HARVESTING OF WATER FROM FOG USING SPONGES

by

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2016

Acknowledgements

First of all, I would to like appreciate my supervising professor Dr. Cheng Luo for his support and guidance in my master's study. I have not seen anyone who is working this hard to achieve his/her own career goal and spend a lot of time for his students. As well as outside of the research lab, he inspired me how the engineer should think and approach in the real world. His endless encouragement and patience guided and motivated me to become an independent researcher.

I would like to show my sincere appreciation to my thesis committee member Dr. Hyejin Moon and Dr. Zhen Xue Han, who took the precious time for serving on my thesis and many meaningful advices.

I have enjoyed working with my research lab members. Mr. Mithun Rajaram, Mr. Bharathram Vishweswaran, Mr. Manjarik Mrinal, Mr. Xiang Wang and Mr. Atul Kootathil during my M.S. study. They spared no effort in encourage and help each other as a friend and colleague.

Finally, I would like to dedicate everything to my father Mr. Hyung-sub Lee, my mother, Mrs. Hyung-ja Song and my sister Sunny for their endless love, support, patience and sacrifices they made for giving me a grateful educational opportunities.

April 26, 2016

Abstract

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The University of Texas at Arlington, 2016

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A sponge has porous structures. It is capable of both storing and transmitting water. In this work, we explored the possibility of applying three different types of sponges to collect fog. We also compared their fog-collection efficiencies with that of a typical Raschel mesh that is widely used in the field to collect fog. We found that, for three different fog speeds, the fog-collection efficiencies of three tested sponges were 39% to 93% those of the typical Raschel mesh, indicating that the sponges could serve as alternative fog collectors when well-developed collectors were not available. Sponge 3 has the best performance. Its fog-collection efficiencies were 52% to 93% those of the typical Raschel mesh.

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Chapter 1

Introduction

A water shortage has been a major problem faced by the modern civilization in both arid and humid environments.[1] Many rural areas are still facing severe difficulties in having access to sufficient water supply on regular basis.[2] In an arid environment with little rainfall every year, fog may be an important water source to some desert plants and animals, such as the cactus *Opuntia microdasys*,[3] which originates from Chihuahua Desert, the Namib dune bushman grass *Stipagrostris sabulicola*,[4] the species *Tillandsia landbecki* in coastal Atacama,[5] mesophytic geophytes in Namaqualand and the Little Karoo,[6] and the Namib tenebrionid beetle *Stenocara*.[7,8] A few artificial fog collectors have been recently developed.[7,9-24] Most of them mimic the fog-collection mechanisms of the aforementioned cactus[9-16] and beetle[7,17-21].

Fog is composed of tiny water drops with diameters in the range of 1 to 40 μm. The tiny drops that hit and accumulate on a collector should be quickly drained away to avoid their loss to winds or hot environment.[7] The artificial collectors that have been developed mainly differ in their surface structures or coatings, which are employed to have fast draining of the water drops.[7,9-24] On the other hand, porous structures are capable of both storing and transmitting water. Once water drops are absorbed into the porous structures, their chance of getting lost to winds or hot environment should be much reduced, since these drops are no longer directly exposed to air. A sponge has porous structures. It is also well-known for its property of soaking water. In addition, it is cost-effective. Thus, in this work, we adopt the sponges as testing samples to explore the possibility of applying porous structures to collect fog.

The outline of this paper is as follows. In Section 2, preliminary results and a simple analytical model are given. Experimental results are given and discussed in Section 3. Finally, this work is summarized and concluded in Section 4.

Chapter 2

Preliminary Test and Simple Theoretical Model

2.1 Preliminary test

A preliminary test has been done on a commercially availabe sponge, Trader Joe's pop-up sponge, to understand its response in a foggy environment. Experimental setup is shown in Fig. 1. Each test is conducted at room temperature (24°C ± 1°C). Two humidifiers (model: EE-5301, Crane USA Co., and AOS 7135 Ultrasonic, BONECO USA Co.) are connected to enhance the generation of the mist flow. A plastic pipe is employed to guide this mist flow. A fan (model: Breeze color USB Desktop fan, Arctic USA Co.) is used at 800 rounds per minute to increase the mist flow speed. At the end of the pipe, the mist flow speed is 0.94 m/s, which is measured using a wind speed meter (model: WM- 2 Handheld Weather meter, AmbientWeather USA Co.). The entire process is conducted in a closed chamber. 100% humidity is maintained inside the chamber, and a humidity meter (model: Hydro-Thermometer Humidity Alert with Dew Point-445815, EXTECH USA Co.) is used to monitor the humidity throughout a process cycle. A tested sponge sample with a length of 8.5 cm, a width of 6.0 cm and a thickness of 1.0 cm is placed 5 cm away from the exit of the pipe, and a glass container is put below the sponge to collect water that drains down.

