plant pitaya (~7 cm in length and 2 cm in width) and the 3D fog collector were set along the flow (~60 cm/s) with the thorns perpendicular to the flow. The temperature was maintained at 24 ± 2 °C. A digital camera (SONY DSC-HX200) and an industrial camera (DH-HV1351UM) were employed to record the process of fog harvesting. The fog harvesting efficiency was calculated by dividing the amount of water harvested to the total amount of water that transferred to fog.

Characterization. Fog droplets dispersed in the surface of silicone oil were obtained by an optical microscope (OM, OLYMPUSBX51, Japan). Field emission scanning electron microscope (FESEM) images of copper wires were obtained by a JSM-6701F. The water contact angle and roll-off angle were obtained by a JC2000D goniometer (Zhongchen Digital Equipment Co. Ltd., Shanghai, China). Surface component analysis was conducted by X-ray diffraction (XRD) using an X'PERT PRO diffractometer with Cu Kα radiation and element distribution analysis (EDS, KEVEX, Japan).

Simulation of the Act between Fluid Fog and Copper Wires Based on the Fluent Software. The interaction between the fluid (composed of water droplet and air) and copper wires was simulated with fluid dynamics finite element analysis software ANSYS FLUENT 19.0. The boundary conditions of this two-dimensional simulation velocity were set according to experimental conditions. Here, the

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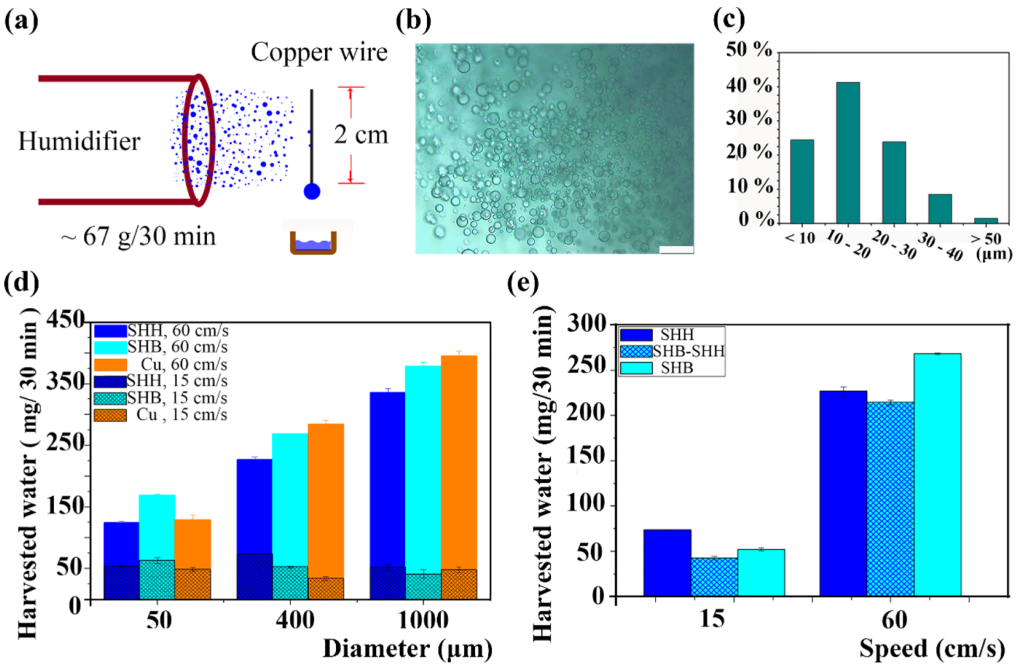

Figure 3. (a) Schematic of fog harvesting experiment. (b) Photomicrograph of fog droplets dispersed in silicon oil (details in Figure S4). Scar bar is 100 μm. (c) Size distribution of fog droplets. (d) Net weight of water collected from fog flow (with speed of 15 and 60 cm/s) on a copper wire 2 cm in length and with different diameter and wettability in 30 min. (e) Amount of water harvested by the copper wire (diameter = 400 μm) with three kinds of wettability: superhydrophobic (SHB), alternate wettability of superhydrophobic and superhydrophilic (SHB-SHH), and superhydrophilic (SHH).

