DE GRUYTER Open Phys. 2019; 17:897–904

Research Article

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Wetting properties and performance of modified composite collectors in a membrane-based wet electrostatic precipitator

https://doi.org/10.1515/phys-2019-0095
Received Aug 29, 2019; accepted Nov 21, 2019

Abstract: The membrane-based wet electrostatic precipitator (MWESP), exhibiting good control of $PM_{2.5}$, has more and more widely applications. Considering traditional flexible collectors' poor rigidity, this paper presents two modified composite collectors (MCC), smooth PVC plates covered by carbon fiber and glass fiber respectively. This paper tries to make a comparative study of performance characteristic between both the MCCs and a same size smooth PVC collector. We compared the collectors in the aspects as follows: water film thickness, ionic concentration, V-I characteristic and dust collection efficiency. Firstly, we compared the three collectors' film forming abilities through a water film thickness measure experiment. Secondly, we measured the ionic concentrations and V-I characteristics, getting the electrical characteristics of the three collectors. At last, through an experiment of collection efficiencies, we compared the three collectors' performance characteristics. The experiment results indicate that MCC with glass fiber not only can guarantee the rigidity of collector, but also proves best wetting properties and best performance characteristic with the water flow rate of 700L/h.

Keywords: Membrane-based wet electrostatic precipitator, Water film thickness, Water flow rate, V-I characteristics, Collection efficiency

PACS: 68.08.Bc, 68.15.+e, 51.50.+v

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1 Introduction

$PM_{2.5}$ is the chief cause of the smog weather [1], leading to atmospheric visibility degradation and doing much harm to ecosystem, as well as global climate change and human health [2–4]. $PM_{2.5}$ is also called respirable particles as it can go directly into the human alveoli and even the blood system, resulting in cardiovascular diseases [5]. The traditional dry electrostatic precipitator (ESP) has far more enough collection efficiency to $PM_{2.5}$ [6]. Furthermore, dry ESP can do nothing about the removal of SO_2 and NO_X [7–9]. However, wet electrostatic precipitator (WESP) can address the problems above very well.

The wetting property and anti-corrosion of collectors play great role in the performance of MWESP. Inevitably, the industrial flue gas contains acid gases that are corrosive to the steel collectors in traditional WESP. Moreover, channel flow and dry spots will appear on the collectors if the wetting property is not enough [10], therefore branched dust will be left on the plate [11]. Thus, steel, the conventional material of the collection plate, has the shortcomings such as low wettability, low anti-corrosion and obviously high cost.

The membrane-based wet electrostatic precipitator (WMESP) is the improved version of traditional WESP. In 1998, Pasic, a professor in Ohio State University proposed to make the carbon fiber textile as dust collectors initially, thus the concept of membrane-based WESP emerged [12–14]. The experimental studies of Bayless [15] found that the ESP with wet membranes collecting electrodes had higher collection efficiencies than the metal ones under the same conditions. Bayless indicated that even semiconductor materials collected as nearly efficiently as steel plate, because the collection surface resistivity is primary dictated by the accumulated ash layer other than the underlying plate conductivity [16]. Moreover, Bayless presented that membrane collectors made of corrosion-resistant fibers was facilitated by capillary action between the fibers, maintaining an even distribution of water. Furthermore, MWESP was more effective at collecting fine particulates, acid aerosols, and oxidized mercury than the metal-plate WESP, even with 15% less collecting area [16]. Xu tested the wetting properties and performance of one kind of modified rigid collector, finding that the modified rigid collector provided high collection efficiency to fine particles with lower energy and water consumption [17]. Chang studied the performance characters of colleting plate made of polypropylene fibers and polyester fibers, getting the V-I characters, water film spreading and working performances, concluding that single terylene or polypropylene collection electrode has significant advancement which could improve WESP's applications [18]. Wang found the collection efficiency of wet membranes electrode was by 3%~5% higher than the dry metal one under the same power consumption [19]. Wang also found that the increased discharge current density is the main reason for the excellent efficiency of MWESP [19].

