

Superhydrophobic carbon papers for electrostatic water collection from fog

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Abstract. Fog collection presents a promising solution to water scarcity in arid regions. Typically, hydrophilic surfaces are used for this purpose. This study demonstrates that electrically conductive PTFE-coated superhydrophobic carbon papers are highly effective for electrostatic fog collection. The wettability of the carbon paper has minimal impact on collection efficiency. Despite the superhydrophobic nature of the carbon papers causing condensed fog particles to aggregate into spherical droplets, this aggregation has little effect on collection performance. Additionally, the efficiency of fog collection is independent of charge type; both negative and positive high voltages yield similar results. The fog collection efficiency is directly correlated with electrostatic air current, though the relationship is nonlinear: efficiency initially increases sharply with current before leveling off.

1 Introduction

Obtaining clean water from natural environment has always been a paramount challenge for human survival and livelihood. Fog, as another common physical state of water, is composed of fine water droplets suspended in the air. Efficient fog collection can offer a solution to water scarcity. Currently, fog harvesting technology can be divided into two main types: passive fog harvesting and active fog harvesting. Passive fog harvesting involves the condensation of fog particles through inertial collision. In nature, various organisms have evolved special structures for fog collection; examples include spider silk [1], cactus spines [2,3], and the unique structures on the back of the Namib beetle [4]. Inspired by these biological fog collection structures, many studies have reported different biomimetic fog collection designs [5-8]. In practical applications, to collect enough amount of water, giant structures were built, such as large fog-catching nets in Bolivian highlands.

The passive fog collection methods rely on airflow to drive fog particles, with the efficiency of fog particle collision depending on the Stokes number (StK). StK is a dimensionless number representing the ratio of particle relaxation time to fluid characteristic time, describing the behavior of suspended particles in the fluid. StK indicates the ratio of particle inertia to diffusion, where smaller values signify lower particle inertia, making them

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more prone to follow fluid motion, thus enhancing diffusion; conversely, larger values indicate greater particle inertia, leading to less noticeable particle motion alignment with the fluid. When $Stk > 1$, particles continue to travel straight along their path even after flow lines bypass obstacles until they collide. When $Stk \leq 1$, particles closely follow the flow lines. Under typical wind conditions, fog particle Stk is around 0.5, causing most particles to lose along the flow pathway. Thus, traditional passive collection methods result in low efficiency. [9,10]

Another category of fog harvesting technology is active fog collection, achieved through active adsorption [11], temperature differentials [12], and electrostatic collection [13]. The electrostatic fog harvesting method shows promise due to its high collection efficiency and low energy consumption. It utilizes ultra-high-voltage electric fields to ionize the air near the emitter, generating breakdown ions and electron currents; the fog particles in the vicinity of the electrode adsorb ions, become charged, migrate towards the grounded collection surface, and condense. The electrostatic force overcomes the drag force of air flow.

The correlation between collection electrode surface hydrophobicity and collection efficiency is not yet clear. It usually requests the collection surfaces to be hydrophilic. In this study, electrically conductive carbon paper is used as the collection surface, and the super-hydrophobicity of the carbon paper is controlled by varying the amounts of PTFE coating. The aims of this study are to investigate the effects of the super-hydrophobicity of the carbon paper as the fog collection surface and the different effects of positive and negative high voltage for electrostatic fog collection. Understanding the correlations of different factors can help to design better fog collection setup in an actual foggy environment.

2 Experimental section

2.1 Materials and instruments

Carbon paper with varying PTFE coating content was obtained from Suzhou Sinero Technology Co., Ltd, China, and used as received. The PTFE content in the hydrophobic carbon paper used was 5%, 10%, 20%, 30%, and 40% by weight. The PTFE coating is prepared by first incubating the pristine carbon paper in a PTFE microparticle water suspension solution with vary concentrations; the carbon paper was then taken out, dried and sintered to fuse PTFE particles on the carbon paper surface. The PTFE content was calculated using the mass before coating and after coating.

The high-voltage power equipment was provided by Dongwen High Voltage Power Supply, Tianjin, China. Two types of power supplies were used in this study: one negative high voltage model, with a maximum voltage of -50 kV and a maximum breakdown current of 1 mA; and one positive high voltage model, with a maximum voltage of +50 kV and a maximum breakdown current of 1 mA.