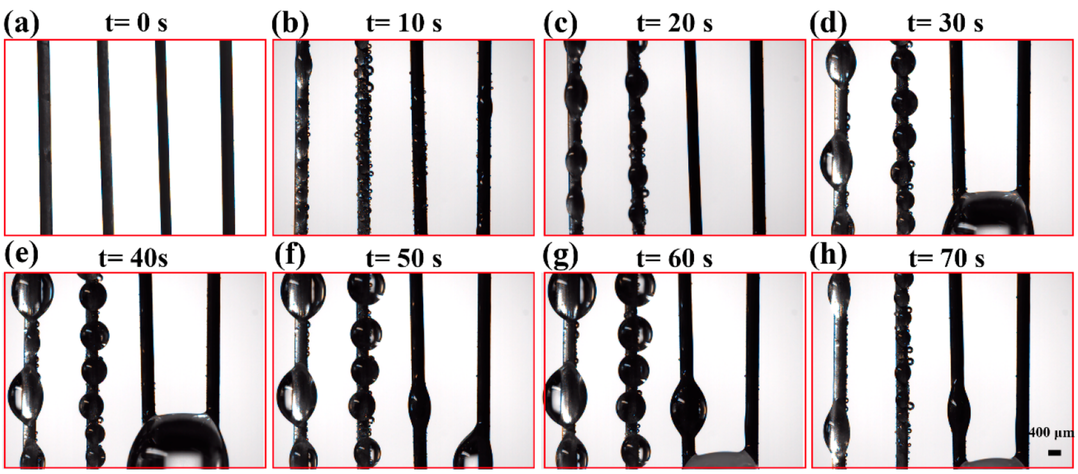

Figure 4. Time-lapse images of the process of water harvesting on original hydrophilic, SHB, SHB-SHH, and SHH copper wires from left to right, respectively (scale bar: 400 μm).

interaction between fluid and copper wire is set trap. Inlet: insert particle, microwater droplets with a diameter of 20 μm, and fluid material, air. The remaining boundaries were set as outlet. The interaction between fog fluid and copper wires with radius of 100, 400, and 1000 μm were simulated. Besides, the interaction between fog fluid and two parallel copper wires was simulated. The velocity of the flow was set at 60 cm s^{-1}, the mass flow rate of water droplet was 0.037 g s^{-1}, and the parameter of air was set according to standard conditions. All the simulations were conducted on a notebook PC (CPU 2.60 GHz, RAM 4GB).

■ RESULTS AND DISCUSSION

Copper wires with diameter of 50, 400, and 1000 μm and length of 2 cm of each one with different wettability, original hydrophilic, superhydrophobic (SHB), alternative wettability of superhydrophobic and superhydrophilic (SHB-SHH), and superhydrophilic (SHH) were prepared for the fog harvesting experiment (Figure 2, Figure S5, Movie S2, and Movie S3). The experiment was conducted as Figure 3a−c. The amount of water harvested in 30 min was recorded in Figure 3. Surprisingly, the combinational wettability (SHB-SHH) did not show apparent advantages in fog harvesting compared with 2D biomimetic flat surfaces (Figure 3d,e), and the micro-/nanostructures on copper wire also have no apparent effect on fog harvesting (Figure 3d). The effect of the diameter of copper wire on the amount of harvested water is greater than that of wettability. Besides, the difference of the amount caused by two fog speeds decreases with the decreasing diameter of copper wire, which demonstrated the importance of 1D wire-like microstructure. In addition, a single copper wire with