Flexible electrodes made of fiber fabric not only have excellent corrosion resistance, but also have good film-forming properties because of capillary action. However, Owing to their low mechanical strength, flexible electrodes are likely to appear deformation and vacillation, which will lead to the changes of electrode distance and poor stability of voltage. In order to avoid great deformation and vacillation, the electrode distance in MWESP with flexible electrode is designed much smaller. For example, the dust collection space was adopted as square tubes [16]. Mean while, as the electrodes distance decreases the online water flushing tends to unavailable because of spark discharge and tripping operation. Without enough washing the flexible electrodes' conductivity will sharply decrease because of much dust gathered on it. In short, the low mechanical strength becomes the significant drawback of flexible electrodes. In order to improve this situation, two kinds of novel modified composite collectors are proposed in this paper.

PVC plates, showing good rigidity, can be made into collectors, but the wettability needing to be improved. Grooved PVC plates are more conducive to film forming than smooth one, which had been studied by our research group [20]. Smooth PVC plate covered by fiber fabric, as we called it modified composite collector (MCC), is put forward in this paper. It is anticipated that the novel MCC has good wetting properties besides good rigidity, for the purpose of improving the performance of MWESP further.

2 Materials and experimental methodology

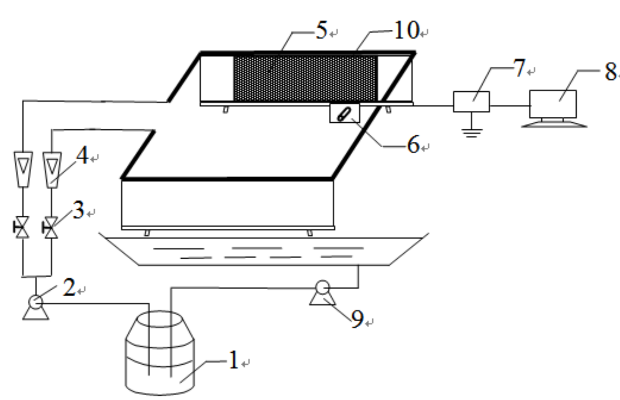
2.1 Materials

The MCCs are 1m long and 0.4m wide, covered by carbon fiber cloth or glass fiber cloth with gluing techniques. The model of glass fiber cloth is non-alkali CWR600-100(China), while the carbon fiber cloth is II-300(China), which means the grammas per square meter are 600g/m^2 and 300g/m^2.

The experimental dust shall have stable chemical property and be close to industrial powder in particle size. The talcum powder whose main composition is $Mg_3(Si_4O_{10})(OH)_2$ has good chemical property. The size of 800 meshes is close to industrial powder [20], thus 800 meshes talcum powder is used as experimental dust in the study.

2.2 Experimental methods

Two experimental systems are built in the study. One is water film thickness measuring system; the other is dust collection system. The water film thickness measuring system, which is shown in Figure 1, consisted of three parts: spraying system, measuring system and circulation system. The measuring system comprises capacitance probe, capacitance gauge and computer data output terminal. The water flow rate is monitored by rotameter in the spraying system.



1-water tank, 2-water suction pump, 3-regulating valve, 4-flow meter, 5-measured plate, 6-capacitance probe, 7-capacitance gauge, 8-personal computer, 9-back water pump, 10-water feed tube

Figure 1: Experimental system of water film thickness

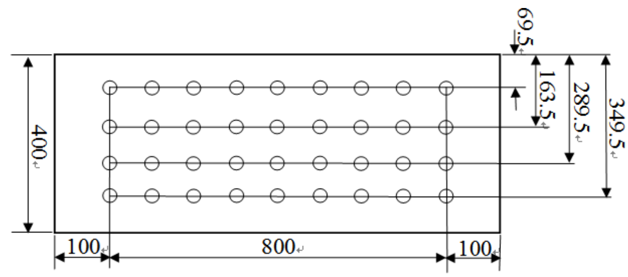


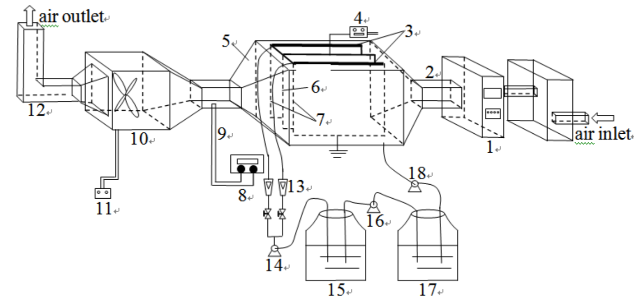
Figure 2: Distribution of measure points

