Effect of the Angle of the Crossed Fibres of a Fog Harvester on its Collection Efficiency

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Abstract. Although fog harvesting technology was firstly invented in the 1980s, the theoretical research is still in its infancy. To enhance the collection efficiency of fog harvester, lots of work have been done such as surface modification and 3D structure of the fibres of the fog harvester. In this study, based on observation of daily phenomenon, relationships between the angle of crossed fibres of the fog harvester between collection efficiency are discussed. Results show that as the angle of fibres changes, the effective collection rate per unit length of the fibre keeps unchanged, except near the maximum/minimum limits of the angle, where the collection rate drop significantly, caused by clogging according to the experimental observations. It is also found that the existence of fibre node will influence the collecting process of fog harvester, which can explain why harp-like fog harvester performs well in fog collection.

1. Introduction

Water is the source of life. Although nearly 71% of the earth’s surfaces is covered with water, only a little bit of it can be harnessed by people directly. According to the “World Water Resource Development Report” released by the United Nations in 2019, with the increasing pressure on global water resources, severe water shortages have affected nearly two-third of the world’s population. Fog in nature is a kind of water resource with great potential. In addition to the conventional precipitation approaches, the deposition of fog, the formation of dew and the adsorption of water vapor are the three main sources of non-precipitation water resources in nature. Studies showed that at present one third of fresh water resources on the earth are scattered in the air. So, it is of vital significance to make good use of these potential freshwater resources with the lowest energy consumption. Among these measures, fog harvesting has received extensive attention because of its ability to efficiently collect fog water. In addition to its great potential in solving the problem of water shortage, it can also play an import role in the water saving terminal of many industrial fields. For example, fog harvesting can be used to recycle the evaporated water in the cooling tower of the thermal power plant.

Fog harvesting technology originated in Chile, which has foggy and rainless weather. Due to the influence of geographical features, this area suffers from drought. Inspired by the fog-collecting
creatures in nature such as cactus and Namib Desert beetle, people here used fishing nets to catch the droplets in fog. And now fog harvesting technology has been widely used in Chile, Peru, Ecuador, Canada, Namibia, Nepal and the United States [1]. Figure 1 shows one kind of fog harvesters used in Chile. As is shown in figure 1, a typical fog harvester consists of mesh, support, base and water storage tank.

![Figure 1. Fog harvester used in Chile [2]](image)

The working process of the fog harvester can be mainly divided into the following three stages. First, when fog flows to the fog harvester, due to the resistance of the device, obvious circumfluence will take place around the fog harvester. So only a part of the incoming flow will flow through the fog harvester, which will collide with mesh of the device. b. Then some of the droplets that collide with the mesh will be captured by the mesh fiber and continue to grow and merge with the surrounding water droplets; c. Finally, when droplets captured by mesh fiber grow up to its critical volume, they will leave the mesh under the action of gravity and be collected by the water storage tank below the fog harvester.

The schematic diagram of a typical fog harvester is shown in figure 2. In addition to environmental factors such as wind velocity, temperature and droplet size distribution, geometry characteristics and surface wettability of the fog harvester will influence the collection efficiency of this device [3]. One of the most important features is the shade coefficient (SC) which represents the ratio of fiber area to the area of the mesh. Larger SC means the fog harvester mesh is less porous. Nowadays, the design of fog harvester is constrained by the shadow coefficient, when SC is large, droplets collected will clog the mesh, causing a decrease in collection efficiency. When SC is small, most of the incoming flow will pass through the gap of fibers, which mean most of the droplets in fog can't be effectively collected. Rivera et al. [4] and Park et al. [5] have deduced the theoretical formula of collection efficiency using superposition principle and in Park’s study, he figured out that when shade coefficient equals 0.5 to 0.6, the collection efficiency of the traditional fog harvester shown in figure 2 will reach the maximum value. So how to effectively enhance the collection efficiency of fog harvester has been the core issue in this field.