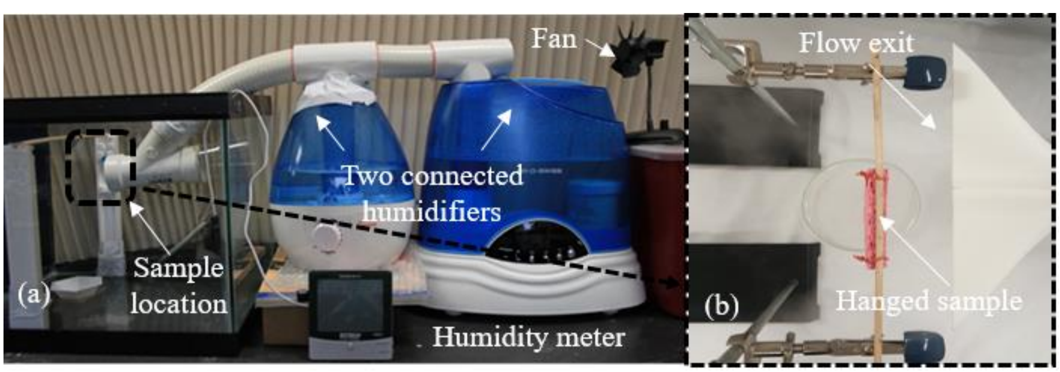

Figure 1: (a) Experimental setup for the water collection and (b) closed-up view of flow exit and sample location.

Four points are observed from testing results. First, once a tiny drop in the mist flow contacted a sponge sample, it was absorbed into the sponge pores (Fig. 2(a1)). Second, in about 30 min, the sample was saturated, and water began to drip down from the bottom of the sponge till the end of the collection period (Figs. 2(a2) and 2(b1)). Third, water did not drain down from the surface of a vertically-placed sponge. Instead, it went through the porous structures inside the sponge. Fourth and finally, after a 2-hr collection period, the amount of water that drained down from the sponge was more than what was stored inside the sponge. 34 mL water was collected from the glass container, which was the amount of water that dripped down from the sponge. Meanwhile, after the fog test, around 29 mL water was stored inside the sponge, which was calculated based on the following equation:

$$V_s = \frac{W_a - W_b}{\rho g}, \tag{1}$$

where V_s is the amount of water stored in the sponge, W_b and W_a stand for, respectively, the weights of a sponge before and after the collection period, ρ denotes water density, and g is gravitational acceleration. However, not all the stored water could be manually squeezed out from the sponge. Only about 20 mL water could be pressed out (Fig. 2(b2)). The amounts of water that dripped and was squeezed out of the sponge were what could be collected. Hence, totally around 54 mL water was harvested during this collection test. These four points provide us a basic understanding about the process to collect fog using a sponge sample.