With the MWESP no-load, we measure the film thickness non-contactly with capacitance precision micrometer (JDC-2008, China) as the water flow rates are 200 L/h, 400 L/h, 600 L/h and 700 L/h. When the flow rate is raised to 800 L/h or more, water splash will happen, which is harmful to electrical safety of WMESP. The nozzles, being a series of small holes with a diameter of 1.5 mm are evenly distributed on the water feed tube with a distance of 3 cm between two adjacent ones. There are 33 nozzles in all on the tube of one side. The nozzles at both ends are 5mm away from left edge and right edge of the experimental collector respectively. There are 36 test points located in 4 rows and 9 columns, as shown in Figure 2. The distances of the 4 lines from the upper edge are 69.5 mm, 163.5 mm, 289.5 mm and 349.5 mm. The water film thickness is recorded per second in 2 min for one test point. Computing the average value of the 120 data, we shall get the film thickness of this test point.

The dust collection efficiency experimental system is shown in Figure 3. It consists of powder feeder, dust collector body, exhaust fan and some accessories. The dust collector body is properly sealed and comprised of discharge electrodes, dust collectors, water distribution system, high voltage power supply system and tank body. A needle-plate device with tooth length of 20mm is adopted as discharge electrode. Distributing water on the collectors by feed tube, feeding powder continuously, making the voltage as 20kV, 25kV, 30kV, 35kV, 40kV and 45kV, the V-I characteristics, the ionic concentration and dust collection efficiency is tested. Air ion measuring instrument (DLY-3, China) is used to survey the ionic concentration.

2.3 Calculation of Collection Efficiency

In this study, the feeding powder is regulated by a powder feeding controller (Daze, DZT-1000, China) with the scale ranging from 10 to 200 g/min. Mixed with simulated flue gas, the dust is led into the dust chamber by the airflow. Dust concentration of the simulated flue gas at the inlet



1-powder feeder, 2-conical inlet duct, 3-water feeder tube, 4-high-voltage silicon rectifier, 5-main body of MWESP, 6- discharge electrode, 7- dust collecting plate, 8- dust sampling meter, 9- dust sampling gun, 10- variable frequency fan, 11- fan inverter, 12- flue gas exhausting pipe, 13-glass rotameter, 14,16,18- water pump, 15,17- water tank

Figure 3: Experimental system of V-I characteristics and dust collection efficiency

of MWESP(c_{in}, mg/m^3) is calculated by the following formula (1).

$$c_{\text{in}} = \frac{1000W}{60vS} \quad (1)$$

Where c_{in} is the dust concentration at the inlet of MWESP (mg/m^3); W is feeding amount of powder in unit time (g/min); v is gas velocity, measured by the anemometer (Testo 405-V$_1$, Germany) (m/s); S is gas flow area, received by measuring the duct size (m^2).

The dust concentration of outflow gas (c_{out}) is sampled and obtained by Pitot tube parallel automatic smoke-gas sampler (Qingdaolaoshan, WJ-60B, China). The measured data can be taken back to the host computing sampler and then calculated.

Collection efficiency, which is defined as the ratio of the collected dust to the inlet dust in unit time can be expressed by formula (2):

$$\eta = \frac{c_{\text{in}} - c_{\text{out}}}{c_{\text{in}}} \times 100\% \quad (2)$$

Classification efficiency is the collection efficiency of a certain diameter, which can be expressed by formula (3) as following:

$$\eta_{\text{c}} = \frac{c_{\text{c-in}} - c_{\text{c-out}}}{c_{\text{c-in}}} \times 100\% \quad (3)$$

Where $c_{\text{c-in}}$ and $c_{\text{c-out}}$ are the concentration of dust within a certain diameter range in the simulated flue gas at the inlet and outlet of MWESP respectively. Malvern laser particle size analyzer (Mastersizer 2000,UK) is used to measure the particle size distribution of dust. However, the result provided by Mastersizer 2000 is the volume share of different particle size. The result multiplied by the average density of the simulated dust 2.7kg/m^3 the concentration of dust within a certain diameter range is obtained.

