An Experimental Study of the Collection of Fog Droplets Using a Mesh Fabric: Possible Application to Cooling Towers

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An experimental study is presented of the ability of fine meshes to remove fog drops from an air flow. Specifically, the collection efficiency (CE) was measured for fog drops passing through mesh fabrics. Meshes composed of cotton, nylon, and Teflon were investigated, and the effect of the material as well as mesh porosity was determined. Collection efficiencies ranging from 5% to 50% were obtained. The ultimate goal of this work is to employ such meshes in a parachute configuration above power plant cooling towers, so that condensed fog may be collected and returned to the cooling loop. It is shown that the drop diameters and velocities investigated here are similar to those observed above cooling towers. [DOI: 10.1115/1.4031969]

1 Introduction

Growing strains on water resources due to economic and population growth have motivated the search for ways to reduce water use across all industrial sectors. One sector where significant savings can be attained is thermoelectric power generation which accounted for 41% of all U.S. freshwater withdrawals in 2005 [1]. In spite of their recirculating nature, cooling towers used in such generation consume significant quantities of water due to large evaporative loss [2]. For example, using data compiled by the USGS it can be shown that a 1000 MW power plant using cooling towers has an evaporative loss that may range from 10,000 to 20,000 gpm [1,3]. Accordingly, reducing evaporative loss from cooling towers could significantly reduce freshwater usage. Of course, eliminating evaporation is undesirable since this is the primary means by which cooling towers reject waste heat. However, it is often the case that evaporated water is recondensed above the cooling tower, as is evidenced by the dense fog plumes that are often seen above these structures. In these situations, the atmosphere does the work of condensation, and reduction in water use could be enabled if there was a method to collect the fog drops. We have developed the idea of a "collection parachute," wherein the condensed drops in the fog plume emanating from a cooling tower are collected by a mesh located above, and tethered to, a cooling tower. The orientation of the parachute would be maintained by the buoyancy of the upward directed plume, while simultaneously removing fog drops from that plume. Such an approach has not been attempted to the best of our knowledge. Herein, we experimentally test the ability of a fine mesh to filter out fog drops, a first step in demonstrating the viability of such a technology.

We note that technologies similar to what is presented here are mist eliminators which are used to remove spray drops from cooling tower outflows [4–6] and fog collectors which are used to obtain potable water from naturally occurring fog. [7–10]. Both technologies differ from that considered here.

2 Experimental Method

The primary goal of these experiments was to determine the CE and pressure drop as a function of porosity for meshes that are readily available and that could conceivably be used in a collection parachute. The CE is defined as

$$\mathrm{CE} = \frac{m_c}{m_T} \tag{1}$$

where m_c is the mass of liquid water collected by the mesh and m_T is the total mass of liquid water that passes through the mesh. The overall approach was to use salt water and apply conservation of mass on the salt to determine how much water was collected by the mesh versus that which passed through the mesh.

Figure 1 shows that the experimental setup consists of the drop generation container (1) that contains three ultrasonic fog generators (Little Giant FG-1-PW), which created the fog. The container held a salt water solution having a volume of 1500 ml at the beginning of each experiment. The mass of salt used to create the solution was measured using an analytical balance (Scientech ZSA 210, resolution of 0.0001 g). Typically, 14 g of salt was added to this, giving a salinity of 9.33 ppt. The fog was pushed out of the drop generation container using a flow of humid, room temperature air which came from the humid air generator shown in Fig. 2 and consisted of an Erlenmeyer flask filled with water, a rubber stopper to create a seal, and a glass frit in the water through which house air flowed creating a fine bubble plume. The air left the flask at ~95% relative humidity minimizing evaporation of the drops once they were formed. Other than the single inlet and outlet, the drop generation container was air tight. The fog flowed out of the drop generation container through the outlet tubing (2) and through the collection mesh which was tightly fitted over the exit of the outlet tubing. The fog drops which were collected by the collection mesh combined to form large drops which dripped into a graduated cylinder beneath the mesh. Each experiment lasted 5 min.

