Fog Harvesting with Harps
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ABSTRACT: Fog harvesting is a useful technique for obtaining fresh water in arid climates. The wire meshes currently utilized for fog harvesting suffer from dual constraints: coarse meshes cannot efficiently capture microscopic fog droplets, whereas fine meshes suffer from clogging issues. Here, we design and fabricate fog harvesters comprising an array of vertical wires, which we call “fog harps.” Under controlled laboratory conditions, the fog-harvesting rates for fog harps with three different wire diameters were compared to conventional meshes of equivalent dimensions. As expected for the mesh structures, the mid-sized wires exhibited the largest fog collection rate, with a drop-off in performance for the fine or coarse meshes. In contrast, the fog-harvesting rate continually increased with decreasing wire diameter for the fog harps due to efficient droplet shedding that prevented clogging. This resulted in a 3-fold enhancement in the fog-harvesting rate for the harp design compared to an equivalent mesh.

KEYWORDS: fog harvesting, fog harp, vertical wires, droplet sliding, contact angle hysteresis

INTRODUCTION

Two-thirds of the world’s population faces the specter of water scarcity.1 Fog harvesting is a useful technique for obtaining fresh water in arid regions.2−4 To date, virtually all real-life fog harvesters comprise of mesh netting,5 where fog droplets are caught by the mesh and subsequently fall into a collector after growing to a critical size. Researchers have investigated how the fog-harvesting rate is modulated by variations in the geometry and wettability of these mesh structures.6−10 It is well known that the classical mesh design suffers from dual constraints: coarse meshes cannot efficiently capture the micrometric fog droplets suspended in the wind, whereas the fine meshes become clogged, thus disrupting the aerodynamics of the fog stream.11−19

One approach to minimizing clogging for fine meshes is to use superhydrophobic or lubricant-impregnated surface structures, which promote highly mobile Cassie droplets with greatly reduced contact angle hysteresis. Indeed, such approaches have been shown to enhance the drainage and collection rates of fog or dew droplets.6,8,18−25 However, it is now well known that the thin, conformal hydrophobic coatings required for superhydrophobic surfaces are not durable,26,27 particularly under prolonged exposure to the humid conditions inherent to fog harvesters. Lubricant-impregnated surfaces also suffer from durability issues, in particular the oil tends to cloak the shedding water droplets, which gradually depletes the lubrication layer and could contaminate the collected water.28

Here, we develop “fog harps” comprising an array of fine, vertically oriented wires that simultaneously bypass the clogging constraint of conventional meshes and the poor durability of nonwetting surfaces. The vertical wires running parallel to the drainage pathway serve to reduce the pinning force of captured droplets, such that droplets can shed at small Bond numbers to prevent clogging. As a result, harps comprised of micrometric wires can maximize the fog capture efficiency while avoiding clogging, which is not possible with conventional mesh structures. We observed up to a 3-fold enhancement in the fog-harvesting rate for harps compared to equivalent mesh netting, far superior to the 50% enhancement reported when making a mesh superhydrophobic.28 The water-harvesting rate of our fog harps increased as the wire diameter decreased from $D \sim 1$ mm down to $D \sim 100 \mu$m. A theoretical model predicts that the fog collection efficiency plateaus around $D \sim 100 \mu$m, indicating that the smallest harp tested here may be approaching the performance ceiling.

EXPERIMENTAL SECTION

Harp Fabrication. First, two-piece acrylic frames were made via laser-cutting and the two pieces were connected together with threaded bolts. A long, uncoated metal wire was then repeatedly threaded through an array of holes in the top and bottom of each frame to produce two staggered arrays of exposed vertical wires. The wires were either comprised of steel or aluminum (depending upon commercial availability for a given wire diameter), but exhibited similar wettabilities and were microscopically smooth (Figure S1). To hold the vertical wires under tension, stainless steel nuts located on the threaded rods were used to increase the spacing between the top piece and bottom piece of the acrylic frame. Finally, two different three-dimensional-printed plastic pieces were snapped onto the top and bottom halves of the frame and spray-coated with a superhydrophobic treatment (Rust-Oleum NeverWet). The lower piece helped droplets

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to shed into a collecting reservoir after they reached the bottom of the exposed wires. The upper piece served to redirect any fog that was captured above the exposed wires away from the reservoir to allow us to focus solely on the fog-harvesting performance of the wires themselves.