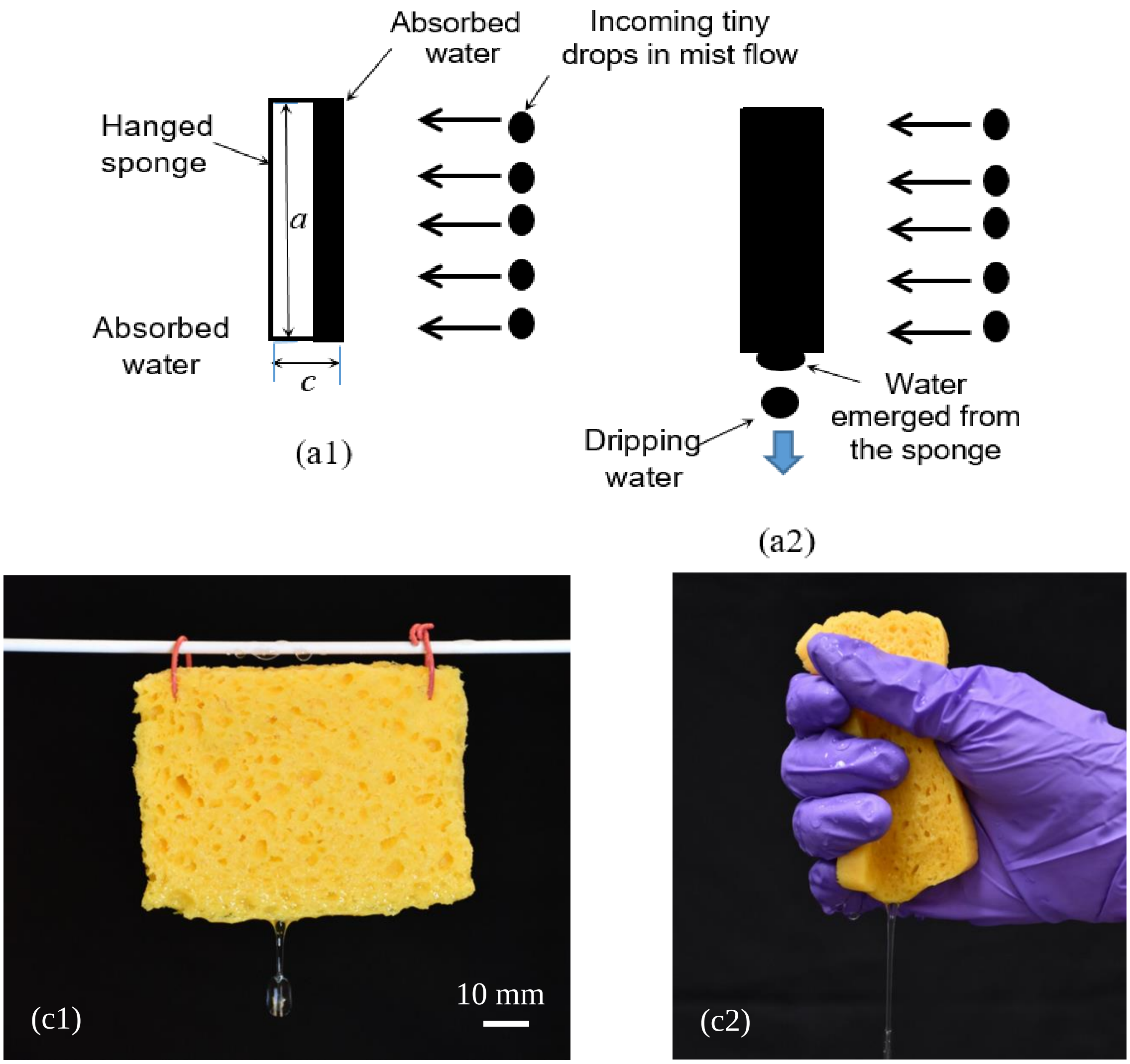

Figure 2: Water collection during the condensation process: (a1) a water drop that hits the sponge surface is absorbed into the sponge to form a film, and (a2) after it is saturated, water first emerges and then drips down from the bottom of the sponge.

2.2 Theoretical Model

Darcy's law is often used to describe the propagation of underground water in a saturated porous structure.[25] It is also applied here to sponges. According to this law, the flow rate at the bottom of a porous structure (*Q*) is linearly proportional to the cross-sectional area of the porous structure (*A*), hydraulic conductivity (*K*), the spreading distance along this structure (*L*), and pressure head difference between the two ends of the structure (*H*) by

$$Q = \frac{AKH}{L} \tag{2}$$

Relation (2) can be re-written as

$$Q = \frac{\beta AKH}{L} \tag{3}$$

where β is a numerical factor that will be determined through experiments. In a normal application of Darcy's law, the surface of a porous medium that receives water supply is fully covered by water, and the corresponding value of β is 1. In our case, the incoming fog drops do not simultaneously cover the whole surface of a sponge. That is, only part of this vertical surface receives water supply. Although this may not affect the scale law expressed in Relation (2), we expect that the numerical factor β is less than 1.

As observed from Eq. (3), *Q* increases with the increase in *K*. *K* is a property of the specimen. It describes the ease with which a fluid can move through pore spaces. *K* generally increases with the increase in, for example, pore size. Since we do not see much difference in the porous structures of a sponge along both horizontal and vertical directions, *K* is considered to have the same values along these two directions.

Let *a*, *b* and *c*, respectively, represent the height, width and thickness of a vertically oriented sponge. After a sponge is saturated, all the pores in the sponge are filled with water.

Pressure head difference between the top and bottom of the sponge is *a*. Meanwhile, *L* also equals *a*, and A is *bc*. Thus, by Eq. (3), we have

$$Q = \beta bcK \tag{4}$$

Set V_d to be the amount of water discharged from the bottom of the sponge during the collection period. Let t_s denote saturation time. In our preliminary tests, we found that there was no water collected before the saturation. Thus, when $t<t_s$, $V_d = 0$. If $t>t_s$, then, by Eq. (4), we get

$$V_d = \beta bcK(t - t_s) \tag{5}$$

As observed from this equation, for a given sponge, fog-collection period, and foggy environment, the amount of water collected depends on *K* and *β*.

Chapter 3

3.1 Tested Samples

In addition to Trader Joe's pop-up sponge, another two types of sponges, O-Cel-O Sponge and Scotch-Brite Heavy Duty Scour Pad, were also tested in this work (Fig. 3). They were purchased in a local grocery store. For simplicity, they are, respectively, referred to as "Sponge 1," "Sponge 2" and "Sponge 3," thereafter. A typical Raschel mesh with the same size was also tested to compare its collection efficiency with those of the sponges (Fig. 4). Sponge 1 includes a 0.1 cm thick rough layer at its bottom. In the preliminary test, this layer was not removed, while it was taken away in the subsequent tests on this sponge.

