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An experimental study of relative humidity and air flow effects on positive and negative corona discharges in a corona-needle charger

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ABSTRACT

In this paper, the effects of inlet air RH and air flow rate on positive and negative corona discharges in a corona-needle charger have been experimentally studied and discussed. Its corona discharge characterizations in terms of current-to-voltage relationships of the corona-needle charger on the effects of inlet air RH and air flow rate were evaluated at applied corona voltages between 0 and 3.1 kV, an air flow rates between 5 and 15 L/min, a relative humidity between 20 and 90%, and an operating pressure of about 101.3 kPa. Experimental results were shown that discharge current is strongly affected by the RH level of the inlet air. The positive discharge current was found to be decreased with increasing RH value at RH values below 60% and increased with increasing RH value at RH value above 60% in the same corona voltage. The negative discharge current was found to be stable with increasing RH value at RH values below 40% and increased with increasing RH value at RH value above 40% in the same corona voltage. For the air flow rate effects, the positive discharge current was found to slightly decrease when the air flow rate increased at RH value below 90% and to increase with the air flow rate at RH value of 90%. For the negative corona, the discharge current was also found to monotonically decrease when the air flow rate increased.

1. Introduction

Producing unipolar ions by corona discharging has been applied successfully in unipolar aerosol charging and several designs of aerosol corona charger have been employed and described in the published literature [1]. Unipolar aerosol corona chargers have been widely used in the measurement of aerosol particle charge based on unipolar corona charging and electrostatic detection of charged aerosol particles such as the electrical aerosol detector. This is because of its simplicity and capacity to provide high concentration of ions [2]. A typical electrical aerosol detector consists of two key components, one for unipolar aerosol charging and the other for measuring the electric current on charged aerosol with an electrometer. The output signal of an electrometer depends strongly on the particle charging technique used [3]. However, the detector was very stable at relative humidity (RH) values below 60% but the detector zero reading starts to drift away from the manufacturers expected stable value at RH higher than 60%. This makes the detector unstable, its output unreliable and a strong indication that the detector is not suitable for use under inlet air RH of above 60% such as ambient atmospheric conditions, water content of ambient aerosol particles is usually to be below and above 60% [4]. Placing some silica gel dryer or dehumidifier before enter the detector however reduced the drift, allowing its use under conditions of over 60% RH.

In the aerosol particle charging by corona discharge, the air RH had significant effects on both positive and negative corona discharges and electrostatic characteristics of the charger. Corona discharge is a gas discharge phenomenon and it is influenced by many factors, including air humidity and temperature. At higher RH, the adsorption of water on the surface of a particle will have a significant impact on the corona onset electric field, the electric conductivity enhancement and electrical mobility of ions. The corona onset electric field decreased with the increase of air RH [5–8]. Back in 1920, Peek proposed his well-known empirical