Experimental Methods. To obtain controlled measurements of fog-harvesting rates, the test samples were placed in an environmental chamber (Electro-Tech Systems, Model 5503) held at room temperature and 100% humidity (Figure S2). The dimensions of the chamber, 61 cm × 46 cm × 38 cm, were large compared to the dimensions of the wire arrays, which ranged from 1.9−2.4 cm × 4.0−4.5 cm depending upon the sample. Fog was generated at a flow rate of 141 g/h from an ultrasonic humidifier (PureGuardian H940) and directed toward the face of a sample using tubing. A high-speed camera (Phantom v711) with a high-magnification lens (Canon MP-E 1−5X) was used to measure an unperturbed fog stream velocity of \( v_0 = 0.15 \) m/s, with an average fog droplet radius of \( r_{avg} = 7 \) μm. The inner diameter of the tubing was 2.2 cm, similar to the width of the exposed wire array. This way, the entire fog stream was directed toward the face of the exposed wires, which enables an estimation of the water capture efficiency of the fog harvester.

The fog stream was not turned on until the chamber reached a uniform 100% humidity, to prevent the formation of any condensation that would interfere with the fog-harvesting measurements. Note that the humidifier used to maintain 100% humidity throughout the chamber was separate from the second humidifier used to produce the local fog stream. The humidity chamber contained small holes to ensure that consistent and steady-state fog-harvesting rates were obtained (Figure S3). To obtain movies of captured droplets growing and sliding down the fog harvesters, a digital camera (Nikon D5300) was placed on the same side of the sample as the incoming fog stream, and sliding down the fog harvesters, a digital camera (Nikon D5300) obtained (Figure S3). To obtain movies of captured droplets growing to focus solely on the fog-harvesting performance of the wires.

RESULTS AND DISCUSSION

Figure 1 illustrates the concept of our fog harp design, see the Experimental Section and Figure S4 for detailed information. In contrast to conventional mesh netting, which is comprised of both vertically and horizontally oriented wires, our fog harp is comprised solely of vertical wires that are held under tension within a supporting frame. It should be noted that some older field studies also utilized a harp geometry to collect fog samples.29−31 However, these field studies did not vary the size of the wires, characterize the dynamics of droplet shedding, or directly compare harvesting rates to equivalent mesh collectors. Here, our unique focus is to systematically vary the geometry of both harps and meshes under controlled laboratory conditions to gain a mechanistic understanding of how harps enhance the fog-harvesting dynamics. To accomplish this, we fabricated several different miniature harp prototypes exhibiting different wire diameters but the same pitch-to-diameter ratio, analogous to a recent study using conventional meshes.

Specifically, three different wire diameters were used: \( D = 254 \) μm spring steel wire (harp 1), \( D = 508 \) μm aluminum wire (harp 2), and \( D = 1.30 \) mm aluminum wire (harp 3). The pitch (i.e., center-to-center separation) between adjacent wires on the same row was designed to be exactly \( P = 2D \) for each harp, although for harp 3, the pitch did vary slightly across the sample due to difficulty in threading the larger wire. This resulted in a shade coefficient of \( SC = 0.5 \) for all three harps. To serve as a control, three different steel meshes were purchased with near-equivalent dimensions: \( D = 229 \) μm, \( P = 2.2D \), and \( SC = 0.7 \) (mesh 1); \( D = 711 \) μm, \( P = 2.2D \), and \( SC = 0.69 \) (mesh 2); and \( D = 1.60 \) mm, \( P = 2.0D \), and \( SC = 0.75 \) (mesh 3). For simplicity, the three harps will be referred to as H1−H3, whereas the three meshes are M1−M3 (Table 1). No surface functionalization was performed to emphasize the practicality of our fog harvesters. Note that the use of both steel and aluminum materials was purely due to limitations in what was commercially available for the various geometries; however, the surface wettability did not vary significantly (Table 2).