3 Results and discussion

3.1 Water film thickness

The water flow in MWESPs belongs to the realm of vertical wall falling film. It was Nusselt who firstly showed the empirical relationship between vertical wall falling film thickness and Re, and the basic function was

$$\delta = aRe^{b}(v^2/g)^{1/3} \quad (4)$$

Where v is kinematic viscosity, g is gravitational acceleration, a and b are undetermined coefficients.

The Re of vertical wall falling film flow can be described as

$$\mathrm{Re} = \frac{4M}{\mu L} \quad (5)$$

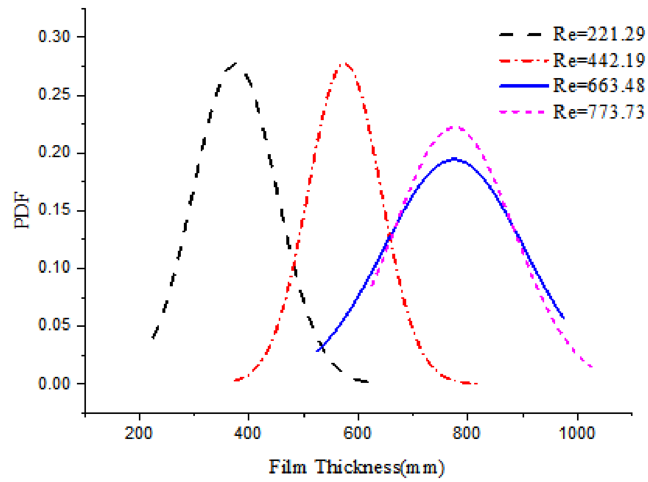
where M is the water flow rate, μ is water's dynamic viscosity and L is the width of collectors, It should be noted that the width here means the size vertical to the flow direction. Water's dynamic viscosity is determined as $\mu = 1.005 \times 10^{-3}$ Pa·s and the width of collectors L is 1m. Then Re corresponding to the water flow rates of 200, 400, 600 and 700 L/h is 221.29, 442.19, 663.48 and 773.73.

Because of the heterogeneity of water spray from nozzles and the falling film's fluctuation, the measured film thickness of each test point is not exactly the same. The probability density function (PDF) is suitable to reveal the possible film thickness on the collectors. Aggregating all of the data from the 36 measure points, calculating various probabilities of occurrence of different film thicknesses, we shall get the corresponding curve about probabilities and film thickness. In order to find something regular, then fitting the curve by GaussAmp model of non-linear analysis, the curves of probability density function (PDF) are achieved and displayed in Figure 4.

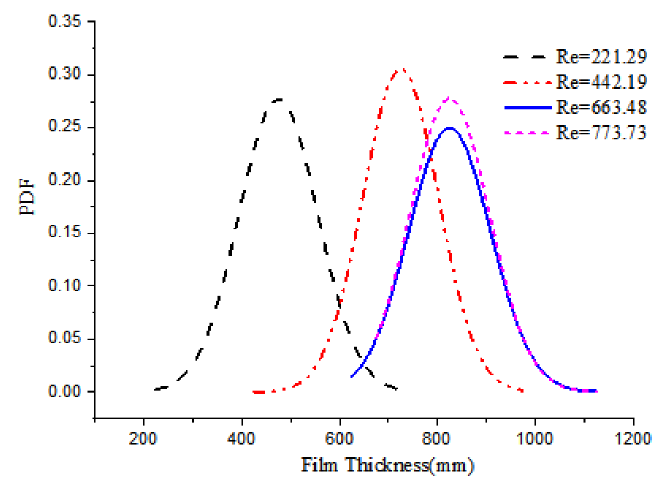
The PDF curves of film thickness with different Re look similar. On one hand it is easy to find that the bigger of Re becomes, the higher of the width of curves appears, which means the vibration amplitude of vertical wall falling film is going up. On the other hand the peak position moves to right when Re increases, meaning the possible maximum film thickness increases. It shall be noted by the comparison that the corresponding film thicknesses of PDF from big to small are glass fiber, carbon fiber and smooth PVC at the same Re.

In order to get the averaged film thickness, all the 36 test points' measurements are averaged and the result is shown in Figure 5.