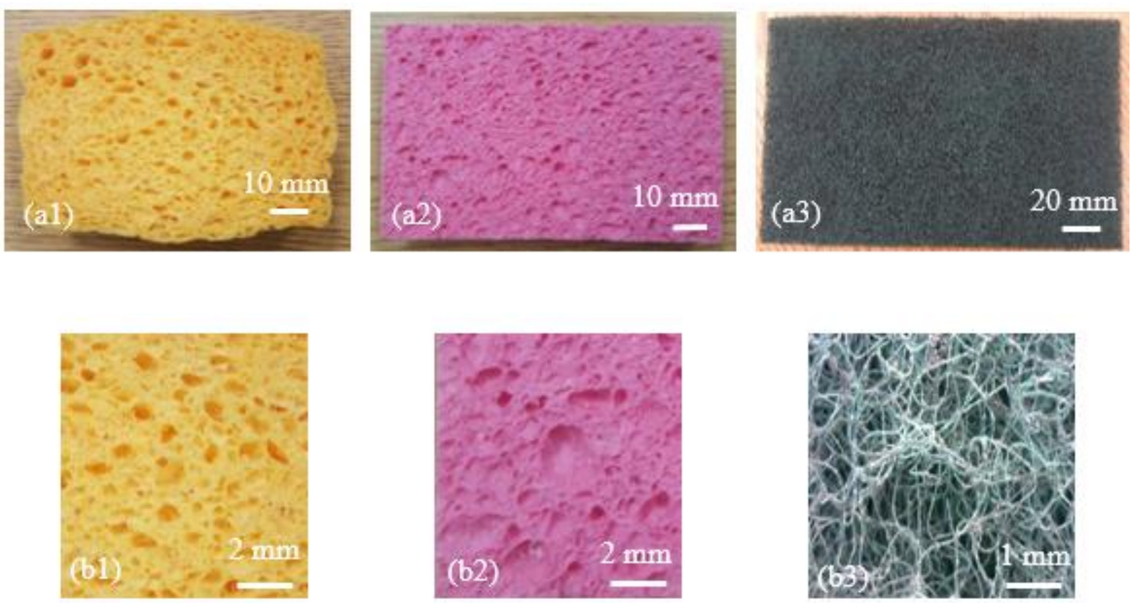

Figure 3: Perspective views of three commercial sponges that were tested in this work: (a1) Trader Joe's pop-up sponge, (a2), O-Cel-O Sponge, and (a3) Scotch-Brite Heavy Duty Scour Pad. (b1)-(b3): Their respective close-up (top) views.

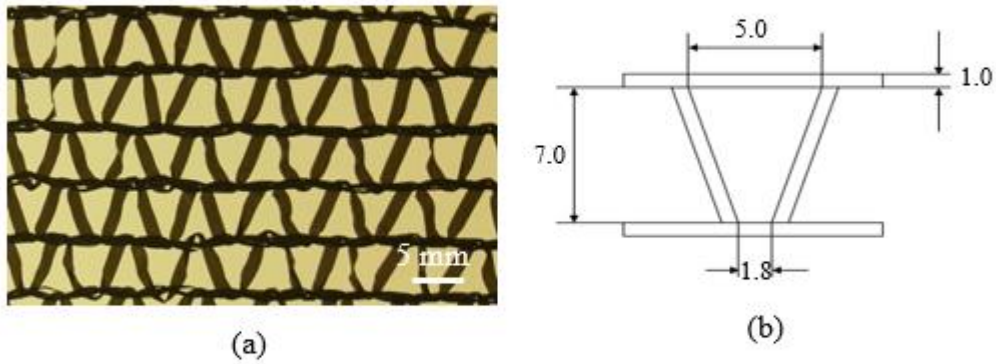

Figure 4: (a) Front view of part of a typical Raschel mesh, and (b) dimensions of its pores and the filament (unit: mm)

Sponges 1 and 2 were made by cellulose fibers, while Sponge 3 by synthetic nylon fibers. Cellulose fibers are made with ether or esters of cellulose, which can be obtained from the bark, wood or leaves of plants, or from a plant-based material.[26] Sponge 3 is originally designed to clean hard and rough surfaces, such as those of grills and ovens.

As shown in Figs. 3(b1)-3(b3), most of pores in Samples 1 and 2 have elliptical shapes, while the pores of Sample 3 have random shapes. For simplicity, the pores were approximated as circular shapes. DinoCapture software was employed to measure the pore sizes and count the number of pores. The corresponding results are given in Table 1. Five points were observed from these results. First, for all the three samples, the pores have large variations in their sizes. Meantime, the size variations in Sponges 1 and 2 are larger than that of Sponge 3. For instance, the smallest and largest pores in Sponge 3 have the radii of 0.3 and 2 mm, respectively, while these sizes range from 0.2 to 5 mm in the case of Sponge 1. Second, Sponge 1 has the smallest number of pores per unit area, while Sponge 3 has the largest number. On average, the three samples have 2.7, 4.4 and 14.7 pores over an area of 1 cm^2. Third, Sponge 3 has the largest planar porosity, while Sponge 1 has the smallest value. These values are 25%, 31% and 48%, respectively, for Sponges 1 to 3. The planar porosity refers to the percentage of the cross-sectional sponge area that the pores occupy. Fourth, Sponge 3 has the largest bulk porosity, while Sponge 1 has the smallest value. These values are 87%, 83% and 82%, respectively, for Samples 1 to 3. The bulk porosity refers to the percentage of sponge volume that is occupied by pore space, and it equals V_S/V, where V represents the volume of a dry sponge. Fifth and finally, Sponge 1 has the largest squeezed-out ratio, which is 81%. This ratio refers to the percentage of stored water that is manually squeezed out of a sponge after the sponge is saturated. The amount of water that is squeezed out is related to both the strength and the way used to squeeze the sponge. Therefore, the measured squeezed-out ratio has a relatively large error, which in our case is 10%. In summary, according to these five points, although Sponge 3 has smaller pores, since its pores are densely distributed, it has more pore space than Sponges 1 and 2.