### Table 1. Summary of the Wire Material (Mater.), Wire Diameter (D), Ratio of the Center-to-Center Pitch between Wires to the Wire Diameter (P/D), Shade Coefficient (SC), and Stokes Number (St) for Each of the Harps (H1−H3) and Meshes (M1−M3) Used in This Study

<table>
<thead>
<tr>
<th>mater.</th>
<th>D (mm)</th>
<th>P/D</th>
<th>SC</th>
<th>St</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>steel</td>
<td>0.25</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>M1</td>
<td>steel</td>
<td>0.23</td>
<td>2.2</td>
<td>0.7</td>
</tr>
<tr>
<td>H2</td>
<td>Al</td>
<td>0.51</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>M2</td>
<td>steel</td>
<td>0.71</td>
<td>2.2</td>
<td>0.69</td>
</tr>
<tr>
<td>H3</td>
<td>Al</td>
<td>1.30</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>M3</td>
<td>steel</td>
<td>1.60</td>
<td>2.0</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Table 2. Receding and Advancing Contact Angles (θr/θa) and the Critical Values of the Theoretical Volume (Vc,t), Experimental Volume (Vc,e), and Bond Number for Droplet Sliding to Occur on the Three Fog Harps (H1–H3) and Equivalent Meshes (M1–M3)\(^{44}\)

<table>
<thead>
<tr>
<th></th>
<th>θr (deg)</th>
<th>θa (deg)</th>
<th>Vc,t (μL)</th>
<th>Vc,e (μL)</th>
<th>Bo</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>33 ± 3</td>
<td>51 ± 6</td>
<td>1.3 ± 0.7 (eq 6)</td>
<td>0.81 ± 0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>M1</td>
<td>33 ± 3</td>
<td>51 ± 6</td>
<td>6 ± 3 (eq 7)</td>
<td>4.1 ± 1.5</td>
<td>0.59</td>
</tr>
<tr>
<td>H2</td>
<td>31 ± 4</td>
<td>50 ± 2</td>
<td>2.6 ± 0.8 (eq 6)</td>
<td>1.8 ± 0.7</td>
<td>0.45</td>
</tr>
<tr>
<td>M2</td>
<td>33 ± 3</td>
<td>51 ± 6</td>
<td>5.8 ± 1.5</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>31 ± 4</td>
<td>50 ± 2</td>
<td>3.3 ± 1.0 (eq 5)</td>
<td>2.2 ± 0.5</td>
<td>0.48</td>
</tr>
<tr>
<td>M3</td>
<td>33 ± 3</td>
<td>51 ± 6</td>
<td>3.9 ± 1.6</td>
<td>0.58</td>
<td></td>
</tr>
</tbody>
</table>

Values of contact angles and volumes represent averages of five trials and uncertainty corresponds to ±2 standard deviations.

Figure 2a shows the fog-harvesting rates for each harp and equivalent mesh. For the classical mesh design, the mid-sized mesh (M2) harvested about 70% more water compared to the fine mesh (M1) and 48% more than the coarse mesh (M3). This is due to the aforementioned dual constraints of clogging for fine meshes and inefficient fog capture for coarse meshes. In contrast, the harvesting rate for our fog harps increased monotonically with decreasing feature size due to its unique ability to prevent clogging. Specifically, the fine harp (H1) harvested about 34% more water than the mid-sized harp (H2) and 58% more than the coarse harp (H3).