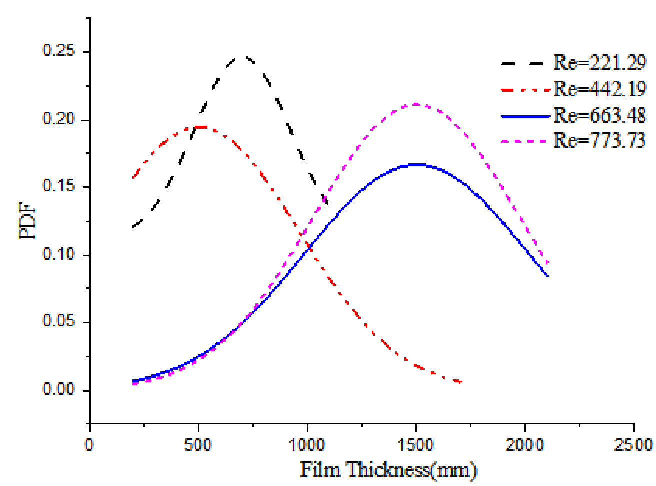
As is shown in Figure 5, the average film thickness on three collectors all increases with the increase of supplying water. However, the increase rate tends to be reduced.



(a) smooth PVC



(b) MCC with carbon fiber



(c) MCC with glass fiber

Figure 4: PDF of film thickness on three collectors

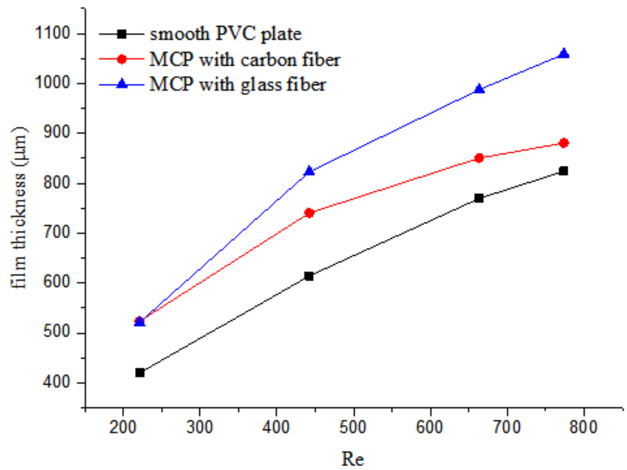


Figure 5: Average film thickness on three collectors

Table 1: Empirical correlations of water film thickness

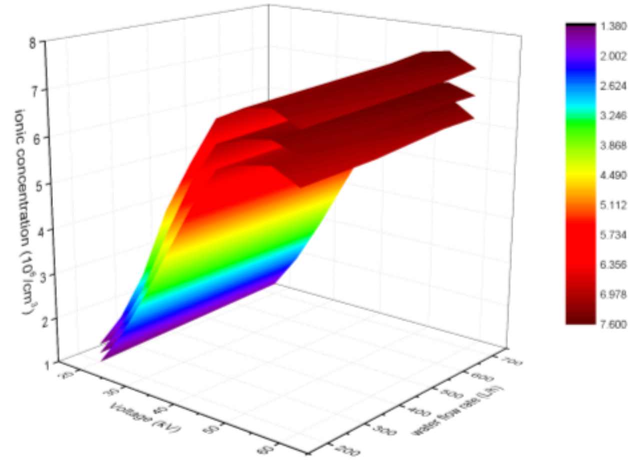
collectors	water film thickness
PVC	$\delta = 0.487Re^{0.540}\left(\frac{\nu^2}{g}\right)^{1/3}$
MCC with carbon fiber	$\delta = 1.283Re^{0.406}\left(\frac{\nu^2}{g}\right)^{1/3}$
MCC with glass fiber	$\delta = 0.648Re^{0.536}\left(\frac{\nu^2}{g}\right)^{1/3}$

The reason is that when the water is going up to the critical flow rate the average film thickness will reach and keep a constant critical value. The collector water holdup is the mass of total water on the collector. Evidently, an increase in average film thickness raises the collector's water holdup. In light of the above findings, it is concluded that MCC with glass fiber's water holdup is the largest with the same water flow rate.