The static water contact angles of the carbon papers were measured with a 5 μ L water drop using a contact angle instrument from Chengde TuoWei Technology Co., Ltd, China. The morphology of the collected water droplets was characterized by a P-60V microscope and a USB industrial high-definition CCD camera from Kunshan Gaopin Precision Instrument Co., Ltd, China. The surface microstructure and morphology of the carbon paper were examined using a scanning electron microscope (SEM, Thermo Scientific Apreo 2).

2.2 Electrostatic fog collection design

The ultra-pure water was used as to exclude interference from other factors in nature fog, such as contaminates [14]. The test of this method in a real foggy environment will be the

future work. The distances between carbon paper and the electrostatic discharge array tips were 2 cm, 3 cm and 4 cm. The voltages applied were ± 5 kV, ± 6 kV, ± 7 kV, ± 8 kV, ± 9 kV, and ± 10 kV. The scheme of experimental design and the actual experimental setup are shown in Figure 1A and B. In the setup, a humidifier was used to produce a continuous fog stream with an ultra-pure water consumption of 7.9 ± 0.1 g/min. The fog stream passes the electrostatic generation array with sharp copper needles as the electrical discharging electrodes, and the copper needles face perpendicularly toward the collection surface. The fog path is designed in this way so that all the fog particle generated from the humidifier can enter the electric field completely and an overall collection efficiency can be easily calculated. As the fog collection surface, the carbon paper was cut to $10\text{ cm} \times 10\text{ cm}$ and supported with a $10\text{ cm} \times 10\text{ cm}$ insulative glass plate; the electric conductive carbon paper was electrically grounded. A microammeter (Model S02, ZhongXinDa Electric Co. China) is connected in series between the carbon paper and the ground wire to measure the electrostatic air current received by the carbon paper. The microammeter records the current every 0.5 second automatically. The charged fog stream was condensed onto the carbon paper surface and the dripping water was collected with a clean flask, then measured with an analytical balance. The insert image of Figure 1B is the electrode; 36 sharp needles are distributed evenly in the $10\text{ cm} \times 10\text{ cm}$ plate with a distance of 2 cm between each needle. For every condensation condition, the condensation process continues for the first 10 minutes to reach a stable condensation state; after which, condensed water was collected for every interval of 3 minutes continuously to obtain the collection efficiency (gram per minute). The collection was repeated for 3 times to obtain average collected mass and deviation.

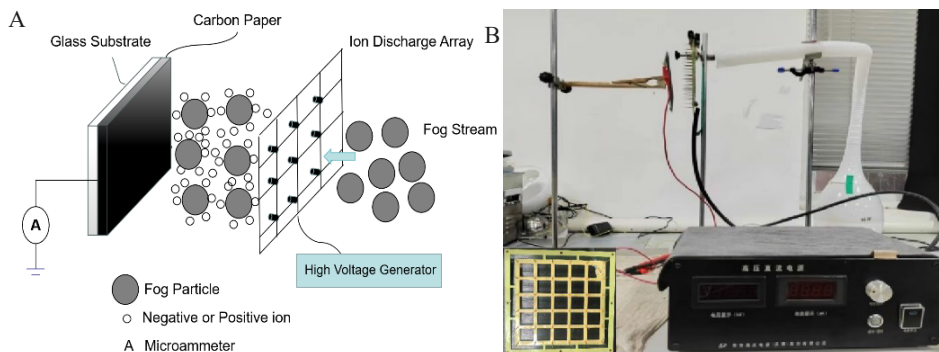


Fig. 1. Electrostatic fog collection setup scheme (A) and the actual setup (B); the insert image displace the electrostatic copper needle discharge array.