The harp’s ability to avoid clogging even at small scales is due to the reduced pinning force of droplets shedding parallel to the axis of the wires, compared to a mesh where orthogonal wires impede the contact line. This is somewhat analogous to the well-known case of droplets easily sliding parallel to superhydrophobic grooves, as both cases exhibit only liquid–air interfaces between the axial features and avoid any obstacles orthogonal to the receding contact line. To illustrate the contrast in droplet mobility between harps and meshes, Figure 2b quantifies the number of droplets per minute that were able to slide down a surface to fall into the collector. For all three sizes of wiring, the harp was able to shed more droplets by at least an order of magnitude. For the fine-scale wiring, the rate of droplet shedding was 2 orders of magnitude higher for H1 compared to M1, which explains how the small-scale harp can avoid clogging.

By avoiding the clogging limit, harp H1 harvested over 3 times as much water as mesh M1 (Figure 2a). Even when comparing the mid-sized wires, where the mesh performance was optimal, H2 harvested 40% more water than M2. In short: our harps always collect more water than an equivalent mesh, with the comparative benefit increasing dramatically with decreasing wire diameter. Only fine-scale fog harps can both capture and shed droplets efficiently (Figure 3c), in contrast to coarse harps/meshes, which cannot capture fog efficiently (Figure 3b,d), or fine meshes, which cannot effectively drain the collected water and become clogged (Figure 3a).

The water-harvesting rate is directly correlated with a structure’s overall fog collection efficiency: \( \eta = \eta_h \eta_d \), where \( \eta_h \) is the aerodynamic efficiency of the wind stream and \( \eta_d \) is the deposition efficiency of fog droplets shed in the wind passing through the wires. A previous work modeled \( \eta_d \) by relating the drag of the wire structure to the resulting decrease in velocity of the wind passing through. By conservation of mass, the cross-sectional area of the wind upstream that will pass through the structure continually decreases with increasing drag, which would diminish the amount of fog heading toward the harvester. This can be expressed analytically as

\[
\eta_d = \frac{SC}{1 + (C_0/C_d)^{1/2}}
\]

where \( C_0 \) is the pressure drop coefficient of the harp/mesh and \( C_d \) is the drag coefficient for an equivalently shaped plate that is impermeable. For fog harvesters where the total width and height are comparable to each other, \( C_d \approx 1.18 \). For metal wires

\[
C_0 = k_{re} \left[ 1.3SC + \left( \frac{SC}{1 - SC} \right)^2 \right]
\]

where \( k_{re} \) is an empirical correction factor (see Figure S6) required when \( Re = \rho_D v_0 D/\mu_D < 400 \), where \( \rho_D \) and \( \mu_D \) are the density and viscosity of air, respectively. The local maximum in aerodynamic efficiency occurs for \( SC \approx 0.55 \), which informed our design choice of \( P/D = 2 \) for our fog harps used here (i.e., \( SC = 0.5 \)).

The deposition efficiency depends upon the Stokes number, which compares the response time of suspended fog droplets to that of their streamlines getting perturbed by the wires. In other words, larger values of \( St \) result in more droplets impacting the wires of a harvester, whereas smaller values result in more droplets flowing around the wires. Algebraically
where \( \rho_{\text{water}} \) is the density of water and \( R_{\text{wire}} \) is the wire radius. The numerical values of \( St \) are listed in Table 1 for each harp and mesh. The deposition efficiency is a direct function of the Stokes number

\[
\eta_d = \frac{St}{St + \pi/2}
\]