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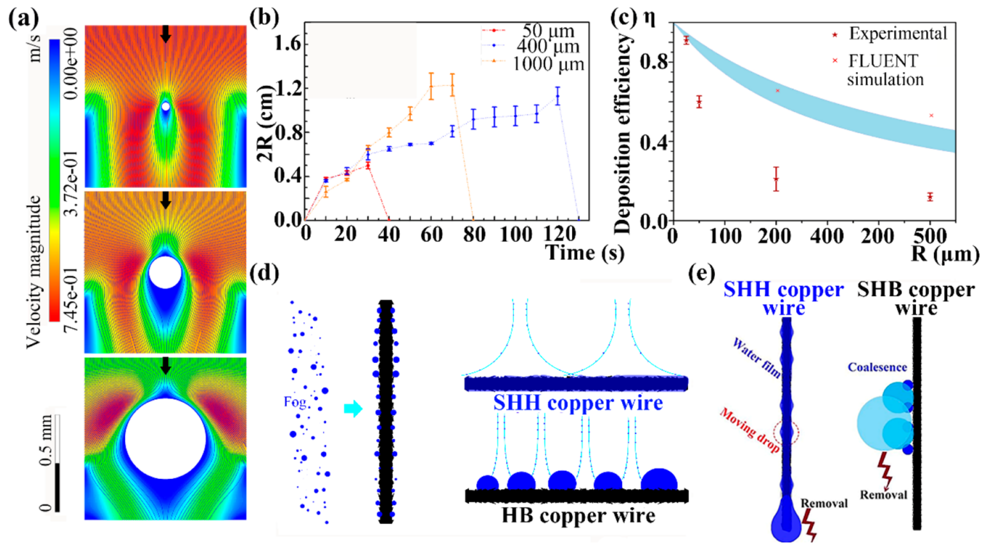

Figure 5. (a) 2D image of the path lines and velocity magnitude of the flow when interacted with copper wires with different diameters (D = 100, 400, and 1000 μm). (b) Droplet growth on superhydrophobic copper wires. (c) The symbol ★ denotes the experimental deposition efficiency of fog on copper wires, and × denotes the result of FLUENT simulation (details in the Supporting Information). The shadow area presents the theoretical efficiency evaluated from eq 1. Here, the diameters of fog droplets are set from 5 to 20 μm in the theoretical equation and set to be 20 μm in the FLUENT simulation. The velocity of the fog is ~60 cm/s. (d) Schematic of the process of fogwater capture and water supply on SHB copper wires. (e) Schematic of the process of water removal on SHH copper wire (left) and SHB copper wire (right). The SHH copper wire was covered by a layer of water film. Through continuous water supply, the water drop formed as a result of Laplace pressure and minimum surface free energy. Fog droplets captured on the SHB surface coalesce and spherically grow to a critical volume and then depart.

length of 2 cm and diameter of 400 μm can harvest about 0.3 g of water per 30 min (0.4 g for the copper wire of 1000 μm), which gives it potential in the application of accessing freshwater from fog. Next, the fog harvesting mechanism will be studied based on three processes of fog harvesting: water capture, water supply, and water removal.

Water Capture. A fog droplet with a certain speed is easily captured. The first batch of fog droplets was captured by the solid surface to the extent where there is no fresh surface area to hold new droplets, which is termed water capture. Next, when water fully occupied the solid surface, the fog droplets begin to merge into the water (in the form of droplets or film) on the solid surface, which is termed fogwater supply (Figure 1a). Among the 2D biomimetic surface, surface chemistry is vital to water capture. The hydrophilic surface is energetically favorable for water capture compared with hydrophobic surfaces.[39] Those biomimetic surfaces that mimic the back of a desert beetle were designed to possess alternative surface wettability, and they were proved to be effective in fogwater capture.[11−13] When the fresh SHH copper wire was exposed to fog, it was immediately covered by a layer of water film, which showed a great ability of water capture (Figures 4 and 5, Movie S4). For the original copper wire and SHB-SHH copper wire, they can also capture the droplets easily. They were covered by tense tiny droplets within 10 s, while for the SHB surface, extra energy was necessary for the adhesion between it and droplets. Especially, the amount of water harvested by the surfaces (Figure 3) with different wettability showed little difference, which also revealed the excellent performance of SHB wire in water capture.

Here, the 1D wire-like microstructure played a key role. 1D wire deviated the pathlines of the flow but the deviation aroused by the 1D wire is far less than that by 2D plat surface (Figure 5a).[30] What is more, with the decrease of the diameter of copper wire the deviation is also weaker. Initially, flowing air carried fog droplets with a certain speed normal to the surface of the fog collector. Then, the deviation decreased the velocity of droplets that are normal to the 2D flat. But for the 1D wire, the deviation slightly affected the speed. Therefore, the droplets reached it with a relatively high speed that is approaching the original speed. High speed equipped the droplets with enough kinetic energy, E_k. For the capture process, fog droplet needed to conquer the energy barrier E to it to be caught. Besides, the droplets are of about 10 μm, and the Ohnesorge number is larger than the critical value of 0.1.[40] Therefore, the viscous energy dissipation, W, cannot be neglected. From the point of energy, the relation should be drawn as follows: $E_k > E + W$. Here the kinetic energy of fog droplets and the viscous energy are of the same order of magnitude; especially the former is larger than the latter (details in the Supporting Information). Therefore, the fog droplets with an initial velocity are energetically favorable to be captured by the SHB copper surface. The 1D wire-like topography allows for easier water capture. Once the surface was fully covered with fogwater, it is can further promote the capture due to the strong function between water and water.

