IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received August 13, 2019, accepted September 3, 2019, date of publication September 10, 2019, date of current version September 23, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2940613

New Design of Ion Blower Based on Needle-Dielectric-Needle Bipolar Corona Discharge

RONGGANG WANG[1,2,3], YU ZHANG[4], ZHAORUI JIANG[2], TONGKAI ZHANG[2], JITING OUYANG[2], AND YURONG SUN[3]

[1]School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China
[2]School of Physics, Beijing Institute of Technology, Beijing 100081, China
[3]Suzhou TA&A Ultra Clean Technology Company Ltd., Suzhou 215121, China
[4]Beijing Orient Institute of Measurement and Test, Beijing 100094, China

Corresponding author: Jiting Ouyang (jtouyang@bit.edu.cn)

This work was supported in part by the Electrostatic Research Foundation of Liu Shanghe Academicians and Experts Workstation, Beijing Orient Institute of Measurement and Test under Grant BOIMTLSHJD20181005.

ABSTRACT We present here a new design of ion blower based on bipolar corona discharge of needle-dielectric-needle configuration. With the help of the dielectric plate, the new ion blower can endure higher voltage before spark than the traditional bipolar corona discharge, with the similar discharge characteristics and current-voltage curve. The high operating voltage provides a much greater ionic wind velocity compared with the traditional needle-to-needle corona. The neutral ionic wind can reach as far as 0.45m with a velocity of 0.2m/s. This feature is very helpful for eliminating mechanical rotating components in the design of ion blowers, so that the size of ion blower can be greatly compressed and the noise significantly reduced, which is more suitable for electrostatic elimination in small areas and some specific scenarios. The design of self-balancing regulation unit can effectively monitor the charged characteristics of mixed ion wind and make corresponding adjustments to ensure the neutrality of positive and negative discharge. This new ion blower has an excellent performance, including an offset voltage of ±5V, a short discharge time of 5s or less at distance of 20cm.

INDEX TERMS Ion blower, ionic wind, bipolar corona discharge, needle-dielectric-needle.

I. INTRODUCTION

Electrostatic is one of the common phenomena in electronic industries. Avoiding and reducing the damages of electrostatic discharge (ESD) is a mandatory requirement for electronic products [1]. Frictional charging of insulating material and human body are the main sources to disturb the electronic products. Traditionally, human body can be earthed via footwear or wrist strap and ion blower based on corona discharge is the most popular method to control the electrostatics of insulating objects. There is generally a mechanical rotating fan in the ion blower, which help to transfer the positive and/or negative ions from the discharge devices to the objects. But there are at least two disadvantages of this kind of ion blower. One is the noise coming from the rotating component which makes the operator irritable feelings and uncomfortable experiences. This moving component is also a source of micro-particles which results in pollution of cleanroom environment in some special processing like hard disk and semiconductor sealing,and causes hazards to the electronic products. Another shortcoming is the dimension of the mechanical fan which is generally too large to be used in micro-areas.

Ion blower free of mechanical moving component is a potential measurement to solve these problems. Corona ionic wind [2], [3], without mechanical rotating components, has shown great potential in a lot of applications due to the low power consumption, low noise, and high ionic concentration [4], [5]. E.g. this corona ionic wind can provide an alternative technology in enhanced heat dissipation at micro-scale integrated circuit [6]–[9]. it also helps in recent the flow control for the purpose of improving boundary layer hydrodynamics in aeronautics [10]–[12]. Moreover, the ionic wind can remove atmospheric particle [13] and help to modify

The associate editor coordinating the review of this manuscript and approving it for publication was Luca Cassano.

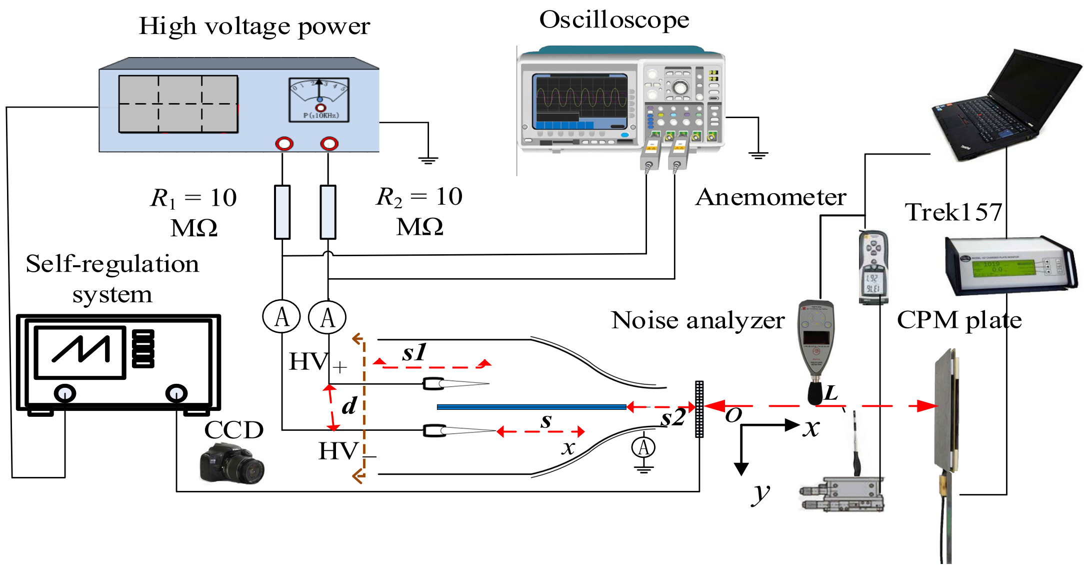


FIGURE 1. Schematic of experimental setup.