In nature, there will be droplets hanging on the pine tree when it rains. Pan found that crossed fibers such as pine leaves will contain more liquid than horizontal fibers by observing phenomenon in nature, and then found that droplets adsorbed by fibers with different bending angles have three different forms, as shown in (a), (b), (c) in figure 3 by experimental and theoretical methods [6]. As the angle of fiber decreases, the bottom of the droplet becomes flatter. The top of the droplet becomes thinner and eventually forms a thin film shape. Through a semi-theoretical method, they derive the estimation of formula of the critical volume of the fiber with different angles, which is verified by experiments and
high-speed camera methods. Study has shown that there is an optimal angle of fiber with which the fiber node can accommodate the maximum volume of the droplet.

In the actual process, the angle of fiber of the traditional fog harvester is 90 degrees as is shown in figure 2. Based on Pan et al.’s research, if the angle of fiber changes, the maximum volume of the droplet contained in the fiber node will change, which may improve the clogging problem of the mesh surface. And the collection efficiency will be enhanced. Providing this inference is true, if the relationship between collection efficiency and the angle of fiber can be figured out, it will have a certain help for the improvement of the collection efficiency. So, based on this topic, the following experiment was carried out.

2. Experimental setup
To explore the relationship between the angle of fiber and collection efficiency under fog condition, it is necessary to construct a controllable fog environment artificially and design a fog harvester of which the angle of fiber can change. At present, relevant research studies on fog harvester in laboratory use air humidifier as the simulated fog source [7-9]. Since the relative humidity of the air at the nozzle is 100%, the water flow generated by the air humidifier can be regarded as a simulated fog environment. By changing the gear of the air humidifier, the purpose of adjusting the parameters of the fog environment is achieved. When the gear of the air humidifier is adjusted to a fixed value, the environmental parameters can be kept relatively stable.

Figure 4 and figure 5 are the fog harvesters used in this research. By rotating the spiale, the angle of the frame can be adjusted to alter the fiber anger. The physical picture of the experimental devices is shown in figure 6, which is mainly composed of six parts: air humidifier, tubing, fog harvester, bracket, electronic balance and positioning platform. The tubing is a PVC pipe with an inner diameter of 30mm, whose function is to change the direction of the fog generated by the air humidifier so that it can flow vertically to the mesh surface of the fog harvester. The fog harvester net is woven from nylon fibers with a radius of 1mm and the frame is made of stainless steel. In this study, it analyzes the indication change of the balance within five minutes to characterize the collection rate of the fog harvester and then calculated the collection efficiency of this device. The positioning platform can adjust the relative position of humidifier nozzle and mesh surface of the fog harvester to ensure that the incoming flow can completely pass through the mesh surface. During the pre-experiment process, each time the experiment was performed, the initial values of the experimental data obtained would continue to increase and eventually balance around a fixed value. Through literature research and theoretical analysis, it was
found that during the experiment, the droplets in fog would continue to hit the surface of fiber, and then immerse in the microstructure of the fiber, eventually reaching a stable state [4]. The essence of this phenomenon is changes in the contact angle of fiber.

Figure 4. Structure of fog harvester net.  
Figure 5. Fog harvester used in this study.  
Figure 6. Experimental device