Water Supply. Water supply means the merging between the fog droplets and the water droplets (film) captured on the solid surface (Figure 1a). Our previous work demonstrated that the surface topography has an effect on water supply. The bulgy surface can harvest more water than the corresponding flat surface by the enhanced water supply.[30] Objects in the flow will affect the path lines of the flow. For the 2D flat surface, when embedded into the fog flow, it will deviate the flow dramatically. A large part of flow could not approach the surface and coalesce with the water droplets (film) captured on the solid surface, while for the 1D wire, the deviation of the flow is weaker (Figure 5a). Besides, with the decrease of the diameter of copper wire the deviation is further decreased. So, more fog droplets can get to the surface of copper wire per unit

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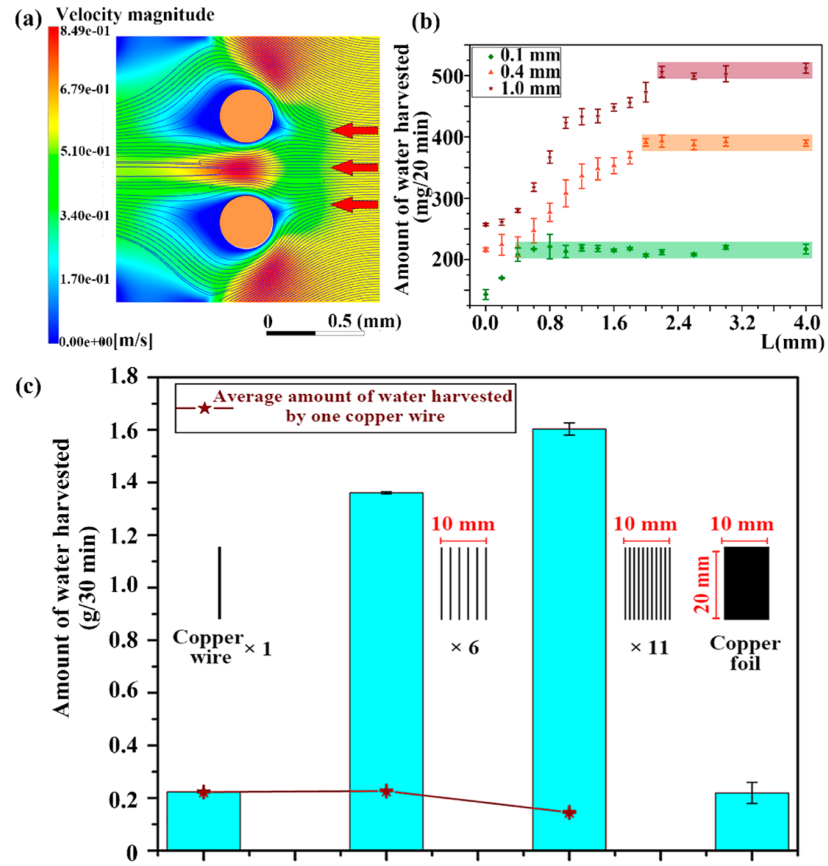

Figure 6. (a) Streamline and velocity field of fog droplets when the fog flowed through two copper wires (arranged in parallel with an interspace, L, of 400 μm). The red arrows indicated the inlet of flow (~60 cm/s). (b) Relationship between the amount of water harvested by two parallel copper wires (diameter: 400 μm; length: 2 cm) and their interspace, L. (c) Amount of water harvested by 1, 6, and 11 copper wires. In the case where there are 6 and 11 copper wires, they distributed within 10 mm, and the interspace is 2 and 1 mm, respectively. The control group of 2D copper foil (10×10 mm^2) was also constructed. The inserted curve shows the average amount of water harvested by one copper wire.