3 Results and discussion

3.1 Scanning electron microscope (SEM) characterization

Figure 2 illustrates the surface micro-structure and micro-morphology characterized by SEM. Figure 2A1 and A2 depicts the micro morphology of the pristine carbon paper. A high film porosity with intersecting carbon fibers is shown, and some fibers reveal carbon film patches fused with carbon fibers. The fiber diameter is measured to be 7-10 μm , and the surface of the carbon fiber exhibits grooves and stripes. Figure 2A3 is the energy dispersive spectroscopic (EDS) image for the pristine carbon paper; carbon elements are represented in red. Figure 2B is the representative SEM images for PTFE coated carbon paper for 20wt% PTFE carbon paper. From Figures 2B1 and B2, the porosity of the film remains after the coating process. Figures 2B2, the SEM images of 2000-times magnification, shows that

PTFE floss covers the fiber and carbon film patch surfaces. EDS image, Figure 2B3, shows that distribution of PTFE coating is uneven on the film surface, and PTFE distribution on fibers is notably less than on the surface of carbon film patches. Closer to the fibre's curve top surface, fluorine distribution further reduces; therefore, PTFE mainly distribute below the top carbon fiber layer. As PTFE percentage increases, the green colour intensifies in the EDS results (SEM images are not shown in this paper). The fluorine weight percentage can be derived from the EDS results; however, the results do not accurately reflect the actual content of PTFE. Considering the weight percentage of fluorine element and the weight ratio of fluorine element in the repeating unit $-CF_2-$ of PTFE, the calculated PTFE weight percentages of films are 37%, 50%, 51%, 61%, and 71%. These values significantly differ from the actual PTFE weight percentages of 5%, 10%, 20%, 30%, and 40%. The disparity can be attributed to the non-uniform distribution of PTFE. The uneven PTFE distribution is possibly caused by the PTFE coating preparation method and the porosity of the original carbon paper.

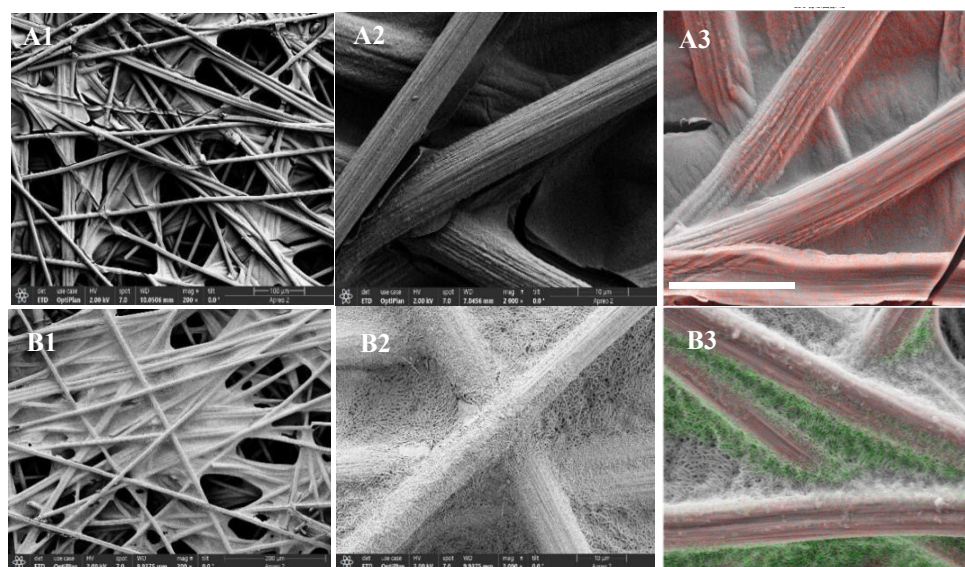


Fig. 2. SEM characterization. A1, A2 are SEM images of the pristine carbon paper, A3 is energy dispersive spectroscopic (EDS) image for the pristine carbon paper. B1 and B2 are SEM images of carbon paper with 20 wt% PTFE, and B3 is the corresponding EDS image. Red color indicates carbon elements, while green color denotes fluorine elements. Magnification factor of A1 and B1 is 200; magnification factor of A2 and B2 is 2000; the scale bar in A3 and B3 is 25 μm .