The CE defined in Eq. (1) was computed as

$$\mathrm{CE} = \frac{M_3}{M_1 - M_2} \tag{2}$$

where M_1 is the mass of salt that left the drop generation container, M_2 is the mass of salt deposited in the outlet tubing, and M_3 is the mass of salt collected by the collection mesh. The mass of salt that left the container, M_1, was calculated by pouring what remained of the salt water solution from the container into an

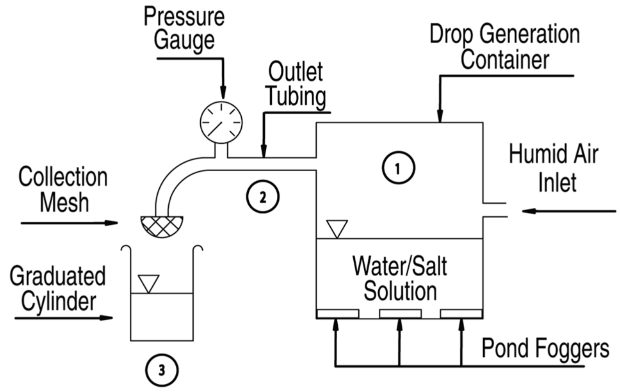

Fig. 1 Experimental setup

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Contributed by the Advanced Energy Systems Division of ASME for publication in the JOURNAL OF ENERGY RESOURCES TECHNOLOGY. Manuscript received July 23, 2015; final manuscript received October 10, 2015; published online December 1, 2015. Assoc. Editor: Mohamed A. Habib.

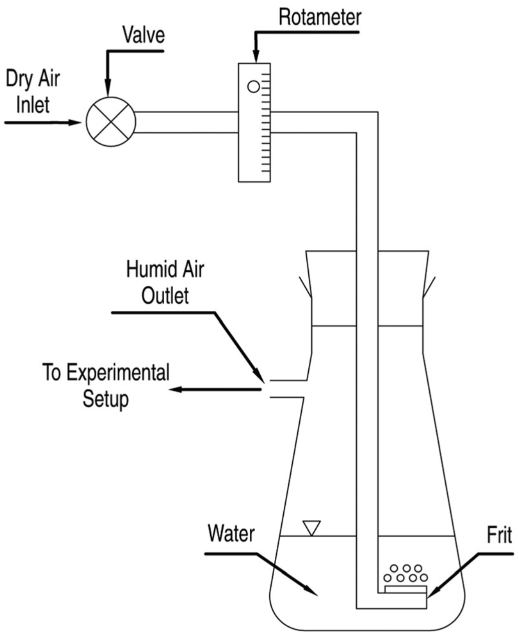

Fig. 2 Humid air generator

accurate 2-l volumetric flask at the end of the experiment. Water was gently sprayed over the inner walls of the drop generation container and then poured into the volumetric flask. This was repeated several times to ensure that all salt was removed from the drop generation container. Once this was complete, additional water was added until the water level in the volumetric flask precisely lined up with the 2-l mark. The measurement resolution obtained in this fashion is estimated to be 0.1 ml. The salinity of the resulting solution in the 2-l volumetric flask was then measured using a salinity meter (Extech EC170, 0.01 ppt resolution, accuracy $\pm$ 1.0% of full scale), which was placed in the solution for 15 min while stirring (per manufacturer's instructions). The salinity meter was calibrated before each set of runs. The measured salinity multiplied by the 2-l volume of the water gave the mass of salt remaining in the drop generation container at the end of the experiment. Subtracting this number from the measured mass of salt that was used to create the salt water solution gave the mass of salt that left the container, M_1.

The mass of salt that was deposited on the outlet tubing, M_2, was determined by capping the end of the tube and filling the tubing with water. A process similar to that described above for the drop generation container was followed. Finally, the mass of the salt that was collected by the collection mesh was determined by removing the collection mesh and placing it in the graduated cylinder that was used to collect the water which had dripped from the mesh during the course of the experiment. Again, the salinity of the resulting solution was measured and multiplied by its volume to give the mass of salt collected by the collection parachute, M_3. The resulting M_1, M_2, and M_3 were inserted in Eq. (2) to give CE.

The air flow rate through the apparatus was 75 lpm for all experiments as measured by a rotameter (Dwyer) located just upstream of the humid air generator (Fig. 2); this corresponded to a velocity of 2.47 m/s through the collection mesh. The pressure drop across the collection mesh was measured using a Fluke 700 G02 pressure gauge located just upstream of the mesh.