area, which is the efficient water supply. Here, the water supply can be described by the growth rate of water droplet on the SHB surface (Figure 5b). Compared with the droplets that grew on the SHB 2D flat in ref 30, droplets growing on 1D SHB copper wire grew ~100 times faster, and they all departed from it within 120 s. That is to say, a large amount of those microdroplets merged with the captured droplets (or film). Fast merging accelerated the growth rate of droplets on the SHB wire. Furthermore, we measured the deposition efficiency of fog onto the SHH copper wire. For a single copper wire, we use η to denote the deposition efficiency of fog (Figure 5c):

$$\eta = \frac{M}{M_f} \tag{1}$$

where M is the amount of water the copper wire harvested in 30 min and M_f is the total weight of fog flow through the project area of the copper wire in 30 min. We also made a comparison to the empirical expression:[41]

$$\eta_d = \frac{St}{St + \frac{\pi}{2}} \tag{2}$$

where St is the Stokes number. The experimental fog deposition efficiency is smaller than the theoretical value and the FLUENT simulation (details in the Supporting Information; for accuracy, only the interaction on copper wire with diameter of 1000 and 400 μm was simulated). This is due to that the arrangement of fog droplets in the air flow is less erratic. While the tendency is the same, the smaller the diameter of copper wire, the higher the fog deposition efficiency. When surface wettability allows for the droplet-like growth of supplying water on copper wire, the water supply can be further enhanced (Figure 3d). Water harvested on the hydrophilic or hydrophobic copper wire in the form of a droplet (like a spindle), which affected the flow of fog and allowed for more contact between tiny fog droplets and the larger droplet than that on the SHH copper wire (Figure 5d). This further enhanced water supply. It also demonstrated the micro-sized structure is good for water supply. For the copper with a diameter of about 50 μm, the fog deposition efficiency reached 90%. This result agrees with previous work.[27,32]

Water Removal. As reviewed above, special chemical and structure gradient will generate driving force for water removal which enhanced the total amount of water harvested. While for the 1D copper wire without special chemical and structure gradient, it also showed efficient water removal.

As for the SHH copper wire, once exposed to the fog-laden winds, it will be covered by a layer of water film quickly (Figure 4). Efficient water supply continuously generated a spindly water drop due to the effect of Laplace pressure and surface energy (Figure 5e).[42] Then, gravity drives the drop to move downward with a speed of few 10 cm/s, which is different than the 2D SHH flat surface,[30] which trapped lots of water in the form of a water puddle that impeded further water capture. The 1D wire can act as a path for water transportation due to

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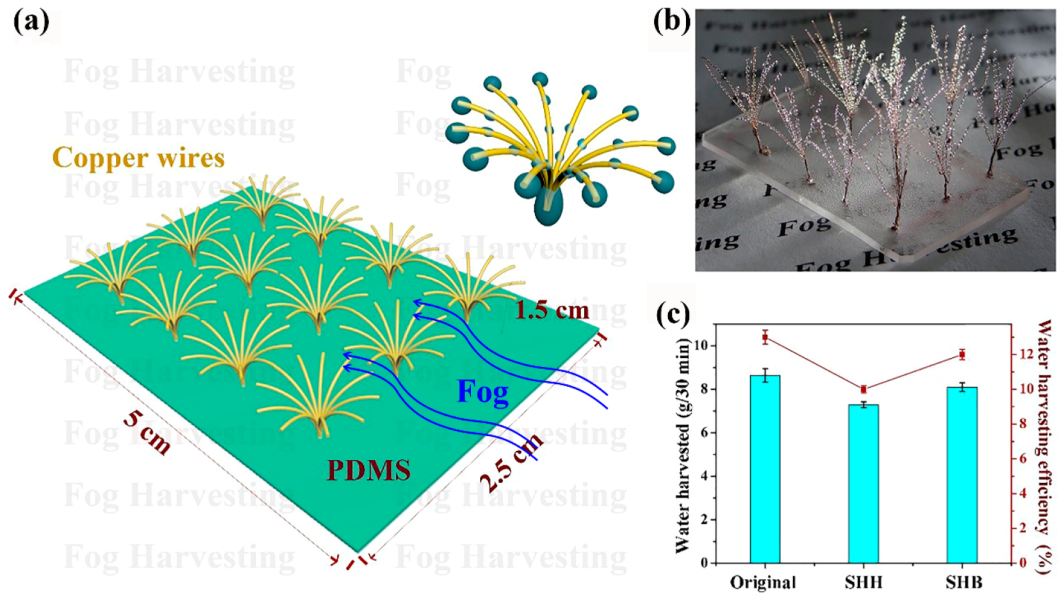