To make generalized remarks about the theoretical collection efficiency of fog harps, we assign typical real-world conditions of \( r_{\text{fog}} = 5 \mu m \) and \( v_0 = 6 \text{ m/s} \) to the above model. The calculated values of \( \eta_a, \eta_d \), and \( \eta = \eta_a \eta_d \) are then plotted against the main design parameter of interest: \( R_{\text{wire}} \) for a fixed SC = 0.5 (Figure 4). It can be seen that \( \eta_a \) only decreases by about 2% as the wire size decreases from \( R_{\text{wire}} \sim 1 \text{ mm} \) to \( R_{\text{wire}} \sim 100 \mu m \), whereas \( \eta_d \) increases by nearly 40%. Continuing to decrease, \( R_{\text{wire}} \) beneath 100 \( \mu m \) results in slight decreases in \( \eta_a \) that mostly cancel out increases in \( \eta_d \). Thus, as the wire size decreases from \( R_{\text{wire}} \sim 1 \text{ mm} \) to \( R_{\text{wire}} \sim 100 \mu m \), the overall capture efficiency increases from \( \eta \approx 12\% \) to plateau at a performance ceiling of \( \eta \approx 20\% \).

This increase in \( \eta \) by a factor of 1.7 with decreasing wire size is in good agreement with our experimental results, where harp H1 harvested 1.6 times the water collected by harp H3. The actual value of the experimentally measured collection efficiency is a direct function of the Stokes number

\[
St = \frac{2 \rho_{\text{water}} v_0^2}{\eta_{\text{air}} R_{\text{wire}}}
\]

Figure 3. Photographs and corresponding illustrations (inset) that encapsulate the performance of each type of fog harvester. (a) Fine-scale meshes (M1) become almost entirely clogged with water, disrupting the aerodynamics of the fog stream. (b) Large-scale meshes (M3) are only partially clogged, but are not able to catch a large percentage of the micrometric fog droplets. (c) Small-scale harps (H1) avoid the constraints of the other systems: they can both capture and drain fog efficiently for maximal performance. (d) Large-scale harps (H3) can still drain water effectively, but suffer from an inefficient capture rate analogous to large meshes. See Figure S5 and Movies S1 and S2 for the dynamics of droplet shedding.

Figure 4. Theoretical model for the aerodynamic efficiency (\( \eta_a \), eq 1), droplet deposition efficiency (\( \eta_d \), eq 4), and total efficiency (\( \eta = \eta_a \eta_d \)) of fog harps as a function of wire radius for a fixed shade coefficient (SC = 0.5). In the absence of appreciable clogging, \( \eta \) increases by a factor of 1.7 as the wire radius shrinks from \( R_{\text{wire}} \sim 1 \text{ mm} \) to \( R_{\text{wire}} \sim 100 \mu m \). A performance ceiling is then reached with no significant increase in \( \eta \) with further shrinking of the wires due to \( \eta_d \) nearing 100% efficiency by \( R_{\text{wire}} \sim 100 \mu m \).
efficiency for H1 was about $\eta \approx 15\%$ (Figure S7), somewhat less than the $\eta \approx 20\%$ predicted by the model. This is readily explained by the slower wind speed of our scale-model laboratory system ($v_0 = 0.15\, \text{m/s}$), which resulted in smaller Stokes numbers of $St \sim 0.1$ (Table 1) compared to the assumed real-world conditions of $v_0 = 6\, \text{m/s}$ and $St \sim 1$–10. Finally, note that this explicit model only has high fidelity for fog harvesters that have negligible clogging, i.e., the fog harps. For the meshes tested here, clogging issues dramatically hampered the aerodynamics of the system; for example, the collection efficiency of the heavily clogged mesh M1 was only $\eta \approx 5\%$. This is consistent with a previous report that measured experimental values of $\eta$ for microscale meshes that were far beneath their predicted values due to clogging.  

The effective drainage of droplets down fog harps can be quantified using a contact angle hysteresis model. As demonstrated by Kawasaki, Furmidge, and many follow-up reports, the pinning force is caused by contact angle hysteresis and acts along the receding contact line.  