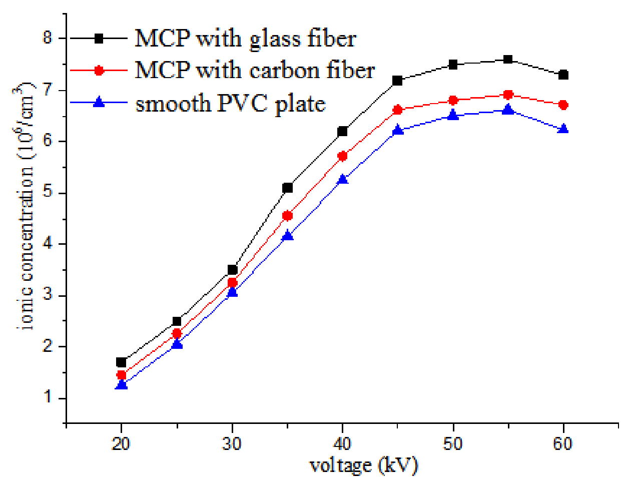
Similar to Nusselt's expression of vertical wall falling film, this paper puts forward the empirical correlations of water film thickness on three collectors by curve fitting. Using the user-defined function fitting method to fit the curves in Figure 5, the empirical expressions are achieved in Table 1 as follows.

3.2 Ionic concentration and V-I characteristics

The ionic concentration not only embodies the discharge characteristics of an electric field, but also influences the dust charging significantly. The concentration of ions whose mobility is less than 1.0m^2/V·s is measured and is shown in Figure 6 as follows. Map a represents the ionic concentrations of three kinds of collectors with different



(a) Ionic concentration with different water flow rates



(b) Ionic concentration with the flow rate of 700 L/h

Figure 6: Ionic concentrations in MWESP with three collectors

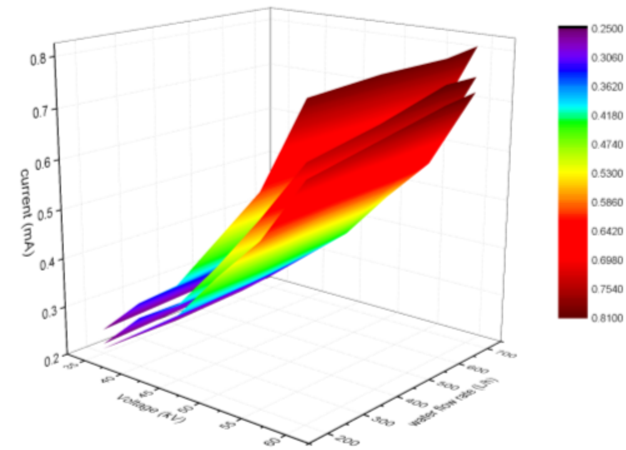
voltages and different water flow rates. The order of surfaces from high to low is MCC with glass fiber, MCC with carbon fiber and PVC. The ionic concentrations of three collectors with the water flow rate of 700L/h are taken as an example and shown in Map b.

It can be found from Figure 6 that the higher the voltage rises the higher the ionic concentration becomes, because higher voltage aggravates the electro-discharge more apparently. At the same time, when the voltage is same, the ionic concentrations with three kinds of collectors decreases in turn of MCC with glass fiber, MCC with carbon fiber and smooth PVC plate, being the same turn as collector's water holdup, indicating that an increase in collector's water holdup has the effect of increasing the ionic concentration. The collector which has more water holdup makes more water evaporating into the airflow. Essentially, it is the fabric constructions that not only increase the evaporation area but also raise the water holdup.

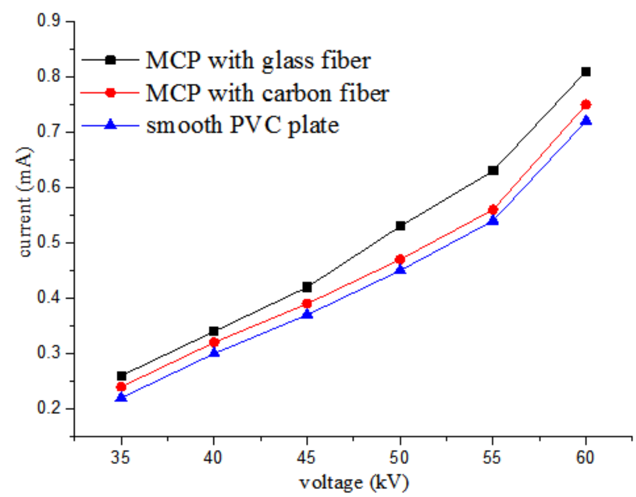
Compared with air the water molecules are easier ionized, thus the more water molecules evaporate into airflow the more number of free electrons arises. In addition, water molecules, free electrons and ions can merge into hydrated ionic groups, which have more weight and less ion mobility. As a result, the more water evaporates into the air, the more ions whose mobility are less than $1.0\text{m}^2/\text{V}\cdot\text{s}$ are produced.