The porosity ϕ of each mesh was obtained from the digital images of the mesh, which were transformed into a black and white image using a thresholding algorithm. Figure 3 presents sample images for each of the three materials used here: nylon, cotton, and Teflon, and the corresponding thresholded images are presented in Fig. 4. Porosity is defined as

$$\phi = \frac{n_v}{n_t} \tag{3}$$

where n_v is the number of void pixels and n_t is the total number of pixels, void plus fiber. In addition to using meshes of different porosities, ϕ was varied by stacking multiple meshes (1, 2, 4, or 6 meshes) together. Five experiments were conducted for each porosity/mesh material investigated.

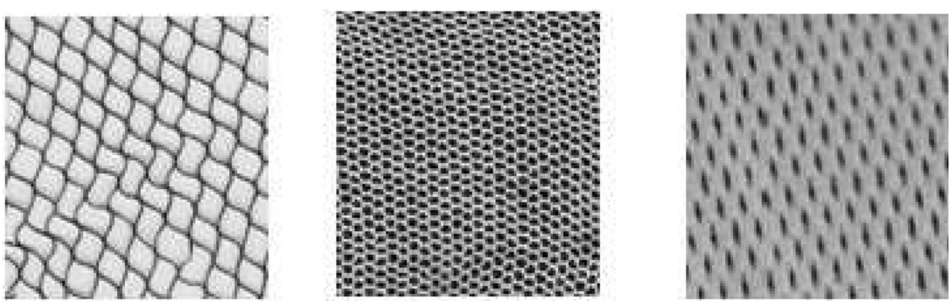

Fig. 3 Sample grayscale images of nylon, cotton, and Teflon meshes

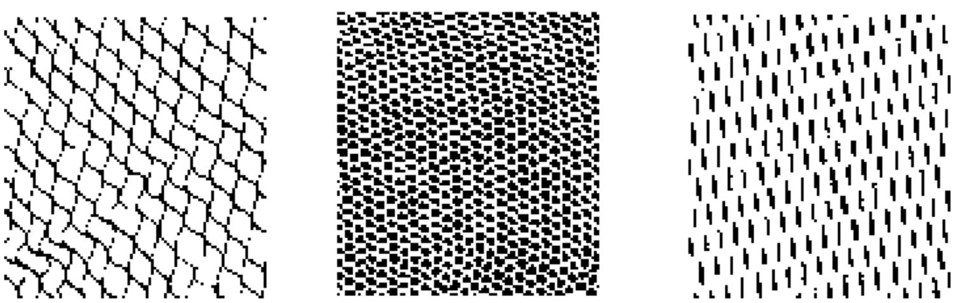

Fig. 4 Thresholded versions of the grayscale images presented in Fig. 3

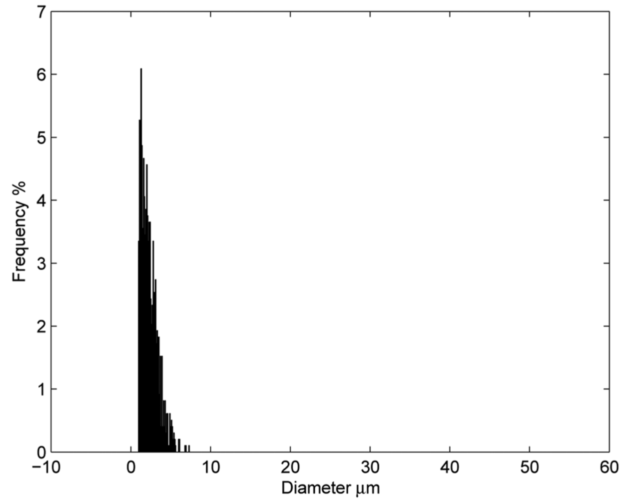

Fig. 5 Drop size distribution for fog drops generated in the drop generation container