3.2 Condensed water-drop morphology

The optical microscopic characterization results of water drop condensed on carbon papers are depicted in Figure 3. The inset images show the contact angle images of a 5 μL water drop on the carbon papers. The optical microscopic characterization reveals the status of water drops present on the carbon surface. In Figure 3A, without the PTFE coating component, condensed water wets the surface, and the fused water drops spread out to form a water layer. A lower water contact angle of $\sim 70^\circ$ is observed in the contact angle image, indicating a relatively hydrophilic nature of the carbon paper. In the inset image of Figure 3B, a water contact angle of $148 \pm 3^\circ$ is observed for the carbon paper with 20 wt% PTFE coating. Notably, a surface with a water contact angle exceeding 150° is classified as a superhydrophobic surface. The PTFE coating turns carbon paper into a superhydrophobic

surface when the PTFE content is greater than 20 wt%. According to Figure 3B, on the superhydrophobic surface, the condensed water drops form spherical water droplets with sizes ranging from several hundred micrometers to several millimeters in diameter.

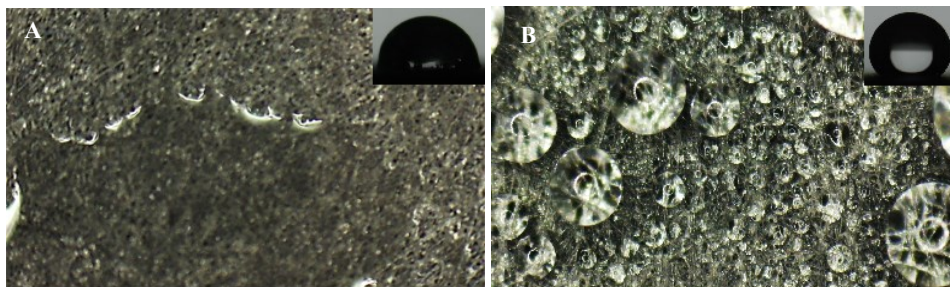


Fig. 3. Morphology of condensed water on the carbon paper surfaces; the insert image is the contact angle image for the carbon paper. (A) is optical image of water condensed on an un-treated carbon paper with a contact angle $CA = 70 \pm 2^\circ$; (B) is optical image of water drops condensed on a 20 % PTFE carbon paper with a $CA = 148 \pm 3^\circ$. The magnification factor of the optical image is 21.

3.3 Electrostatic fog collection efficiency

This study examined how collection distance and voltage affect fog particle collection efficiency using an ion discharge copper array. Figure 4 illustrates fog collection efficiency (in g/min) versus voltage at different collection distances (left) and the correlation between electrostatic current and voltage (right). Results show similar collection efficiencies and air currents across all carbon paper surfaces; due to paper length limitations, hydrophilic carbon paper (Figure 4A) and 40% PTFE carbon paper (Figure 4B) are shown as the examples.

Without an electric field, fog particles exhibit random and sluggish movement, resulting in a collection efficiency of less than 0.1 g/min. Significant electrostatic air currents emerge only when the voltage exceeds a certain threshold. At a 2 cm distance, voltages of ± 5 kV and ± 6 kV generate electrostatic currents below 1 μ A, leading to limited efficiencies (~ 0.5 g/min). At ± 7 kV, both efficiency and current improve, with efficiency increasing to 1.5-2.2 g/min and current rising to 3.0-4.0 μ A. At ± 8 kV, efficiency further increases to 3.0-3.3 g/min with currents of 10.0-14.0 μ A. At ± 9 kV and ± 10 kV, currents rise to 28-35 μ A and 45-58 μ A, respectively, with efficiencies reaching 3.8-4.2 g/min and 4.1-4.6 g/min. Beyond ± 9 kV, the efficiency increase with current slows. With larger collection distances, both efficiency and current decrease significantly: at 3 cm, efficiencies are 1.5-2.3 g/min and 2.7-3.3 g/min for ± 9 kV and ± 10 kV, with corresponding currents of 5-6.5 μ A and 10-13 μ A. At 4 cm, efficiency and current values further decline, with efficiency around 2 g/min for ± 10 kV and a current of ~ 3.5 μ A. For ± 9 kV at 4 cm, efficiency drops to ~ 1 g/min with a current of ~ 1.5 μ A, while below ± 9 kV, collection efficiency becomes negligible due to diminished current.

Figure 4C and Figure 4D illustrate the relationship between collection efficiency and charge current for (C) negative voltage and (D) positive voltage. The data demonstrate a clear correlation between collection efficiency and electrostatic air current. Initially, collection efficiency increases sharply with rising current, but this rate of increase diminishes beyond 20-30 μ A, with efficiency eventually leveling off. This suggests that collection efficiency is primarily influenced by the current received by the carbon surface. The observed decrease in current with increasing collection distance corresponds to a reduction in collection efficiency. The plateau in efficiency with higher currents may result from the saturation of fog particles with electrostatic ions. Further research is required to investigate additional factors, such as the impact of fog concentration on collection efficiency.