surface properties [14]. Bipolar corona discharge can generate the electroneutral ionic wind [15]–[17] which is useful in the fields of electrostatic control and electricity elimination [18]–[21]. Ionic wind from corona was firstly reported by Guericke [22] in 1672. Thereafter this electro-generated airflow in corona discharge in different structures was detected experimentally by some other researchers. The speed of ionic wind is generally of 0.8 ∼ 9m/s [23]–[26] and the wind pressure is of 10Pa measured by various methods (e.g., Kawamoto's group [20] and Ouyang's group [21], [27]). Both positive and negative ionic wind can be generated depending on the polarity of the corona electrode. Cavallo et al. [28] deduced and estimated the ion motion in corona discharge process, and qualitatively pointed out the difference between positive and negative corona. Since unipolar ionic wind has strong polarity, a single unipolar corona cannot satisfy the application of electrostatic elimination. However, ionic wind can also be achieved in neutral according to the electrode arrangement [29]–[31]. For example, Dau et al. [32], [33] developed a bipolar corona structure to generate neutral airflow, in which needle-needle-to-ring structure (i.e., including both negative and positive corona needles) was used. This bipolar ion blower is also able to be applied in field of micro-fluidics. But there still exist some problems of this ion blower. The active distance is generally shorter, less than 1cm. Also, the powered bare electrodes may be bridged by spark during the operation.

To overcome these problems, we developed a novel ion blower based on bipolar coronas with a dielectric plate which has been assembled in the middle of the positive and negative needles. In this paper, we present the study on the electroneutral ionic wind in this needle-dielectric-needle configuration of corona discharge. The electrical and mechanical characteristics, wind profiles as well as the electrostatic elimination ability were investigated in details. The effects of parameters including the dielectric plate, the overvoltage, the electrode gap, the gap from the tip of needle to the margin of the dielectric plate on the discharge were investigated experimentally. The dielectric plate can suppress the spark discharge sufficiently and improve the discharge stability as well as the axial discharge intensity. Compared with the needle-needle bipolar corona structure, the axial velocity of the ionic wind and the active area can be improved sufficiently in the novel design. In order to improve the electrostatic elimination ability, we also designed a self-regulation system, which can automatically adjust parameters such as overvoltage, so as to obtain more stable offset voltage performance.

II. EXPERIMENTAL SETUPS

The experimental setup is schematically shown in Fig.1. The ion blower consists mainly of a discharge cell and a wind collector. The discharge cell is needle-dielectric-needle bipolar corona, with a dielectric layer inserted between the two needles. For comparison, the needle-needle bipolar corona structure without dielectric layer is also tested. The two needles are made of tungsten, with 15mm in length and 52μm in tip radius. They are placed in parallel, separated by a dielectric SiO_2 plate of 2mm in thickness. The needles and the dielectric plate are put in the center of a PTFE cylindrical collector, with inlet size of 19.6cm^2 and outlet of 5cm^2. The collector is in shape of Laval nozzle to control the ionic wind. A conductive ring is put outside the smaller exit of the collector as grounded electrode. The separation between the powered high-voltage electrode and grounded electrode is of $\boldsymbol{d}_{\mathbf{H-G}} = 20$mm.The distance between the tips of two needles (or $\boldsymbol{d} = 5$ to 16mm) and the needle tip to the outer edge of dielectric plate (or $\boldsymbol{s} = 20$ to 45mm) are adjustable. The distance between needle tips and the collector's edge is fixed at $\boldsymbol{s}\mathbf{1} = 70$ mm, and the distance between the collector's edge to ion balance feedback device is $s2 = 20$ mm.

The two corona needles are powered by a positive and a negative DC power supply ($U+$ and $U-$ for former experiments) through ballast $R1 = R2 = 10M\Omega$, respectively. Micro-ammeter (Brand: HM; Measuring range: 0 to 1999μA, Resolution: 1μA) is connected in series with each needle to measure the discharge current and pico-amperemeter (KEITHLEY Company, Type 6485) is connected to the grounded electrode to measure the net current. The applied voltages are recorded by an oscilloscope (TekTronix TDS3054) through a high voltage probe (P6015A). When the current reaches 1μA, we record the oscilloscope readings as inception voltage. An ICCD camera (Andor istar DH734) is used to record the images of corona discharge. A thermo-sensitive anemometer (DT-8880) is used to measure the axial average wind speed under different discharge conditions. The position of the anemometer can be changed longitudinally (or along x-axis). To evaluate the performance of the ion blower, an ion blower evaluation instrument (TREK157) is used to measure the offset voltage and the discharge time at different positions. The feedback device is set at the position of 20mm away from the collector's edge. It consists of a metal mesh which collects the balance and neutral status and sends back to the self-regulating system, so that the self-regulating system can adjust the negative high voltage accordingly. A noise analyzer (AWA6218B) is used to record the noise of the ion blower. The measurements are carried out in the ambient air at temperature of 22 to 25° and relative humidity of 30% to 65%.

III. EXPERIMENTAL RESULTS

A. DISCHARGE CHARACTERISTICS

The needle-dielectric-needle bipolar corona shows a very different inception characteristic from the typical needle-to-ring corona or needle-needle bipolar corona, as shown in Fig.2(a) for the inception voltage (or U_{br}) at increasing needle-needle distance d. The inception voltage is nearly constant, with a value of ~ 9kV, compared with that of needle-needle bipolar corona which increases with the electrode gap d increasing. The latter is the typical case of needle-to-needle. Also the inception voltage of needle- -dielectric-needle bipolar corona is much higher than that of needle-needle bipolar corona.

But the inception voltage U_{br} increases with the distance s which is from the needle tip to the outer edge of the dielectric plate even if the electrode gap d is constant, as shown in Fig.2(b). This indicates the dielectric plate near the corona electrode influences significantly the inception characteristics. This can be understood as follows. Under the new structure, due to the help of dielectric plate, two discharge needles are isolated and the discharge path is changed. The inception voltage, which is originally affected by the distance d for system without dielectric plate, is now mainly determined by the distance s, rather than the distance d.