Figure 7. (a) Schematic diagram of the 3D fog collector. (b) Fog collector made up by thorns (original copper wire) and supporter (PDMS) during fog harvesting. (c) Amount of water and the fog harvesting efficiency of fog collector made up of original copper wire, SHH copper wire, and SHB copper wire.

the low friction between the water drop and the wetted surface of copper wire. Thus, water transported downward continuously and departed from the wire. As for the superhydrophobic copper wire, water droplets were captured in the form of a sphere. With faster water supply, the growing droplet coalesced with its neighbor and then grew until its departure within 120 s. Especially, the upper departure will drive the lower droplets to depart (Figure 5, Figure 4, and Movie S4). Efficient water supply contributed to its efficient water removal.

As studied above, 1D wire-like microstructure enhanced water capture, water removal, and especially water supply that endowed the 1D copper wire with a high fog harvesting efficiency. Hydrophility allowed the water to easily gather on the copper surface in the form of a water drop (Figure 4 and Figure S5) which enhanced the water supply by enlarging the chance of contact between it and the fog, so the hydrophilic copper wire harvested more water than the SHH copper wire. This is similar to the thorn of the pitaya whose surface is not superhydrophilic or superhydrophobic but slightly hydrophilic. As discussed above, the 1D wire-like microstructure cannot provide special driving forces for droplets transportation, but it is efficient in water supply. The efficient water supply can offset the amount difference of harvested water aroused by surface micro-/nanostructure[43] and surface chemistry.[8,44] Traditional fog collection rate was usually termed WCR, which is the amount of water collected per unit area and per unit time.[31] For these 1D copper wires, the WCR was ~11.6 g/cm^2 h^{-1} (50 μm), ~2.1 g/cm^2 h^{-1} (400 μm), and ~1.2 g/cm^2 h^{-1} (1000 μm). They are higher than that of the 2D flat surface. That is, for one copper wire with radius of 50 μm and length of 1 m, it theoretically can harvest ~17 g of water per hour (27 and 38 g of water for copper wire with radius of 400 and 1000 μm). Tian et al.[18] fabricated a kind of cavity microfiber for water harvesting. For the fiber work with an equivalent length of ~28.49 m, it can harvest ~1 L of water for 3 h (fog mass flow rate: 0.408 mL min^{-1}). For the original 1D copper wire, it can harvest ~3.3 L of water with same length and time (fog mass flow rate: ~ 2 mL min^{-1}). Therefore, the 1D wire-like structure is of high efficiency in fog harvesting. This is of great significance in lowering the cost of fabricating the 3D fog collector and enhancing the fog collection rate by using more cheaper and tougher 1D wire-like materials.

Design of 3D Fog Collector with High Fog Harvesting Rate. The 1D copper wire has potential for large-scale fog harvesting. It is reasonable to assume that the amount of water harvested will be multiplied by the increase of the number of copper wire within the limited space. We studied the relationship between the amount of water harvested by two parallel SHH copper wires and their interspace, L. As shown in Figure 6, there is a plateau for the amount harvested by two wires whose spacing is larger than a critical value, which denotes that the amount of water harvested by two copper wires is twice the single wire. With the decrease of their interspace, the amount is decreasing. Apparently, the interspacing of wires affected the fog harvesting. The FLUENT calculation gives the explanation (Figure 6a) that when L is smaller than a critical value, the inhibition of wires to the flow is prominent. Thus, a higher resistance slowed down fog harvesting. Besides, a high-speed channel of the flow was formed when L is small enough, which led to the decrease of the amount of water harvested. Furthermore, the diameter (100, 400, and 1000 μm, termed D_{100}, D_{400}, and D_{1000}) of copper wires has an effect on the resistance behavior. We define L^* as the shortest spacing that the amount of water harvested by two wire is twice the single one. Here L_{100}^* = 0.4 mm, L_{400}^* = 2.0 mm, and L_{1000}^* = 2.2 mm (Figure 6b). That is to say, within 10 mm, 21 copper wires (D_{100}) can be set and enhance the amount to 21 times (6 times for D_{400}, 3 times for D_{1000}). Based on this, control experiment was constructed to test the fog harvesting ability for 1, 6, and 11 copper wires that are arranged parallel within the width of 10 mm and a copper foil with same project area (they are both surperhydrophilic). For the copper wire D_{400}, when $L < L^*$, the average amount of water harvested by one copper wire is less than that by one single wire (Figure 6c). When $L > L^*$, the average amount of water harvested by one copper wire is the same as that by one