Table 1: Pore Information

	Radius of a pore (mm)	Number of pores per cm^2	Planar porosity	Bulk porosity	Squeeze out availability
Sponge 1	Average: 1.5	2.7	25%	87%	81%
	Maximum: 5				
	Minimum 0.2				
Sponge 2	Average: 1.2	4.4	31%	83%	80%
	Maximum: 6				
	Minimum: 0.2				
Sponge 3	Average: 0.8	14.7	48%	82%	69%
	Maximum: 2				
	Minimum: 0.3				

For the last two decades, in at least five countries, such as Chile, the most commonly used large fog collector in the field employs a Raschel mesh that is vertically oriented between two poles to collect water from fog.[27-29] The Raschel mesh has meter-scaled lengths and widths, and it also has mm-scaled pores and filaments (Fig. 4a). The pores of a typical Raschel mesh have approximately triangular shapes, and some filaments are inclined with lengths close to 1 cm (Fig. 4b). The filaments are about 20 µm thick, while their joints are 200 to 400 µm thick. The fog collection includes two steps. Tiny drops that are carried in a wind hit and accumulate on the surfaces of the filaments. Under gravity, large drops, which are formed due to the coalescence of the tiny drops, may drain off from the surfaces of the filaments to an underneath gutter. As seen from these two steps, the collection mechanism of a mesh is not exactly the same as that of a sponge. Water drains down from the surface of the mesh, and does not go through its body. Raschel meshes are effective in fog collection. Their fog collection rates are typically 1-10 L/m^2 per day.[29] Also, the presence of light rain with the fog has produced collection rates as high as 300 L/m^2 per day for a wind speed of 10 m/s.[29]

3.2 Determination of *K*

A constant head test was done nine times on each sponges to determine its *K* based on Eq. (4). Since the incoming water fully covers the sample surface in the constant head test, β is set to be 1. This test is often used to find *K* of, for example, sand and gravel in the applications of civil engineering. A permeameter was used in the test (Fig. 5). It had a cylindrical chamber to contain a sample. Sponges were cut into circular pieces to fill the chamber. Water was supplied to the chamber from a reservoir through an inlet located at the bottom of the chamber, and it was discharged through an outlet positioned at the top of the chamber. After the flow had been steady, which also implied that the sample had already been saturated, *Q* was determined according to the amount of discharged water during a certain period of collection. *H* was the height difference between the water level in the reservoir and that at the top of a sponge sample, and *L* was the vertical length of the sample. Subsequently, the value of *K* was calculated using Eq. (4). The corresponding values of *K* for Sponges 1, 2 and 3 were 0.07 cm/s, 0.05 cm/s, and 0.11 cm/s, respectively (Table 2). It appears that *K* is affected by both porosity and pore sizes (Table 1). Sponges 1 and 2 have close values in their porosity and pore sizes. Therefore, they also have close *K* values. Although Sponge 3 has the smallest pore sizes, its porosity is much larger than those of the other two sponges, which may be part of the reason why its *K* is much larger than those of Sponges 1 and 2.