Figure 3 shows the *V-I* characteristics of the needle-dielectric-needle bipolar corona at different distance s.

The current increases as a quadratic function of the discharge voltage (see Fig.3(a)). If we plot the equivalent

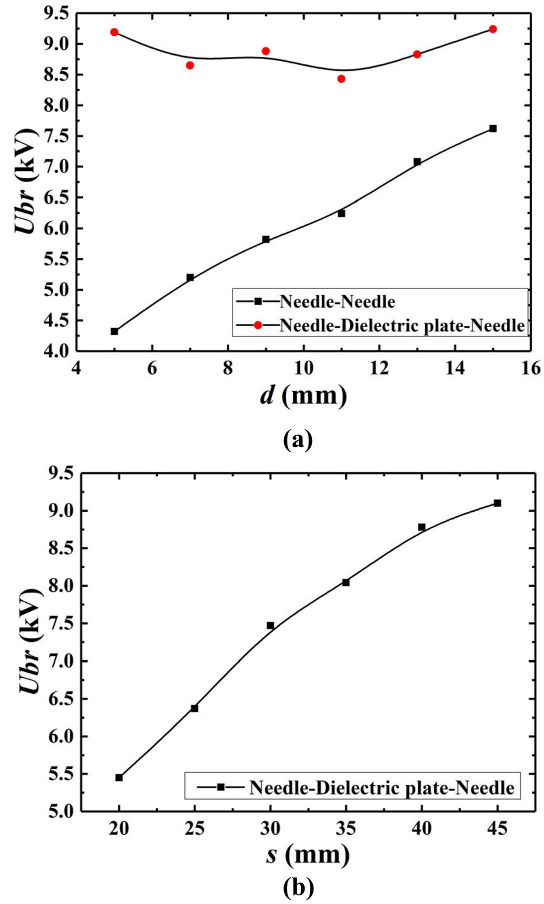


FIGURE 2. Inception voltage of bipolar coronas changing with (a) distance d for needle-needle and needle-dielectric-needle structure when s = 35mm, and with (b) distance s for needle-dielectric plate-needle structure when d = 9 mm.

conductance (or the current over the voltage I/U) versus the voltage, a linear relation is shown in the tested range (see Fig.3(b)). This means that the *V-I* curve follows the classical Townsend relation of typical corona in air or $I = kU \cdot (U - U_{br}) = kU \cdot \Delta U$ (where $\Delta U = U - U_{br}$ is the over-voltage, k is constant determined by the electrode configurations) [13], [34]. The equivalent conductance is 0.2, 0.22, 0.25, 0.3, and 0.42 μA/kV for distance s = 20, 25, 30, 35, and 40mm when $\Delta U = 15$kV, respectively. That is, the current increases faster with the over-voltage, or the equivalent conductance is larger at smaller distance s. This relation is the same as in the needle-needle bipolar coronas, as shown in Fig. 4 for comparison.

The *V-I* curves of needle-needle coronas also follow the Townsend relation, in consistence with the previous results (e.g., Dau *et al.* [32], [33]). However, the maximum over-voltage is much larger in the new design of needle-dielectric-needle coronas, with a value of 20kV compared with 3.5kV in needle-needle bipolar coronas without dielectric layer. This might be due to the dielectric plate which prevents effectively spark between the powered needle and grounded ring, so that the electric field and the discharge intensity can be improved obviously.

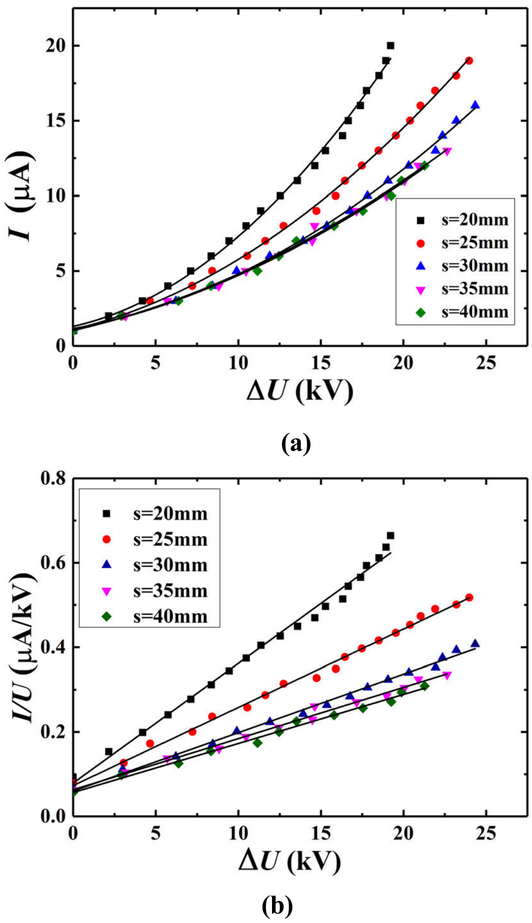


FIGURE 3. Voltage-current curve (a) and equivalent conductance (b) of needle-dielectric-needle corona at different s when d = 9 mm.