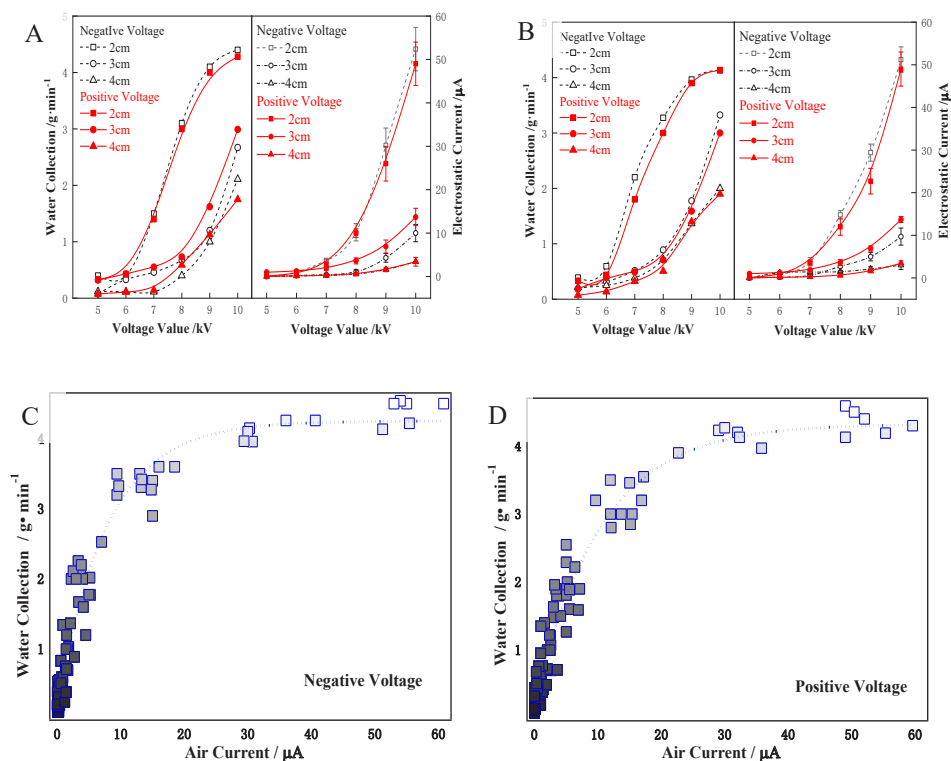


Fig. 4. Correlations between collection distance and voltage with fog collection efficiency and electrostatic air current value for (A) pristine hydrophilic carbon paper and (B) 40% PTFE superhydrophobic carbon paper. Correlations of fog collection efficiency with electrostatic air current are shown for (C) negative voltage and (D) positive voltage.

4 Conclusions

This study elucidates the effects of surface wettability of carbon paper on electrostatic fog collection and examines the influence of positive and negative electrostatic charges when using a copper needle array as the charge dispenser. Despite the formation of spherical water droplets from electrostatically condensed fog particles on PTFE-modified carbon papers, particle aggregation exerts a negligible effect on overall water collection efficiency. Consequently, non-wettable superhydrophobic carbon paper surfaces are demonstrated to be effective for electrostatic fog collection. The results indicate that condensation efficiency is independent of surface wettability; both hydrophilic and PTFE-modified carbon papers exhibit comparable collection efficiencies at identical collection distances and voltages. Similarly, the electrostatic current received by the carbon paper shows minimal dependence on surface wettability. However, a clear dependence on distance is observed: as distance increases, collection efficiency declines rapidly, which correlates with the distance dependence of the electrostatic current. Moreover, condensation efficiency is unaffected by the type of electrostatic charge; both negative and positive voltages result in nearly identical collection efficiencies and electrostatic air currents. The primary determinant of collection efficiency is the electrostatic current: efficiency increases rapidly with rising current, but after reaching a certain threshold, the rate of increase slows and eventually levels off.

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