A droplet on a single wire can either engulf the wire in a barrel state or rest on one side; for harp H3, we observed the latter behavior (Figure 3d). The receding contact line would therefore have a length of approximately $\pi R_{wire}$. Hence, the theoretical critical volume ($V_{c,t}$) required for a droplet to slide down the wire may be approximated as

$$V_{c,t} \approx \pi R_{wire}^2 (\cos \theta_i - \cos \theta_f)$$  

where $\gamma$ is surface tension, $g$ is gravity, and $\theta_i$ and $\theta_f$ are the droplet’s receding and advancing contact angles on steel (H1, M1, M2, and M3) or aluminum (H2 and H3) wires. The receding and advancing contact angles were measured from video footage of fog droplets sliding down fog harps, with five trials averaged together for both aluminum and steel wires (Table 2). Plugging in all of these values produced a theoretical critical sliding volume of $V_{c,t} \approx 3.3 \pm 1.0\, \mu\text{L}$.  

The experimental critical volume ($V_{c,e}$) for sliding is not explicitly known, but can be estimated from its observed geometry. The volume of a droplet sliding down one side of a single vertical wire may be approximated as the sum of a half-cone of height $h$ and base $a$ and a quarter spheroid of equatorial radius $a$ and polar radius $c$ (Figure 5a). Provided that $a < (P - R_{wire})$, it follows that a droplet will slide down the harp on a single wire without touching any other wires. This was indeed the case for H3, where $P - R_{wire} = 1.94\, \text{mm}$ was greater than $a \approx 0.9\, \text{mm}$. Measurements of $h$, $a$, and $c$ for five different videos of a droplet beginning to slide down a wire yielded an average $V_{c,e} \approx 2.2 \pm 0.5\, \mu\text{L}$, in good agreement with $V_{c,e} \approx 3.3 \pm 1.0\, \mu\text{L}$ from eq 5 given the geometrical simplifications.

For harps H1 and H2, $a > (P - R_{wire})$, such that the droplet will touch a second wire before sliding, which transforms the water into a column shape (Figure 5b). For a water column growing between a pair of wires, the critical departure size is now found as

$$V_{c,t} \approx 2\pi R_{wire}^2 (\cos \theta_i - \cos \theta_f)$$  

where the extra factor of 2 on the right-hand side accounts for the dual receding contact lines that run along the inner half of each wire circumference. Equation 6 results in $V_{c,t} \approx 2.6 \pm 0.8$ and $1.3 \pm 0.7\, \mu\text{L}$ for H2 and H1, respectively. Although the experimental values of $V_{c,e}$ were not explicitly known, they were estimated by measuring the height ($h$) and width ($w$) of five trials of sliding water columns and assuming a cuboid shape: $V = hwD$. The averaged experimental values of $V_{c,e}$ were $1.8 \pm 0.7\, \mu\text{L}$ for H2 and $V_{c,e} \approx 0.81 \pm 0.34\, \mu\text{L}$ for H1, respectively, were a good match with their theoretical counterparts (Table 2). Although the values of $V_{c,e}$ are consistently larger than $V_{c,t}$ by a small margin, this is typical of the simplified Furmidge model used here to model the contact angle hysteresis. More complex models, which take into account the curvature of the receding contact line and the deformation of the droplet shape, have been used to resolve this overestimation of $V_{c,e}$ but at the cost of simplicity.

Most importantly, both the model and the experiments predict that the critical droplet volume is proportional to the wire size for harps. This explains why the fog harps can actually shed water more efficiently at finer scales to avoid clogging. This can be further quantified by considering the critical Bond number of shedding droplets, $Bo_c = V_{c,t}/L_{cap}$, where $L_{cap} = \sqrt{\gamma/(\rho g)} = 2.7\, \text{mm}$ is the capillary length scale of water. The Bond number compares the forces of gravity and surface tension and decreased from $Bo_c = 0.48$ to 0.34 when comparing H3 to H1, but remained relatively unchanged at $Bo_c \approx 0.6$ for the three meshes (Table 2). In other words, decreasing the wire size of fog harps enables the droplets to shed at length scales far beneath that of the capillary length, which is not possible for traditional structures such as meshes.