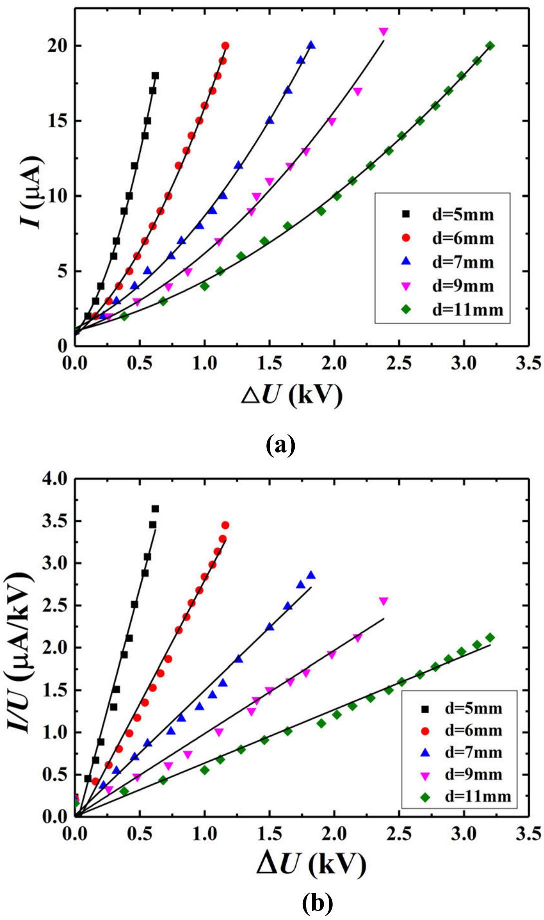


FIGURE 4. Voltage-current curve (a) and equivalent conductance (b) of needle-needle bipolar corona at different gaps d.

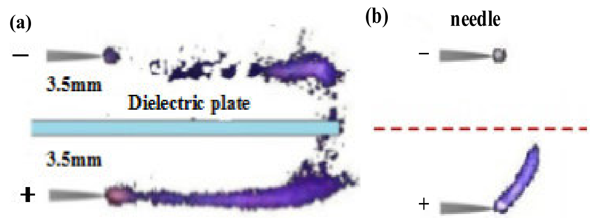


FIGURE 5. Discharge image of (a) needle-dielectric-needle and (b) needle-needle bipolar corona with d = 9mm and s = 20mm. The exposure time of CCD is 300ns. The red dash line in (b) indicates just the central axis of the dimension, not a real object.

Figure 5 is the discharge image of the two bipolar coronas, under over-voltage of (a) $\Delta \boldsymbol{U} = 17.9$kV ($U = 23.4$ kV) for needle-dielectric-needle structure and (b) $\Delta \boldsymbol{U} = 3.2$kV ($U = 8.9$kV) for needle-needle structure. The over-voltage of needle-needle corona is almost the maximum before spark. The other conditions are $\boldsymbol{d} = 9$mm and $\boldsymbol{s} = 20$mm. The needle-dielectric-needle bipolar corona can develop much longer than the needle-needle one, with 23mm in needle-dielectric-needle corona and 3mm in the other. The glow discharge intensity is also stronger.

B. IONIC WIND

The wind speed probe is facing the center of the outlet. The test position moves along the X-axis. We record the average wind speed for a period of time. Figure 6 shows the variation of average ion wind speed with over-voltage at the same position of $L = 20$ mm (L is the distance between collector's edge to the testing position).

The wind velocity of both ion blowers increases linearly with the over-voltage, which is similar to that in the typical coronas. But the velocity in the needle-dielectric-needle bipolar corona is much higher, about 5 times of that in the needle-needle one. This comes from the high operating voltage benefited from the inserted dielectric layer which allows the applied voltage is sufficiently high before transiting into spark. At the same over-voltage (**e.g.,**2.5 kV in Fig.6), the wind speed is 0.3-0.5 m/s under the new structure, larger than 0.2 m/s (or less) of the traditional structure. In addition, a smaller distance s achieves a relative higher ionic wind at the same over-voltage in the new system. This provides a good suggest for the design of ion blower.

The wind velocity decreases at the position far away from the exit of nozzle, as shown in Fig. 7. Increasing over-voltage leads to farther distance of the ion blower. At higher voltage ($\Delta U = 14$kV), the wind can be detected as far as $\boldsymbol{L} = 45$ cm,

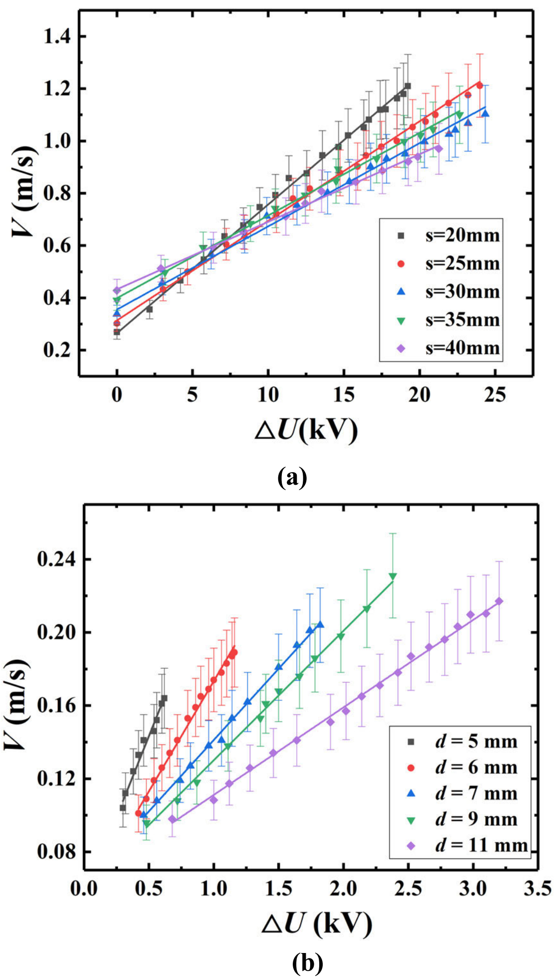


FIGURE 6. Wind velocity versus over-voltage for (a) needle-dielectric-needle and (b) needle-needle bipolar corona.