When the air velocity in electric field is 1.0 m/s and the feeding amount of powder is 17g/min, the V-I characteristics are shown in Figure 7 as follows. Map a represents the current of three kinds of collectors with different voltages and different water flow rates. The surfaces from top to bottom represent MCC with glass fiber, MCC with carbon fiber and smooth PVC. The current of three collectors with the water flow rate of 700 L/h is taken as an example and displayed in Map b.

Figure 7 illustrates that under the same water flow rate and the same voltage, the current happens on MCC with glass fiber, MCC with carbon fiber and smooth PVC plate are in the order from big to small, which is similar to the order of film thickness under the same water supplying. It is shown obviously that MCC with glass fiber has the smallest discharge inception voltage, implying the best energy saving effect.



(a) V-I characteristics with different flow rates



(b) V-I characteristics with the flow rate of 700 L/h

Figure 7: V-I characteristics of three collectors

3.3 Collection efficiency

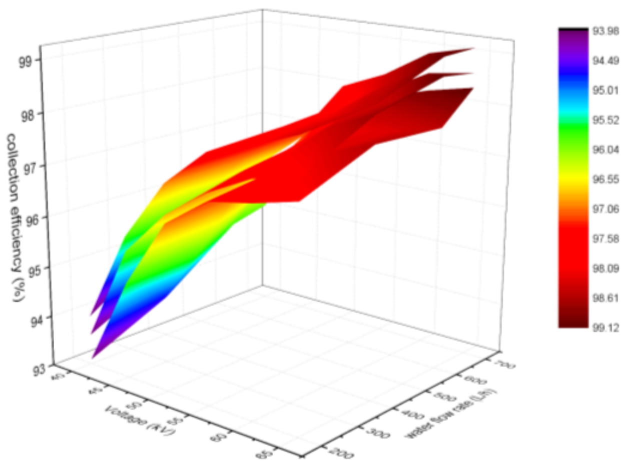
When the air velocity in electric field is 0.8 m/s and the feeding amount of powder is 17g/min, the collection efficiency at different water flow rates is shown in Figure 8 as follows. Map a represents the dust collection efficiency of three kinds of collectors with different voltages and different water flow rates. The surfaces from top to bottom are MCC with glass fiber, MCC with carbon fiber and smooth PVC. The dust collection efficiency of three collectors with the water flow rate of 700 L/h is taken as an example and displayed in Map b.

As shown in Figure 8, the dust collection efficiency increases with the increase of water flow rate. At the same time, if the water flow rate is determined, the descending order of dust collection efficiency, as the same as the descending order of water film thickness, is listed as MCC with glass fiber, MCC with carbon fiber and smooth PVC plate. It is proved that thicker water film is benefit to improve the dust collection efficiency. The cause lay in the fact that thicker water film not only has more scouring capability and electrical conductivity but also can provide more water molecules evaporated into the electric field, which increases the charge density.

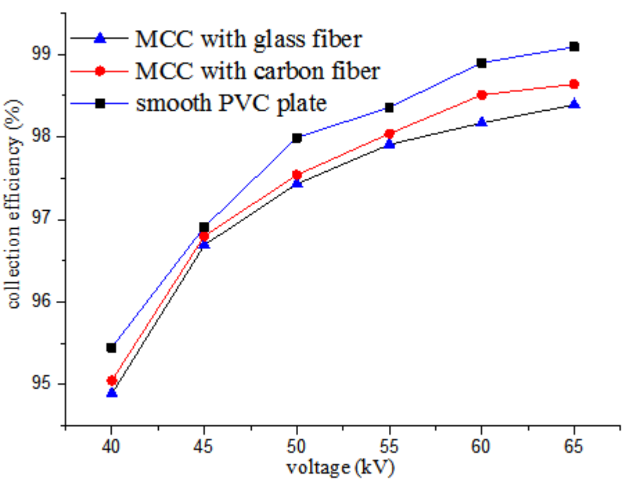
3.4 Classification efficiency

Taking the water flow rate of 700L/h as an example, we carry out the classification efficiency experiment with the air velocity of 0.8m/s and the feeding amount of powder of 17g/min. The result is displayed in Figure 9 below.