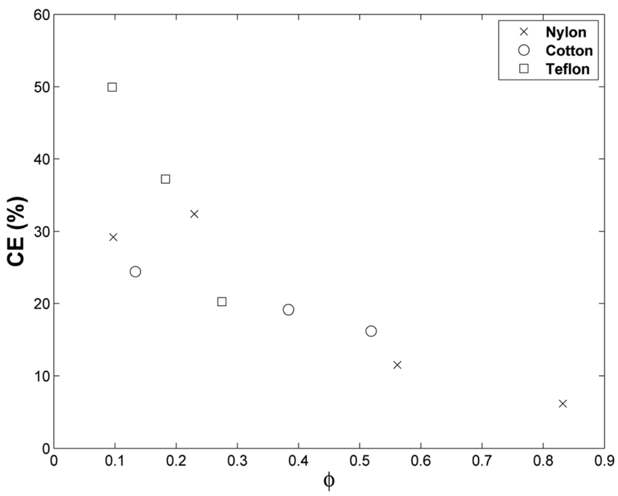

Fig. 6 Averaged CE versus ϕ for each material tested

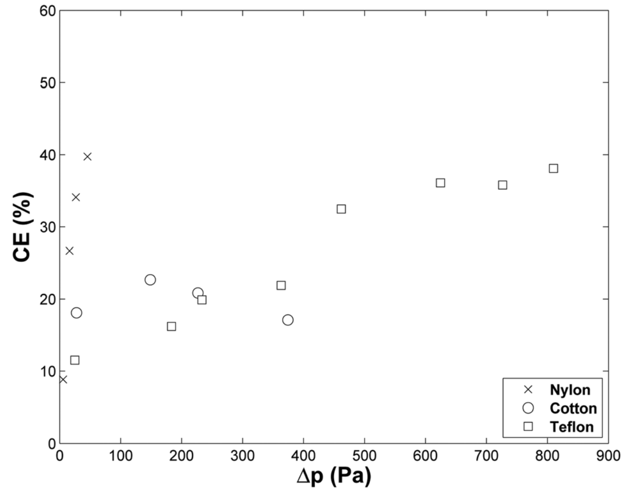

Fig. 7 Average CE versus pressure drop across the mesh

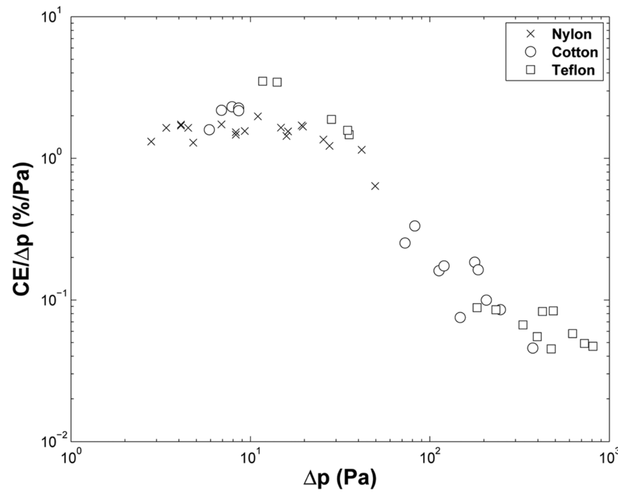

Fig. 8 CE scaled to pressure drop versus pressure drop, presented on log–log coordinates

The distribution of droplet diameters was measured by using a solution of the green dye, disodium fluorescein salt, in the drop generation container. With the fog generators turned on, microscope slides were placed beneath the apparatus outlet. Images of multiple regions of the slides were then obtained using a digital camera (Canon DS126291) mounted on a microscope (Leica DM750). Approximately 300 images were recorded and processed using an image processing algorithm developed in-house to obtain a drop size distribution, which is presented in Fig. 5. Further details of this method can be found in Ran et al. [11]. The average and standard deviation of the fog drop size distribution are 2.32 μm and 1.06 μm, respectively.

3 Results

A plot of CE versus ϕ is presented in Fig. 6, where each point is the average of the five runs conducted for each material/porosity investigated. The experimental uncertainty for these average CE values is $\pm 4.9\%$ (95% confidence interval). The expected decrease in CE with ϕ is seen. Figure 6 also shows that the largest CE exists for Teflon at the lowest ϕ, where CE $= 50\%$. At higher ϕ, the three materials tend to exhibit similar behavior.

Figure 7 is a plot of the averaged CE versus the pressure drop across the mesh. These data show the expected cost of a high Δp for a high CE.