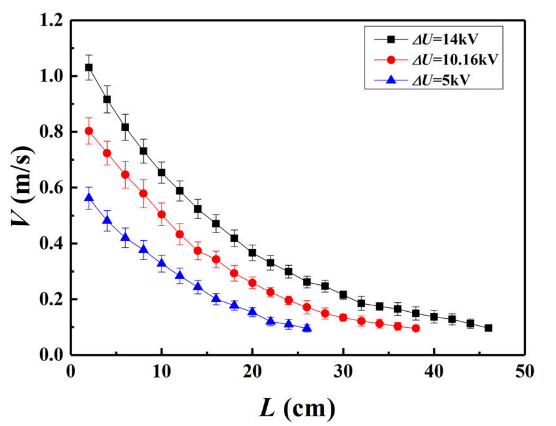


FIGURE 7. wind velocity with distance at three different over voltage.

with $V = 0.2$ m/s which is still greater than that $\boldsymbol{L} = 2$ cm, when $\boldsymbol{d} = 7$ mm, with $V = 0.18$ m/s of the bipolar corona without dielectric plate (see Fig. 6).

C. PERFORMANCE OF THE NEW ION BLOWER

The performance of an ion blower is mainly evaluated by two items, or offset voltage and discharge time according to the international standard of S20.20 which provides the detailed requirement and STM3.1 which provides the detailed test method and procedures. According to current research, we chose $d = 9$ mm and $s = 20$ mm in design. A feedback device is used in the system which is set at the position of 20mm from the edge of the collector. The positive voltage is $\boldsymbol{U}+ = 13.5$ kV and the negative voltage $\boldsymbol{U}-$ can be adjusted automatically between 10 to 15.5kV.

1) OFFSET VOLTAGE

The new ion blower can produce quasi-neutral ion wind if the applied voltage of corona discharge is well controlled. However, the offset voltage will be generally high if there is no feedback system of self-regulation.

Without the self-regulation system, the offset voltage changes in a range of ±60V in 3 hours when the ambient humidity fluctuates within 30%∼65%. When the self-regulation system is working, the offset voltage decreases to ±5V in 24 hours when the ambient humidity fluctuates within 30%∼65%. The self-regulation system is achieved by a feedback device which can detect the ionic electrical neutrality of the ion blower to the system so that the applied negative voltage can slightly be adjusted accordingly. In this way, the offset voltage keeps as low as ±5V or less. The steady state can keep for a long time of 24 hours. This indicates that the self-regulation system is very important for controlling the offset voltage.

2) DISCHARGE TIME

The discharge time of ion blower is another key requirement which describes the time required for an electrostatic potential to be reduced to a given percentage (usually 10%) of its initial value (usually 1000V). The shorter the discharge time, the better the performance of ion blower to prevent ESD damage. According to the international standard S20.20, the requirement of the discharge time can be defined by customer. Most customers require a discharge time being less than 5s when the test position was located in the center of ion bower. According to the Chinese standard of SJ/T11446-2013, the discharge time must be less than 20s within the cover-area of ion blower.

The discharge time of the new ion blower relates to the active distance and the discharge current, as shown in Fig. 8.

Generally, the discharge time increases with the distance L from feedback device. At the same distance, a larger current leads to reduction of the discharge time. Both the positive and negative discharge time show the same trend at increasing distance and current. At larger current, the discharge time increases very little (5s or less) at distance 20cm or less. This results help to optimize the discharge current to get a short discharge time.

IV. DISCUSSIONS

As seen above, the new ion blower follows the similar Townsend relation (or $I = kU \cdot (U - U_{br})$) in V-I curve which is in consistence with the traditional needle/needle-

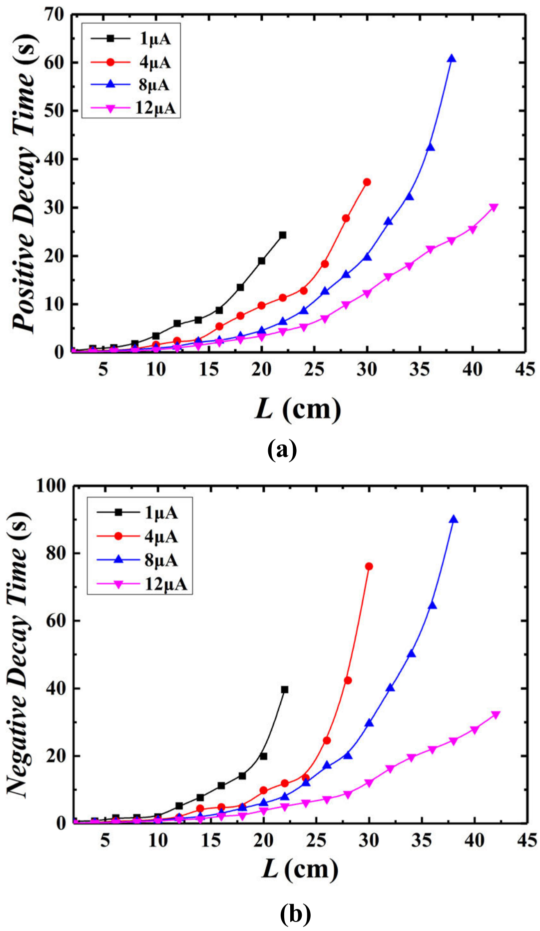


FIGURE 8. Discharge time changing with position at different current for (a) positive and (b) negative ion wind.

needle-to-ring structure. This indicates that the ion/electron motion (at least in the axial direction) should be similar to that in needle-to-ring structure. Actually, the surface charges on each side of the dielectric plate play an important role. They modify the applied electric field, to balance the transverse field (or y-axis) and induce the total field along the longitudinal direction (or x-axis). This makes the corona discharge being almost the same as that in classical needle-to-ring structure. The discharge images (Fig.5) of two bipolar corona discharges obtained by CCD camera also confirmed the results. Under conditions of given pressure and tip curvature, the dielectric plate can effectively change the discharge trajectory, to increase the operation voltage and hence the axial velocity of ionic wind.

The wind velocity of the new ion blower increases almost linearly with the over-voltage, which is also similar to that in typical corona discharge, but with value of ~5 times greater than the traditional ones. This strong ionic wind can cover a larger distance with help of the dielectric plate.

The inception voltage of the bipolar corona discharge is determined by the distance from the needle tip to the outer edge of dielectric plate (or parameter s in bipolar corona system) rather than the gap between the two needles (or parameter d), but the over-voltage relates to the both parameters.