It is shown that the classification efficiency of three kinds of collectors increases when the voltages increase from 50kV to 60kV. And the collection efficiency of the particles with diameter less than 1μm increases more than those with diameter more than 1μm. The collectors in the descending order by classification efficiency are MCC with glass fiber, MCC with carbon fiber and smooth PVC plate, especially for particles with diameter less than 1μm, as



(a) Collection efficiency with different flow rates



(b) Collection efficiency with the flow rate of 700 L/h

Figure 8: Dust collection efficiency of three collectors

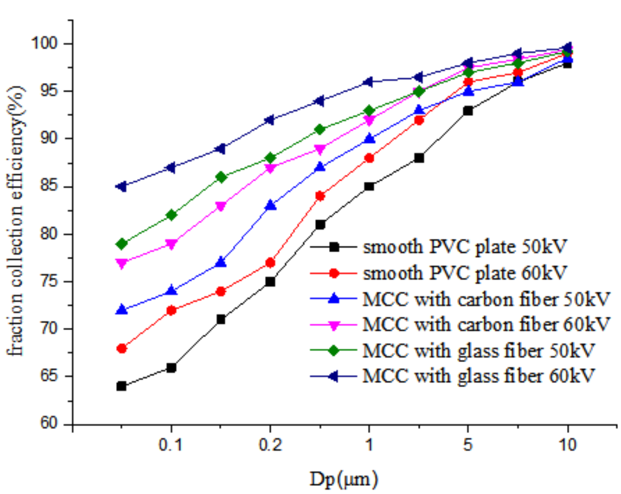


Figure 9: Classification efficiency of three collectors

the same as the descending order of total collection efficiency in Figure 8. The reason for this is that the surface of MCC collectors can be covered with more uniform water film than smooth PVC plate. As to large particles, especially with the diameter more than 5μm, three collectors have almost equal collection efficiency. It seems that the collection efficiency of MCC with glass fiber at the voltage of 50kV is almost equivalent to the collection efficiency of MCC with carbon fiber at the voltage of 60kV, especially to the particles with diameter more than 1μm. It is found that thicker water film is benefit to the dust removal, especially to the particles with diameter less than 1μm. Because the more thicker water film not only has more powerful scouring force to reduce back corona and re-entrainment of dust, but also results in higher discharge current and flue gas humidity as there is more water evaporated into the flue gas, which improves the particles charge number and electro transport speed. So among three collectors above, MCC with glass fiber has the best ability to remove the submicron particles.

4 Conclusions

Two kinds of novel collectors, MCC with glass fiber and MCC with carbon fiber are presented in this paper, and then their wetting properties are studied and compared with smooth PVC plate. It is illustrated by PDF of film thickness and averaged film thickness that the water film on three collectors from thick to thin is as follows: MCC with glass fiber, MCC with carbon fiber and smooth PVC collector. Furthermore, the empirical expressions of averaged film thickness are obtained by curve fitting.

The ionic concentration and electric field current both increase with the growth of water flow rate and voltage. When the water flow rate and the voltage are determined, the order of ionic concentration and electric field from largest to smallest is MCC with glass fiber, MCC with carbon fiber and smooth PVC plate.

The dust collection efficiency enhances with the increase of water flow rate and voltage in the MWESP. When the water flow rate and the voltage are determined, the order of dust collection efficiency from largest to smallest is similar with the ionic concentration and electric field current, such as MCC with glass fiber, MCC with carbon fiber and smooth PVC plate.

By comparison analysis, besides good rigidity, on the condition of same water flow rate, MCC with glass fiber is proved to have best film forming properties, V-I characteristics, total dust collection efficiency and classification efficiency. In conclusion, MCC with glass fiber is the best promising one in above three kinds of collectors.

Acknowledgement: The financial supports from the Basic Research Priorities Program (No. E2018202333) and the Innovation Ability Improvement Program (No. 19453713D) of Hebei Province, China are gratefully acknowledged.

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