Figure 8 presents a measure of effectiveness, CE$/\Delta p$ versus Δp. An exponential decrease is revealed for $\Delta p > 10$ Pa showing that effectiveness continues to decrease beyond this pressure drop. Of course, though meshes at $\Delta p = 10$ Pa show the best effectiveness, such meshes may have poor CE.

4 Discussion

As noted above, Fig. 6 shows a nominally monotonic decrease in CE with ϕ, as expected. Somewhat more complicated is the low Δp behavior observed in Fig. 7, where nylon exhibits significantly larger CE than cotton or Teflon. There is no clear explanation for this. We note that the nylon meshes had some elasticity to them that caused the meshes to expand away from each other rather than sitting flush against one another (for the cases of multiple meshes). It is possible that the fog droplets interacted with each mesh sequentially rather than as a single unit (as was the case for cotton and Teflon). This may have improved CE if drops that did not impact a fiber on the first mesh did hit the second mesh due to a slight deflection of the flow around the first mesh. Further work is needed to demonstrate if this actually occurred. Though cotton and Teflon have a very different wetability, Fig. 7 does not show significant differences between these two materials, at least over the range of Δp where they overlap.

To ascertain the relevancy of the present research to the collection of fog droplets from actual cooling towers requires knowledge of the velocity and drop size of actual fog plumes. There is limited literature in this area. It is generally understood that the exit velocity of typical cooling towers ranges from 300 to 700 ft/min (1.5–3.5 m/s) [12], and the laboratory experiments of Rothman and Ledbetter [13] used an air velocity of 540 ft/min (2.7 m/s), similar to the velocity used here. However, Hanna [14] investigated fog plumes emanating from cooling towers at the Oak Ridge National Laboratory and showed a radial variation from zero at the edge to as high as 14 m/s in the center, and Hall [15] described a cooling tower system where each tower had an average velocity of 9.7 m/s when operated at peak capacity. The velocity of 2.47 m/s used here falls close to that found in the first two studies while the latter two studies give larger velocities, though they do not deviate by an order of magnitude.

While significant information on the diameters of drift drops leaving a cooling tower is available [16–18], little exists for fog plume drops. Rothman and Ledbetter [13] studied a laboratory scale cooling tower and found a bimodal distribution of fog drop sizes with the modes occurring at $\lesssim 5\ \mu$m and at $\sim 20 - 40 \mu$m, with the majority of drops falling in the first mode, hence, similar to the 2–8 μm range of diameters explored here.

Given that the diameter and velocity conditions explored here are similar to those above cooling towers, an estimate of the water savings that could be attained by a collection mesh can be developed. Using the best case scenario found here of a Teflon mesh with $\phi = 0.1$, the CE is 50%. As noted in Sec. 1, a 1000 MW power plant can have an evaporative loss from a cooling tower as large as 20,000 gpm given a savings by a mesh of 10,000 gpm. This is an upper bound in that it assumes that all of the water vapor emanating from the cooling tower is condensed. An extremely conservative estimate would be to assume that none of the vapor condensed, in which case the mesh would only remove drift drops (those already in the condensed phase before exiting the cooling tower). An example of this loss can be obtained from the Chalk Point experiment [19], wherein a dye was introduced into the cooling tower water and measured downwind of the cooling tower, giving a drift loss of 0.328 kg/s [20]. Accounting for the use of only one of the two cooling towers in this study and scaling from the Chalk Point power output to that of the 1000 MW example here give a loss of 14.2 gal/min of which the mesh would save 7.1 gal/min. The 3 orders of magnitude difference between these two cases bounds the possible water savings by a collection parachute. The actual savings is critically dependent on the fraction of evaporated water that recondenses above the power plant which, in turn, is dependent on local meteorological conditions, the height of the collection parachute above the cooling tower, and the behavior of the plume within the parachute. This is left as future work.

5 Conclusions

The results of an experimental study were presented which showed that collection meshes were able to collect anywhere from 5% to 50% of the liquid water present in a fog flowed through that mesh. The highest CE was observed for Teflon. These results were for fogs having drop sizes ranging from 2 to 8 μm and a velocity of 2.47 m/s. There is evidence to suggest that these conditions may be typical of those found above cooling towers and that significant water savings could be obtained using this approach.

Acknowledgment

The authors thank Clemson University for financial support and J. L. Hodges for assistance in figure preparation.

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