This physical model for droplets sliding down fog harps is summarized in Figure 6. The theoretical critical droplet size for sliding down the side of a single wire is predicted as a function of the wire radius (eq 5) for given values of $\theta_i$ and $\theta_f$ in Figure 6a. The different data series represent the various surface materials, with the aluminum (orange line) and steel (green) virtually overlapping due to their similar wettability. The only experimental case of single-wire sliding, aluminum harp H3, is also added to this graph with an excellent agreement to the theory line. The same analysis is repeated in Figure 6b for the case of two-wire sliding, where data points representing $V_{c,t}$ for steel harp H1 and aluminum harp H2 fall along the theoretical lines (eq 6). This model can also be used to confirm that the enhancement in the performance of H2 versus M2 is not due to their moderate ($\approx 33\%$) difference in wire diameter (cf. Table 1), even when hypothetically using an equivalent $D = 0.71\, \text{mm}$ for H2, its $V_{c,t}$ is twice as small as $V_{c,t}$ for M2. For both plots, a third theoretical line (red) represents the hypothetical case of superhydrophobic wires, of surface wettability $\theta_i = 160^\circ$ and $\theta_f = 165^\circ$. For any given value of $R_{wire}$, the superhydrophobic wires reduced $V_{c,t}$ by a factor of 8 compared to the uncoated wires, illustrating that reducing the contact angle hysteresis is an
additional strategy (besides reducing the wire size) for maximizing droplet shedding. Experimental tests of superhydrophobic fog harps were outside the scope of this initial study, which focused on the more practical case of the uncoated, hydrophilic wires. Given that our untreated fog harps do not exhibit any appreciable clogging, it is unclear whether this hypothetical 8-fold reduction in shedding volume for superhydrophobic wires would even increase the water-harvesting efficiency ($\eta$) by a significant amount, as the aerodynamics of our harp H1 are already near-optimal.

Modeling the hysteresis of droplets sliding down the mesh structures is significantly more complex due to the presence of the intersecting horizontal wires and the tendency of the water to partially or fully clog the holes. When observing fog collecting on the surfaces M2 or M3, it was seen that the droplets only partially clog individual holes in the mesh before shedding. Further, the shedding events themselves followed a tortuous path along the mesh and often involved chain reactions between water in adjacent holes. Therefore, any analytical model for M2 or M3 is beyond the scope of this present work, and we simply refer to the experimental values of $V_{c,e}$ in Table 2.

For the fine-scale mesh M1, the holes were uniformly clogged and the shedding dynamics of a droplet were more simple. It was observed that each shedding droplet was much larger than any individual hole size, such that the droplet’s receding contact line extended horizontally along a single wire (Figure 5c). It follows that the critical droplet volume scales as

$$V_{c,t} \approx \frac{\rho_{\text{water}} g \omega (\cos \theta \_l - \cos \theta \_a)}{w h D} \approx 4.1 \pm 1.5 \mu L.$$  

where $w$ is the width of the receding contact line along a horizontal wire and had to be measured to predict $V_{c,t} \approx 6 \pm 3 \mu L$. By measuring both the width ($w$) and height ($h$) of five droplets sliding down the clogged mesh, the experimental critical volume was found by assuming a cuboid shape: $V_{c,e} \approx h w D \approx 4.1 \pm 1.5 \mu L$. Looking at Table 2, it is apparent that sliding droplets on the mesh structure do not seem to get any smaller with decreasing wire size (unlike harps), which causes the clogging issue. Note that the sliding droplets on harp H1 were smaller than with mesh M1 by a factor of 5.

Finally, we demonstrated the scalability of our fog harp by creating a large, 1 m$^2$ model. This full-scale prototype was made with common wood 2×4s, threaded rods, and the same 254 μm diameter steel wire used for harp H1. The harp frame was 101.6 cm long with four 91 cm long threaded rods spanning between the wooden frame (Figure 7). One set of holes drilled into the wood were routed into slots, so one rod could be moved to tighten the wires if they became loose. This square frame structure enabled the wires to be wrapped around the threaded rods to create the parallel wire geometry analogous to the smaller fog harps tested in the laboratory. Threaded rods were used because they provided grooves into which the wires would remain in place at a consistent pitch.