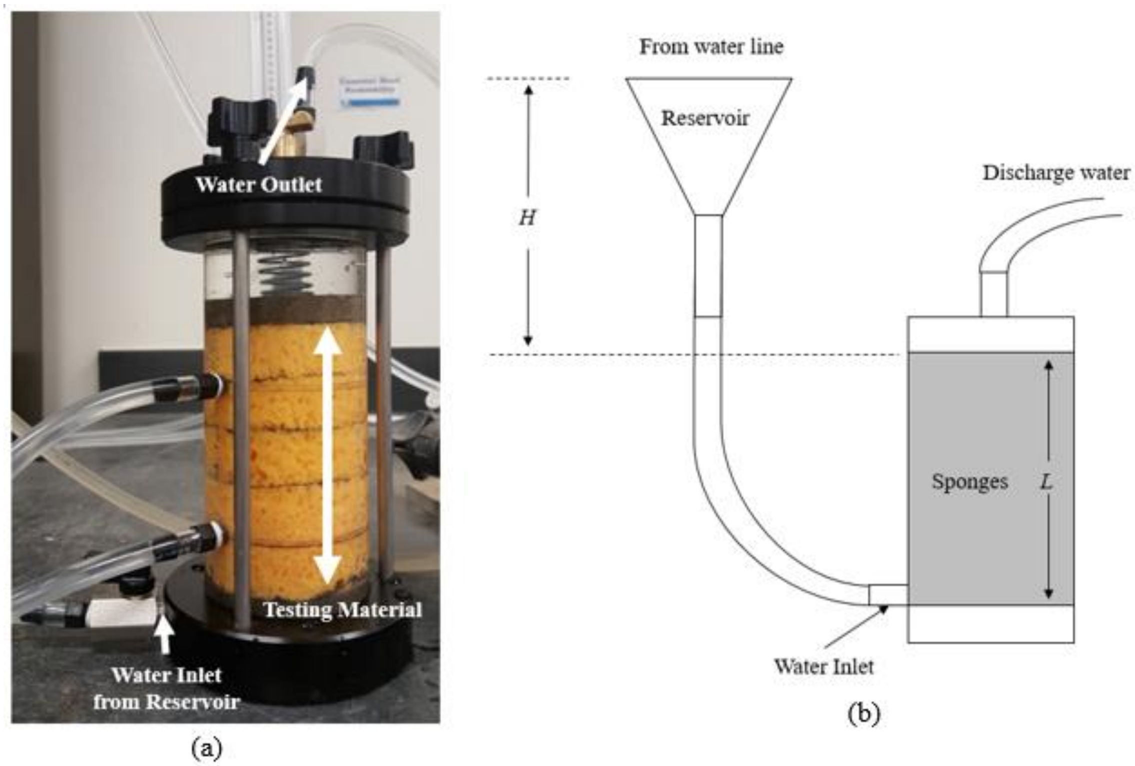

Figure 5: (a) Permeameter used to determine *K* using the constant head test, and (b) its illustration.

Table 2: Information about *K* and *β*.

	K (cm/s)	*β*	Average *β*
Sponge 1	0.07 ± 0.02	At 0.94 m/s: 0.015 At 1.23 m/s: 0.018 At 1.50 m/s: 0.020	0.018
Sponge 2	0.05 ± 0.01	At 0.94 m/s: 0.019 At 1.23 m/s: 0.023 At 1.50 m/s: 0.026	0.023
Sponge 3	0.11 ± 0.03	At 0.94 m/s: 0.028 At 1.23 m/s: 0.033 At 1.50 m/s: 0.037	0.033

When the values of K are over 10^{-1} cm/s, between 10^{-3} and 10^{-1} cm/s, between 10^{-5} and 10^{-3} cm/s, between 10^{-7} and 10^{-5} cm/s, and less than 10^{-7} cm/s, which are corresponding to gravel, sandy gravel, silty sand, silty clay and clay, the degrees of permeability are considered to be high, medium, low, very low, and practically impermeable.[30,31] According to this classification, all the three sponge samples have medium degree of permeability.

3.3 Fog-collection efficiencies

Fog-collection tests were done on the three sponges and Raschel mesh. Each test lasted 2.5 hr. Three different mist flow speeds of 0.94, 1.23, and 1.50 m/s were tested to examine the effect of flow speeds on the fog collection. The experimental setup is similar to the one shown in Fig. 1. The only difference is that these tests were not done in a closed chamber. Instead, they were performed in an open space for easily measuring the amounts of water that were discharged at different time instants during the collection period. The dimensions of the samples are 2.5cm x 2.5cm x 0.9 cm. The testing results are shown in Figs. 6 and 7.