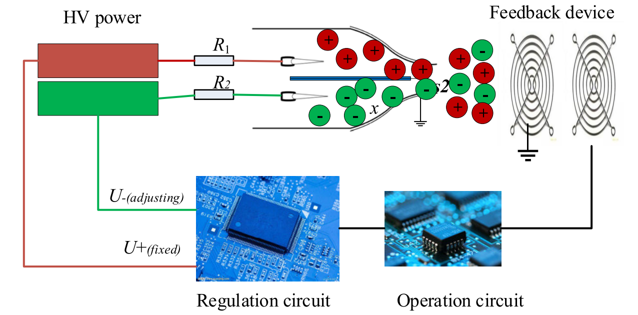


FIGURE 9. Self-regulation system.

The new structure can endure a much higher over-voltage than the traditional needle-needle-to-ring structure due to the dielectric plate. All of these characteristic can help to design a new ion blower without rotating device (e.g. mechanical fan).

Generally, shorter discharge time and better offset voltage range at a longer active distance are the key requirements when evaluating an ion blower. The discharge time can be achieved by higher ion density in the airflow, and the offset voltage depends on the self-regulation system.

On one hand, the velocity of ionic wind is proportional to the over-voltage and inverse proportional relationship to the electrode gap in corona discharge [27]

$$V \approx \frac{1}{d_{\text{H-G}}}\sqrt{\frac{2\varepsilon_0}{\rho}}\Delta U, \tag{1}$$

where $\rho = 1.2\ \text{kg/m}^3$ is the air density, $\varepsilon_0 = 8.85 \times 10^{12}$ F/m is the vacuum permittivity. A dielectric plate helps to increase the over-voltage and prevent spark which easily happens under the needle-needle structure, hence it helps to increase the speed of ionic wind.

On the other hand, the ion/electron density n_i in migration region can be estimated roughly from the current density J, since the current is mainly determined by the drift of charges, or $J = I/A = qn_\text{i}\mu_\text{i}\boldsymbol{E}$ (where μ_i is the ion mobility, $\boldsymbol{E}$ is the averaged electric field, A is the section area of the channel). Take the Townsend relation into account, then the charge density is

$$n_i \approx \frac{kd_{H-G}\Delta U}{qA\mu_i}, \tag{2}$$

which is also related to the over-voltage and the electrode configuration. To get a better performance, adjusting the over-voltage ΔU and the gap d_{H-G} is the good choice. For example, inserting a dielectric plate between the powered electrodes (as we did in the present work) can improve greatly the overvoltage, so that higher wind speed and faster decay time can be achieved, as shown in Figs.6 and 9.

The offset voltage of the ion blower depends on the provide voltage and the self-regulation system. Supplying the same voltage (13.5kV) on the two powered needles, the offset voltage is obviously less than 0 V, with value of -150 ~ -30V. When the negative voltage is decreased to 11.6kV, the offset voltage is in the range of -60V~ +60V. This offset voltage is steady but exceeds the standard's maxim range (-35V to +35V). Reconsidering that the environment humidity and the erosion loss of the needle tip will also affect the offset voltage, the self-adjusting device is therefore needed. It monitors the change of the offset voltage in real time and make the corresponding adjustment to obtain a better offset voltage through adjusting negative discharge voltage.

The self-regulation system consists of three parts: feedback device, operation circuit, and regulating circuit (see Fig. 9)

An electrically neutral ionic wind is obtained at the outer edge of the dielectric plate which was composed of electrons and ions. The neutral or non-neutral flow attaches the collecting layer of the feedback device and then the information is sent to the operation circuit, which can further amplify the feedback voltage. Accordingly, the regulation circuit adjusts the value of the negative input voltage (***U-***). For example, when the neutral bias is positive, the value of the voltage ***U-*** will be increased and the number of electrons/negative ions will increase, and vice versa. When the offset voltage is changed, the accurate self-regulation can be realized automatically. The offset voltage at the outlet can be guaranteed within the range of ±5V in the present system.

Although we have achieved better performance of ion blower under the new structure, two aspects are needed to deal with for the practical application. One is a blower for large area, in which multi-needles should be used. Another is blower for micro region, in which a micro device should be achieved.

V. CONCLUSION

In summary, a new design of ion blower based on needle-dielectric-needle configuration of bipolar corona discharge has been investigated experimentally. The effect of discharge parameters (including the discharge voltage, the over-voltage, the separation between the needle tip and the outer edge of the dielectric plate, and the distance from collector's edge to the testing position) on the wind velocity are investigated in needle-dielectric-needle and in needle-needle configurations for comparison. The performance of the new ion blower (including the offset voltage and the discharge time) have been evaluated according to the related standards. The effect of self-regulation system on offset voltage is also presented. The conclusions are summarized as follows:

1) With dielectric plate, the voltage-current curves of the bipolar corona discharges of the new system also follows the traditional Townsend relation, but the over-voltage of the new design is much larger than the needle-needle bipolar coronas without dielectric plate. The corona discharge and hence the ionic wind develops along the insulating board, which can effectively avoid spark or arc discharge and eventually converge into an electrically neutral ionic wind at the edge.
2) The wind velocity in the new design is much higher, about 5 times, than that in the needle-needle one. In addition, a smaller distance s achieves a relative higher ionic wind at the same overvoltage in the new system. The wind velocity decreases at positions away from the exit of nozzle. Increasing over-voltage leads to a longer distance of ions moving.
3) The new design of ion blower shows excellent performances in offset voltage and discharge time. With help of self-regulation system, the offset voltage of the new ion blower is about ±5V in 24 hours, and the discharge time is 5s or less at testing distance of 20cm. Both the positive and negative discharge times show the same trend at increasing distance and discharge current. A larger current leads to reduction of the discharge time.
4) To use the no-mechanical ion blower in practice, two issues are still needed to be dealt with in the future. One is the blower for large areas of operation. In this case, multi-needles in the bipolar corona are employed. Then the interactions between the needles under the new design should be investigated for optimization. Another is for micro region, in which we should know how to further reduce the size of the system without reducing the performance.