After initial tests of manually wiring the harp by wrapping the stainless steel wire around the rods in loops, we devised a more automated system to expedite the wiring process. We calculated

$$V_{c,t} \approx \frac{\rho_{\text{water}} g \omega (\cos \theta \_l - \cos \theta \_a)}{w h D} \approx 4.1 \pm 1.5 \mu L.$$  

Figure 6. Scaling models that predict the critical departure volume for droplets sliding down (a) single wires (eq 5) and (b) between two wires (eq 6). Each data series represents a different surface wettability, including aluminum ($\theta \_l / \theta \_a = 31/50^\circ$), steel ($\theta \_l / \theta \_a = 33/51^\circ$), and superhydrophobic ($\theta \_l / \theta \_a = 160/165^\circ$). Data points represent the experimental measurements from the three scale-model fog harps.

Figure 7. (a) Large-scale fog harp wired on a 1 m$^2$ frame. The frame rotates about a central axle for efficient wire winding, see Movie S3. (b) The pitch of the wire is determined by the pitch of the threaded rods.
that a 1 m² harp would require over 700 loops. To accelerate wiring the prototype, we mounted the harp to a stand with an axle and rotated the harp while aligning the wire to the threaded groves of the rods. Mass production could be enabled by robotic weaving technology or traditional textile mill technology. At the edges of a harp constructed with an industrial loom, the wires could be anchored in bands of resin such that the wires could be pulled and tightened on the top and bottom similar to what is already done for mesh netting.

The present study was entirely conducted with untreated metal wires that would be practical for field deployment. Future works could probe how fog harp performance varies with wire wettability or cross-sectional shape. Each of our harps exhibited two rows of wires because this required less dramatic U-bends when threading the wire; however, the vast majority of fog appeared to grow on the front row. It would be interesting in the future to characterize how the number of rows of wires affects the aerodynamics and harvesting rate. Another avenue for follow-up research is to vary the size of the fog droplets or the wind speed to see how the harp’s fog collection efficiency increases with increasing Stokes number. It would also be informative to compare our fog harps against other emerging types of fog harvesters, such as tapered needles/barbs that transport droplets via an asymmetric Laplace pressure.\(^{47-53}\) three-dimensional plant-inspired designs,\(^{54-56}\) or artificial spider webs.\(^{56,57}\) Whereas our wires were under sufficient tension to resist appreciable deformation, it would also be interesting to explore the effects of elastocapillarity\(^{58,59}\) (induced by wind or surface tension) on the fog-harvesting rate. This would seem especially germane for large-scale harps such as the one constructed in Figure 7.

CONCLUSIONS

In conclusion, we have demonstrated that harps comprised of vertical wire arrays can harvest 3 times more fog compared to equivalent mesh netting. The mechanism is the reduced pinning force of droplets sliding unimpeded down the parallel wires of the harp, which enables the efficient drainage of small water droplets even for micrometric wire sizes. Thus, our fog harp design allows for ultrafine-scale wires (~100 µm) that exhibit a maximal fog capture efficiency while also avoiding clogging, in contrast to fine mesh structures, which easily clog and become effectively impermeable to the air currents. Unlike studies that have utilized superhydrophobic meshes to promote droplet shedding, our harp design utilizes untreated metal wires that are durable for practical long-term use. It is our hope that this work will inspire the future development of large-scale fog harps that can effectively harvest fresh water for arid regions.

ASSOCIATED CONTENT

1. Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.7b17488.

Fog harvesting on the three meshes (M1, M2, and M3, respectively) (Movie S2) (MPG)
Winding wire on a rotating large-scale frame to create a practical fog harp prototype (Movie S3) (MPG)

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Notes

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