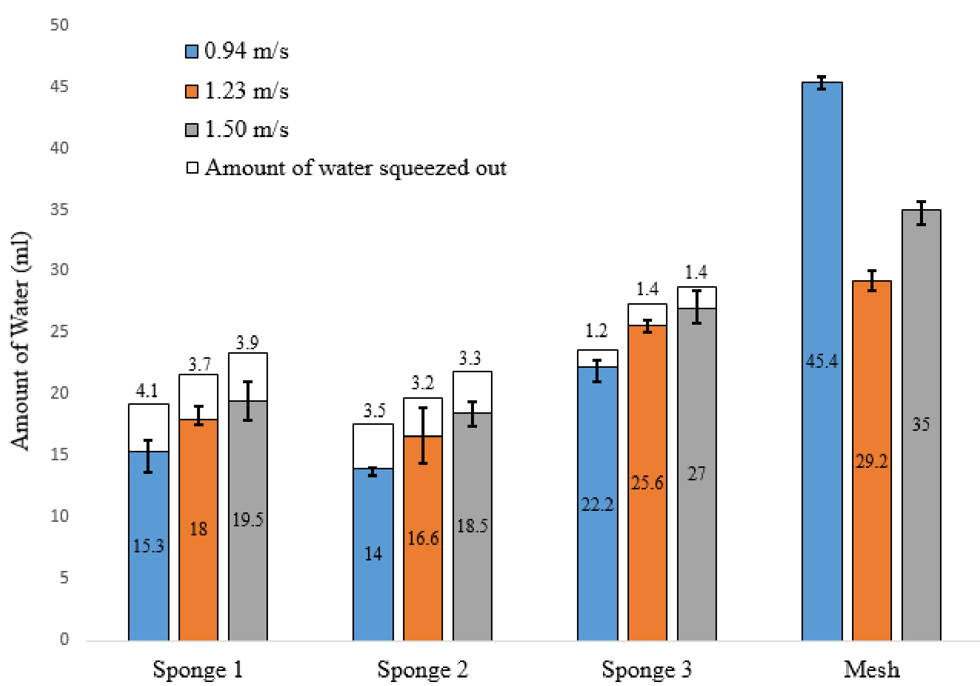

Figure 6: Amounts of water collected for each sample at three different flow speeds.

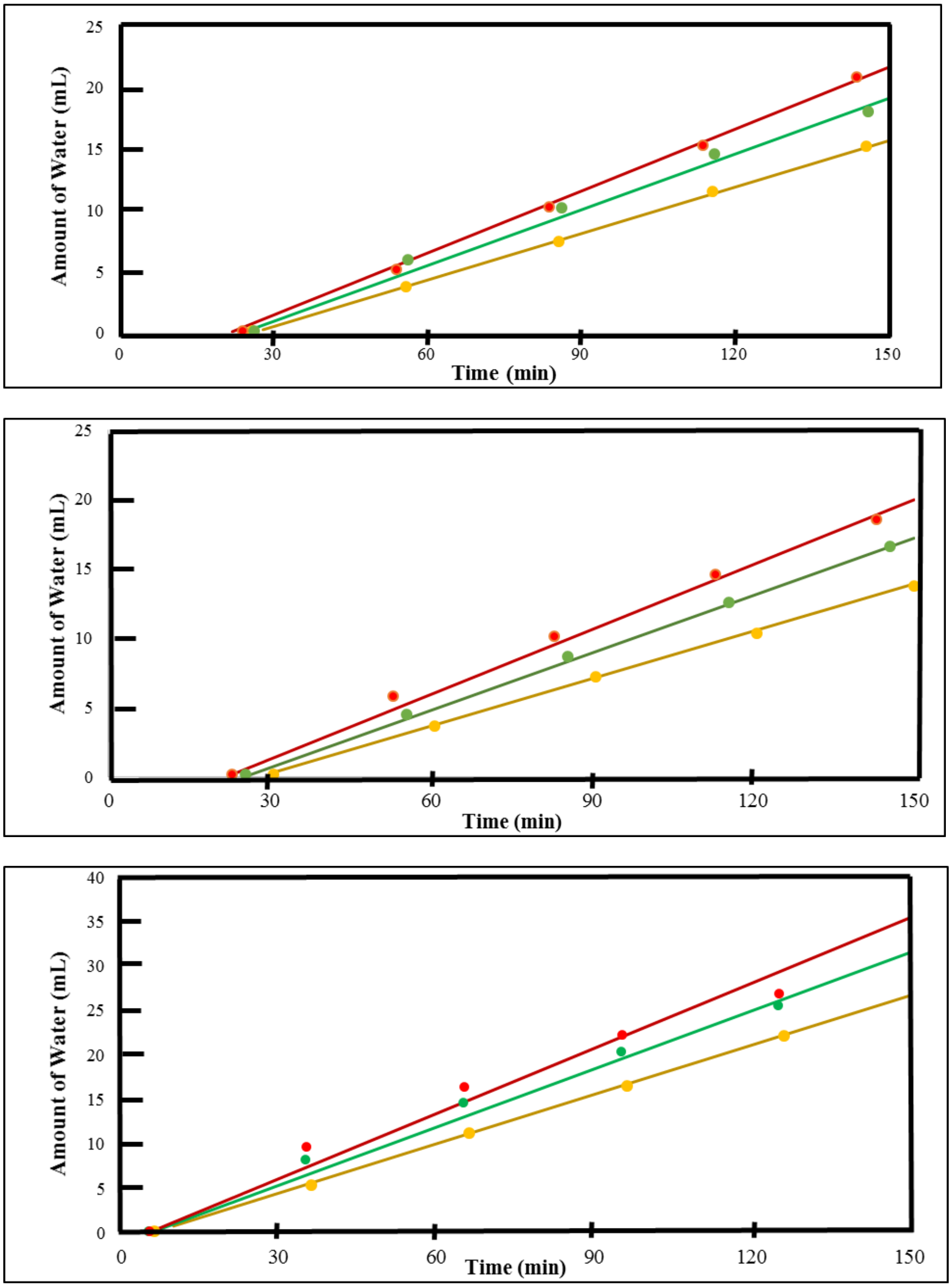

Figure 7: Relations of collected water with time at three different wind speeds: Samples (a) 1, (b) 2 and (c) 3. Lines and scattered points represent the fitted and experimental results, respectively.