REFERENCES

[1] S. H. Voldman, *ESD:Physics and Devices*. Chichester, U.K.: Wiley, 2004, pp. 18–20.

[2] M. Golden and A. Golden, "Corona discharges," in *Gaseous Electronics*, M. Hirsh and H. J. Oskam, Eds. New York, NY, USA: Academic, 1978, pp. 1348–1359.

[3] E. D. Fylladitakis, M. P. Theodoridis, and A. X. Moronis, "Review on the history, research, and applications of electrohydrodynamics," *IEEE Trans. Plasma Sci.*, vol. 42, no. 2, pp. 358–375, Feb. 2014.

[4] J. R. Roth, S. Nourgostar, and T. A. Bonds, "The one atmosphere uniform glow discharge plasma(OAUGDP)—A platform technology for the 21st century," *IEEE Trans. Plasma Sci.*, vol. 35, no. 2, pp. 233–250, Apr. 2007.

[5] D. B. Go, S. V. Garimella, T. S. Fisher, and R. K. Mongia, "Ionic winds for locally enhanced cooling," *J. App. Phys*, vol. 102, no. 5, Sep. 2007, Art. no. 053302.

[6] T. I. J. Goodenough, P. W. Goodenough, and S. M. Goodenough, "The efficiency of corona wind drying and its application to the food industry," *J. Food Eng.*, vol. 80, no. 4, pp. 1233–1238, 2007.

[7] P. Magnier, D. Hong, A. Leroy-Chesneau, J.-M. Pouvesle, and S. J. Hureau, "A DC corona discharge on a flat plate to induce air movement," *J. Electrostatics*, vol. 65, nos. 10–11, pp. 655–659, Oct. 2007.

[8] E. Moreau, C. Louste, and G. Touchard, "Electric wind induced by sliding discharge in air at atmospheric pressure," *J. Electrostatics*, vol. 66, pp. 107–114, Jan. 2008.

[9] Y.-G. Yue, Z.-J. Ding, K. Wang, Z.-L. Ai, L.-J. Yang, and Q.-G. Zhang, "Study on heat transfer enhancement of a heated metal plate with gas discharges," (in Chinese), *Proc. CSEE*, vol. 26, no. 3, pp. 91–95, Feb. 2006.

[10] H.-M. Song, Y.-H. Li, C.-B. Su, Y. Wu, and P. Zhang, "Experimental studies of excitation parameters' influences on plasma EHD acceleration effect," *High Voltage App.*, vol. 42, no. 6, pp. 435–441, Dec. 2006.

[11] F.-D. Li, L.-T Li, J.-F. Sun, and E. Tatsumi, "Effect of electrohydrodynamic (EHD) technique on drying process and appearance of okara cake," *J. Food Eng.*, vol. 77, pp. 275–280, Nov. 2005.

[12] A. Niewulis, J. Podliński, M. Kocik, R. Barbucha, J. Mizeraczyk, and A. Mizuno, "EHD flow measured by 3D PIV in a narrow electrostatic precipitator with longitudinal-to-flow wire electrode and smooth or flocking grounded plane electrode," *J. Electrostatics*, vol. 65, pp. 728–734, Nov. 2007.

[13] L. Li, S. J. Lee, W. Kim, and D. Kim, "An empirical model for ionic wind generation by a needle-to-cylinder dc corona discharge," *J. Electrostatics*, vol. 73, pp. 125–130, Feb. 2014.

[14] L. Yang, W. A. Wei, and L. I. Cen, "Experimental and theoretical research progress in ionic wind produced by corona discharge and its application," *High Voltage Eng.*, vol. 42, no. 4, pp. 1100–1108, Feb. 2016.

[15] J. T. Ouyang, Y. Zhang, and Y. Qin, "Micro-discharge and its applications," *High Voltage Eng.*, vol. 42, no. 3, pp. 673–684, 2016.

[16] J. Wilson, H. D. Perkins, and W. K. Thompson, *An Investigation of Ionic Wind Propulsion*. Washington, DC, USA: NASA, 2009.

[17] A. Yehia, E. Abdel-Fattah, and A. Mizuno, "Positive direct current corona discharges in single wire-duct electrostatic precipitators," *AIP Adv.*, vol. 6, no. 5, May 2016, Art. no. 055213.

[18] B. Wettervik, T. Johnson, S. Jakobsson, A. Mark, and F. Edelvik, "A domain decomposition method for three species modeling of multi-electrode negative corona discharge—With applications to electrostatic precipitators," *J. Electrostatics*, vol. 77, pp. 139–146, Oct. 2015.

[19] X. Dexuan, G. Shiwang, M. Junfeng, S. Yinghao, W. Haijun, and G. Zhiming, "Experimental study on electrostatic precipitation with spraying corona discharges," *J. Beijing Inst. Technol.*, vol. 5, pp. 1–8, Jun. 2006.

[20] H. Kawamoto and S. Umezu, "Electrostatic micro-ozone fan that utilizes ionic wind induced in pin-to-plate corona discharge system," *J. Electrostatics*, vol. 66, nos. 7–8, pp. 445–454, Jul. 2008.

[21] Y. Zhang, L. Li, and J. Ou, "Pressure distribution induced by ionic wind in needle-to-water corona discharge," *High Voltage Eng.*, vol. 39, no. 9, pp. 2187–2192, Sep. 2013.

[22] M. Robinson, "A history of the electric wind," *Amer. J. Phys.*, vol. 30, pp. 366–372, May 1962.

[23] H. Nakamura and R. Ohyama, "An image analysis of positive ionic wind velocity under the DC corona discharge in needle-cylinder electrode system," in *Proc. IEEE Conf. Elect. Insul. Dielectric Phenomena*, Oct. 2009, pp. 192–195.