3. Results and discussion
The relationship between the collection rate of the fog harvester per unit area and the angle of fibre is shown in figure 7. L in the legend represents the distance between two adjacent fibres when the angle of fibre is 90 degrees. When L equals 5mm, the mesh is denser. For experiments under the two working conditions, the collection rate shows the same trend. As the angle of the fibre increases, the collection rate first decreases from a large point, and then reaches a minimum value at 45 degrees. Thereafter, the collection rate continues to increase with the increase of the angle. However, the data do not mean that the difference in the angle of fibre will affect the collection efficiency. When the angle of fibre changes,
the actual effective fibre area per unit area changes, namely, the shade coefficient of the fog harvester changes. Comparing the values of the two working conditions with the same angle, it is found that when $L$ equals 5mm, the collection rate is twice that of $L=10mm$, and the density of the former mesh is also approximately twice that of $L=10mm$. So, the result in figure 7 needs to be revised by the equation: $M' = L\sin(2\alpha) \times M$, where $M$ is the actual collection rate, $M'$ is the revised rate, to eliminate the effect of the change in fibre area caused by the change in the angle on the collection rate and $\alpha$ is the half-angle of the angle of fibre. Figure 8 shows the relationship between the revised collection rate of fog harvester and the fibre angle. It can be found from the result that when the influence of the difference in fibre area is revised, these two working conditions share the same trend when the angle of fibre is small. When $L=10mm$, as the angle of fibre increases, the collection rate reaches maximum and the remains unchanged. However, for the working condition of $L=5mm$, when the angle of fibre increases at a relatively large value, the revised collection rate decreases. By observing experimental phenomenon, it can be found that when the angle of fibre is small, the shade coefficient of the fog harvester is large. Droplets formed on the fibre fail to fall off and attach to the fibre. The clogging phenomenon prevents fog from continuing to pass through the fog harvester, so the collection rate per unit fibre area decreases at this time. As the angle of fibre increases, the shade coefficient of this device becomes smaller at this time, and the collected droplets can be dropped off in time to avoid the clogging of the mesh, so the collection rate of fog harvester remains unchanged at this time. Because the shade coefficient of $L=10mm$ is smaller than that of $L=5mm$, the former working condition is less prone to clogging, preventing the decrease in collection rate at the large angle of fibre.

Therefore, by analyzing and collating the experimental data, it can be found that the angle of fiber does not actually have any effect on the collection rate of the fog harvester. The effect of the geometrical characteristics of the fog harvester on the collection efficiency essentially affected the aerodynamic efficiency of fog harvester by changing its shade coefficient. Therefore, in practical applications or experiments, it is enough to select a conventional fog harvester with the angle of fiber of 90 degrees. This kind of fog harvester is easier to process and manufacture than fog harvester with other angles.

In the experiment of this study, in order to explore the influence of fiber nodes on the collection efficiency of fog harvester, the following control experiment was also carried out. The collection efficiency of a harp-like fog harvester with the same shade coefficient, fiber radius and fiber space as the traditional mesh fog harvester is also measured. Results shows that the collection rate (4.849g) of the vertical arranged harp was much higher than that of the horizontal arranged harp (3.525g), and the sum of the collection rate was not equal to that of the traditional mesh fog harvester, which shows that 1) the collection efficiency of fog harvester consisting of horizontal fibers was much lower than that of
the vertical arranged one. 2) the existence of fiber nodes will have a certain impact on the collection efficiency. Actually, the motion of the droplets is decided by gravity and pinning force. Theoretically, the critical volume of the droplets can be calculated by equation: 
\[ \rho_{\text{water}} g V_c = L_{\text{contact}} \gamma (\cos \theta_r - \cos \theta_a) \], where \( \gamma \) is the coefficient of surface tension, \( g \) is the acceleration of gravity, \( V_c \) is the critical volume of droplet, \( L_{\text{contact}} \) is the length of contact line and \( \theta \) is the contact angle of water on fiber. Because there are fibers in both horizontal and vertical directions on the mesh surface of the traditional fog harvester, the length of the contact line on the harp-like fog harvester is shorter than that of the traditional one as shown in figure 9 (red lines represent the contact line), which results in the smaller critical volume of the droplets collected on the fiber when the harp-like fog harvester is working [8]. Therefore, compared with the traditional fog harvester, the harp-like fog harvester is less likely to be clogged.

\[ \text{Figure 9. Contact line of harp-like fog harvester and conventional fog harvester} \]

4. Conclusion
It is found that there is no obvious relationship between the angle of fiber and the collection efficiency. The essence of the influence of the angle of fiber on the collection efficiency is changes of the shade coefficient of the fog harvester. Therefore, in practical application, when processing and designing the traditional fog harvester, the conventional mesh design method can be selected, that is, the angle of fiber is 90°, and the change of the angle of fiber will not have a significant impact on the collection efficiency.

Acknowledgments
Authors are grateful to Mr, Guo for his assistance in the fabrication of the fog harvester and the cooperation and guide by Prof. Pan from University of Waterloo.

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