Four points are observed from Fig. 6, which are regarding the fog-collection efficiency. First, as expected from the measured values of K, for each flow speed, the amount of collected water, which equals the summation of discharged and squeezed water, increase in the order of Sponges 2, 1 and 3. Compared with Sponge 2, Sponge 3 has 52%, 93% and 81% enhancement in the amounts of collected water, when the flow speeds are 0.94, 1.23, and 1.50 m/s, respectively.

Second, Raschel mesh is the most efficient in collecting water. For example, it collected 45.4 mL at the speed of 0.94 m/s, which was about twice that of Sponge 3. One of the factors that affect the fog-collection efficiency is aerodynamic collection efficiency (η_{ace}). η_{ace} is the fraction of the unperturbed water flux heading towards a fog collector that would collide with the collector. The fog-collection efficiency linearly increases with η_{ace}.[28] The value of η_{ace} is 20% for a typical Raschel mesh,[28] while it is only 9% for a solid plate, which is the case of a sponge. This means that the number of water drops that hit our Raschel mesh sample may be twice that of a sponge. Accordingly, the Raschel mesh should be more efficient in fog collection.

Third, compared with a Raschel mesh, a sponge is still capable of harvesting a certain amount of water. For instance, even for Sponge 2, which had the lowest collection efficiency, it was able to collect at least 39% of the amount of water that the mesh collected. This occurred when the flow speed was 0.94 m/s. When the speed was 1.23 m/s, the amount of water that Sponge 3 collected was 93% of that of the mesh.

Fourth, and finally, for each sponge sample, the water that dripped down increased with the increase in the flow speed. For instance, the amount of water that was discharged from Sponge 3 increased from 22.2 to 27 mL when the speed was changed from 0.94 to 1.50 m/s. It is considered that the higher speed resulted in more water supply to a sponge sample. However, in the case of the mesh, the amount of collected water did not increase with the increase in flow speed. The largest amount of water, which was 45.4 mL, was collected at the speed of 0.94 m/s, while less amounts of water were collected at the other two higher speeds. It is not clear what has caused this to happen, which will be left to a future investigation.

3.4 Amount of water collected with time

As observed from Fig. 7, the amount of water collected from each sponge sample increased in an approximately linear manner with time, which agrees with what was predicted using Eq. (5). Subsequently, we determined the values of β by fitting the experimental data using this equation (Table 2). We found that Curve fitting Fig. 7 to get β for Sponges 1, 2 and 3.

3.5 Effect of fibers on fog collection

It is also noted from Fig. 7 that the time for water to start dripping from Sponge 3 was shorter than those of Sponges 1 and 2. It took 25 and 30 minutes for Sponge 1 and 2 for this to happen, while only 5 min in the case of Sponge 3. When water started to drip, Sponges 1 and 2 were all soaked wet, while Sponge 3 did not get to wet all the way through its thickness.

The corresponding reason behind these differences is given as follows. The cellulose fibers of Sponges 1 and 2 are giant molecules that consist of many small molecules linked together.[26, 32] Most of these small molecules are sugar molecules, which have the opposite polarity of water. When the cellulose is wet, the positive ends of the water molecules are attracted to the negative ends of the sugar molecules. These chemical bonds make water easy to spread along the cellulose fibers. Meanwhile, they also increase the difficulty of releasing water from the pore structures. In contrast, Sponge 3 is made of nylon fibers. These fibers do not form chemical bonds with water molecules. Consequently, although they do not absorb water as fast as cellulose fibers, the corresponding sponge has less resistance to water flow, resulting in quicker draining of water under gravity. It is expected that these different wetting properties between cellulose and nylon fibers are also part of the reason why Sponge 3 has a much higher value of K than Sponges 1 and 2.

Chapter 4

Summary and conclusions

In this work, we have explored the possibility of applying sponges to collect fog. Five critical points have been found during the exploration. First, water drops are easily absorbed into a sponge. Second, the water that is absorbed into a vertically-oriented sponge mainly drains down through the porous structures inside the sponge. Third, the majority of water that is absorbed into the sponge is transmitted, and only a minor portion is stored in the sponge. Fourth, in comparison with cellulose fibers, nylon fibers have less resistance to the transmission of water, and the corresponding sponge is more efficient in collecting fog. Fifth and finally, although our tested sponges have not collected as much water as a Raschel mesh, their fog-collection efficiencies were at least 39% that of a Raschel mesh, and they may be as high as 93% depending on the wind speed.

These five points indicate that, based on a new collection mechanism, a sponge is capable of harvesting a certain amount of water from fog. In comparison with existing artificial collectors, which require much effort to fabricate critical fog-collecting components, such as conical wires[9-16] and microstructures[7, 17-21], a sponge has a distinctive advantage that it is available for fog collection without much fabrication effort.

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