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single wire. Therefore, at a certain spacing, copper wires have no shielding effect on each other. Within the limited space, 1D copper wires can harvest more fogwater by adding its number. Besides, the 2D copper foil (1 cm × 2 cm) harvested less water than one single copper wire which demonstrated the excellent fog harvesting ability of 1D copper wires. This gives the basic principle for design fog collector with maximum efficiency and lowest cost. Besides, the fluid behavior can be significantly affected by the topography of fog collector that ultimately comes down to the water supply of the fog collector, which corresponds to the analysis discussed above.

For a 3D fog collector aimed at large-scale fog harvesting based on 1D copper wires, the precise spacing of L^* between copper wires will make it difficult to be fabricated. For simplicity, we mimic the structure of the plant pitaya. The thorns with a certain arrangement harvest fog, and the lathy leaf drains the harvested water out of the system. Based on this structure, more thorns were incorporated above the PDMS (Sylgard 184) substrate in a form of "grass". The thorns were original copper wires, SHH copper wires, or SHB copper wires (Figure 7). All of them show a high fog harvesting ability. The original hydrophility of copper wires is more effective in fog harvesting. For the fog with a speed of ~60 cm/s and mass flow rate of 0.037 g/s, the fog collector (original copper wires + PDMS) harvested ~8.64 g of water in 30 min (Figure 7 and Movie S5), which corresponds to the excellent behavior of hydrophilic copper wire and of the plant pitaya. Here, we define the fog harvesting efficiency, $\eta_H = M_H/M_F$, where M_H denotes the amount of harvested fogwater and M_F denotes the total amount of fog at the corresponding projected area. Three fog collectors all have a fog harvesting efficiency >10%, which approximates the water collection efficiency reported by Boreyko et al.[32] Note that the fog collector consists of 1.5 m original copper wire with a diameter of 100 μm whose cost was about \$0.16, and it only occupied the space of ~20 cm^3. Based on the efficient fog harvesting of 1D wire-like microstructure, thin plastic fibers with high flexibility can be integrated in a denser arrangement (the spacing is of L^*) to build a fog collector with ultrahigh efficiency and mechanic durability, and there is lots of room for improvement to reach a higher fog harvesting efficiency. This is of great significance in accessing freshwater (even drinkable) in the arid district facilely.

■ CONCLUSION

Inspired by the plant pitaya, the fog harvesting behavior based on 1D copper wire was investigated. The wettability and especially the 1D wire-like microstructure significantly affected the fog harvesting instead of special structure or chemistry gradient. The 1D structure can significantly reduce the deviation of the fog-laden winds which endow it with an efficient water supply, 100 times faster than that on the 2D flat surface. Besides, the 1D wire can also enhance the fog capture and water removal. Therefore, a single copper wire with length of 2 cm and diameter of 400 μm can harvest about 0.3 g of water per 30 min (0.4 g for the copper wire of 1000 μm). Based on the excellent performance of the 1D copper wire, a 3D fog collector was fabricated to harvest fog. With a fog speed of 60 cm/s, the fog collector (made up of 1.5 m original copper wire with a diameter of 100 μm) can harvest ~8 g of water per 30 min with a high water harvesting efficiency of ~13%, which is rarely reported. This work highlighted the importance of water supply in biomimetic fog harvesting since the air phase of fog has a significant influence on tiny fog droplets; thus, it presented a more comprehensive understanding of biomimetic fog harvesting and provided new insights into the design of a more efficient, facile, and economic fog collector.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.langmuir.8b03418.

SEM images of the thorn of pitaya, surface component analysis of copper wires, simulation based on FLUENT, energetic analysis of the fog capture (PDF)

Movie S1 (AVI)

Movie S2 (AVI)

Movie S3 (AVI)

Movie S4 (AVI)

Movie S5 (AVI)

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Notes

The authors declare no competing financial interest.

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