[24] E. Moreau and G. Touchard, "Enhancing the mechanical efficiency of electric wind in corona discharges," *J. Electrostat.*, vol. 66, nos. 1–2, pp. 39–44, 2008.

[25] J. X. Yuan, W. Qiu, C. Zheng, L. J. Yang, Q. G. Zhang, M. Dong, and W. Z. Zhang, "Study on characteristics of ionic wind from atmosphere discharge," *Proc. CSEE*, vol. 29, pp. 110–116, Dec. 2009.

[26] J. Yuan, L. Yang, Q. Zhang, P. Liu, H. Zhao, X. Du, and J. Yan, "Ionic wind characteristic of tine-plat affected by electrode parameter from atmosphere discharge," *Trans. China Electrotechn. Soc.*, vol. 25, no. 1, pp. 24–29, Apr. 2010.

[27] Y. Zhang, L. Liu, Y. Chen, and J. Ouyang, "Characteristics of ionic wind in needle-to-ring corona discharge," *J. Electrostatics*, vol. 74, pp. 15–20, Apr. 2015.

[28] T. Cavallo, *A Complete Treatise Of Electricity In Theory And Practice: With Original Experiments*, 2nd ed. London, U.K.: 1777.

[29] R. Vertriest, R. Morent, J. Dewulf, C. Leys, and H. Van Langenhove, "Multi-pin-to-plate atmospheric glow discharge for the removal of volatile organic compounds in waste air," *Plasma Sources Sci. Technol.*, vol. 12, pp. 412–416, Jun. 2003.

[30] M. J. Johnson, R. Tirumala, and D. B. Go, "Analysis of geometric scaling of miniature, multi-electrode assisted corona discharges for ionic wind generation," *J. Electrostatics*, vol. 74, pp. 8–14, Apr. 2014.

[31] Y. Zhu *et al.*, "Trapping Particulates by Needle-Matrix-to-Plate Corona Discharge," *J. Beijing Inst. Technol.*, vol. 25, pp. 137–140, Mar. 2005.

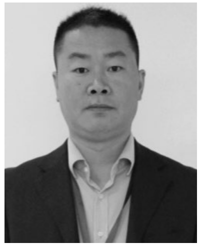
[32] V. T. Dau, T. X. Dinh, T. Terebessy, and T. T. Bui, "Bipolar corona discharge based air flow generation with low net charge," *Sens. Actuators A, Phys.*, vol. 244, pp. 146–155, Jun. 2016.

[33] V. T. Dau, T. X. Dinh, T. Terebessy, and T. T. Bui, "Ion wind generator utilizing bipolar discharge in parallel pin geometry," *IEEE Trans. Plasma Sci.*, vol. 44, no. 12, pp. 2979–2987, Dec. 2016.

[34] J. Ouyang, Z. Zhang, Y. Zhang, and Z. L. Peng, "Experimental study on the characteristics of negative-corona trichel pulses in air," *High Voltage Eng.*, vol. 40, no. 4, pp. 1194–1200, Apr. 2014.

[35] L. Zhao and K. Adamiak, "EHD flow in air produced by electric corona discharge in pin-plate configuration," *J. Electrostatics*, vol. 63, pp. 335–337, Mar. 2005.

[36] A. M. Drews, L. Cademartiri, G. M. Whitesides, and K. J. M. Bishop, "Electric winds driven by time oscillating corona discharges," *J. Appl. Phys.*, vol. 114, no. 14, p. 143302, 2013.



RONGGANG WANG was born in Hengshui, Hebei, China, in 1982. He received the B.S. and M.S. degrees in mechanical and electronic engineering from the Xi'an University of Science and Technology, in 2005 and 2008, respectively. He is currently pursuing the Ph.D. degree with the Beijing Institute of Technology.

From 2008 to 2011, he was a Design Engineer with Eaton Powering Business. Since 2011, he has been the Research and Development Department Manager of the Suzhou TA&A Ultra Clean Technology Company Ltd. He is the author of one book, over 10 articles, and over 40 patents. His research interests include ESD issue and ESD prevention.

YU ZHANG was born in Beijing, China, in 1989. He received the Ph.D. degree in physics from the Beijing Institute of Technology, Beijing, China, in 2017. He is currently an Engineer with the Beijing Orient Institute of Measurement and Test, Chinese Academy of Space Technology. His research interests include electrostatic discharge physics, protections, and its applications.

ZHAORUI JIANG was born in Liaocheng, Shandong, China, in 1991. He received the M.S. degree in physics from the Beijing Institute of Technology, in 2018.

He is mainly involved in the research work on corona discharge.

TONGKAI ZHANG was born in Shenyang, Liaoning, China, in 1991. He received the B.S. degree in physics from the Beijing Institute of Technology, in 2016, where he is currently pursuing the Ph.D. degree. He is mainly involved in the research work on corona discharge.

JITING OUYANG was born in Hubei, China, in 1966. He received the B.S. degree in physics from Zhejiang University, the M.S. degree in physics from the Institute of Physics, Chinese Academy of Sciences, and the Ph.D. degree from the Beijing Institute of Technology.

Since 1991, he has been involved in the teaching and research of low-temperature plasma physics and application, electrostatic technology for a long time. His research interests include atmospheric pressure and low-pressure discharge plasma source, plasma nonlinearity, surface modification of low-temperature plasma and material technology, interaction between plasma and electromagnetic wave, electrostatic testing and detection, electrostatic safety and protection, and so on.

YURONG SUN was born in Hebei, China, in 1982. She received the B.S. and M.S. degrees in physics from Hebei University.

Since 2008, she has been a Research and Development Engineer with Suzhou TA&A Ultra Clean Technology Company Ltd. She is the author of more than five articles, and more than ten inventions. Her research interests include ESD issue and ESD prevention.