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equation for evaluating the corona onset electric field on conductors [9,10]. This equation included the influence of temperature and pressure, but the effect of air humidity was ignored. Many researchers numerically studied the distribution of electric filed and charge density in electrostatic precipitators (ESPs) [11,12]. Peek equation was used in these studies, which considered the effects of temperature and pressure. But the effect of air RH was not included in these studies. A few modified Peek formulas were suggested to account for the effect of air RH [12,13]. Previous theoretically and experimentally studies, investigating the effect of RH on the electrostatic aerosol charge and on current-to-voltage characteristics have been numerous studied in the past several decades [5–18]. For instance, Young et al. [14] was studied the influence of RH on the electrostatic charge and aerosol performance of dry powder inhaler carrier based systems. The authors reported in this paper that increased storage RH resulted in a reduction in net charge to mass ratio with the greatest reduction at RH >60%. Higher RH would allow a greater degree of electron mobility and thus reduce the charging mechanism. Fouad and Elhazek [7] was studied the effect of humidity on positive corona discharge in a three electrode system. The authors reported in this paper that the corona inception voltage increases as the air relative humidity increases up to a certain limit after which the corona inception voltage begins to decrease with increasing air relative humidity. It is also found that the increase of air relative humidity favors the positive glow formation and affects its stability. Nouria et al. [11] was characterized the behavior of DC corona discharge in wire-to-plane ESPs as influenced by the RH of the inlet air. The authors reported in this paper that discharge current is strongly affected by the RH level of the inlet air. The time-averaged current is lower at higher RH for a given voltage, except when RH of 99%. Time evolution of the discharge current is affected by the RH especially in the case of negative corona. Above various works have been experimentally and theoretically presented the effect of air RH on both positive and negative corona discharges for larger voltage range in various electrode geometries such as the wire-to-cylinder, the wire-to-plane, needle-to-plane and the point-to-plane, but was not have taken in the needle-to-nozzle electrode geometry and was also not introduced explicitly the dependence of the air flow rate in these studies. Since the geometrical configuration of electrodes of the corona-needle charger is similar to the needle-to-nozzle electrode geometry, a coaxial needle electrode placed along the axis of a cylindrical tube with tapered ends, and the corona voltage was applied only within a narrow range, typically 2.5–3.5 kV. Therefore, the effect of inlet air RH and air flow rate on positive and negative corona discharges in a corona-needle charger has not been extensively studied for a narrow voltage range in previous work and literature. The knowledge of the inlet air RH and air flow effects on positive and negative corona discharge behavior in the corona-needle charger is of crucial important for measuring water content of ambient aerosol particle charge by the electrical aerosol detector in ambient atmospheric conditions. Some aspect of this effect require further investigations in order to validate a realistic mathematical model of the physical phenomena, as an essential step towards the accurate numerical simulation of the aerosol particles charging by corona discharge.

The aim of the present paper is to experimentally study the effects of inlet air RH and air flow rate on positive and negative corona discharges in a corona-needle charger. Its corona discharge characterizations in terms of current-to-voltage relationships of the corona-needle charger on the effects of inlet air RH and air flow rate were experimentally studied and discussed at applied corona voltages between 0 and 3.1 kV, an air flow rates between 5 and 15 L/min, a relative humidity between 20 and 90%, and an operating pressure of about 101.3 kPa.

2. Description of corona-needle charger

The schematic diagram of the corona-needle charger used to evaluate the relative humidity and air flow effects in this study is shown in Fig. 1. The corona-needle charger's geometrical configuration is similar to the corona-needle charger used by Intra and Tippayawong [19,20]. The present charger consists essentially of a coaxial needle electrode placed along the axis of a cylindrical tube with tapered end, and divided into three sections. The first and second sections (from top to bottom in the drawing) are made of a polytetrafluoroethylene (PTFE), and the third (outlet section) of stainless steel tube. The PTFE tube is an electrical insulator between needle electrode and outer electrode and served to hold the needle electrode coaxial with the outer electrode. The needle electrode could be screwed into the PTFE insulator to connect to a DC high voltage supply, typically in the range between 2.7 and 3.0 kV. The needle electrode is made of a stainless steel rod, 3 mm in diameter, ending in a sharp tip. The needle electrode was polished to an extremely fine surface finish to avoid undesirable electric field effect on particle motion due to non-uniform electric field which results from small surface scratches and imperfections. The tip radius is about 50 μm, as estimated under a microscope. The needle cone angle is about 10°. The diameter of the outer electrode is 20 mm, its length is 20 mm with conical shape. The orifice diameter is about 3.5 mm. The distance between the needle electrode and the cone apex is 1.75 mm. The needle electrode head is connected to a positive and negative high voltage, while the outer electrode is grounded.

3. Corona current and discharge in humid air

In the absence of aerosol particles, Townsend derived an equation to characterize the DC steady corona current–voltage relationship for point-to-plane geometry is given by Ref. [21].

$$I = AV(V - V_o) \quad (1)$$

where I is the corona discharge current, V is the applied voltage, V_o is the corona onset voltage and$A$ is the dimensional constant depending on the inter-electrode distance, the needle electrode

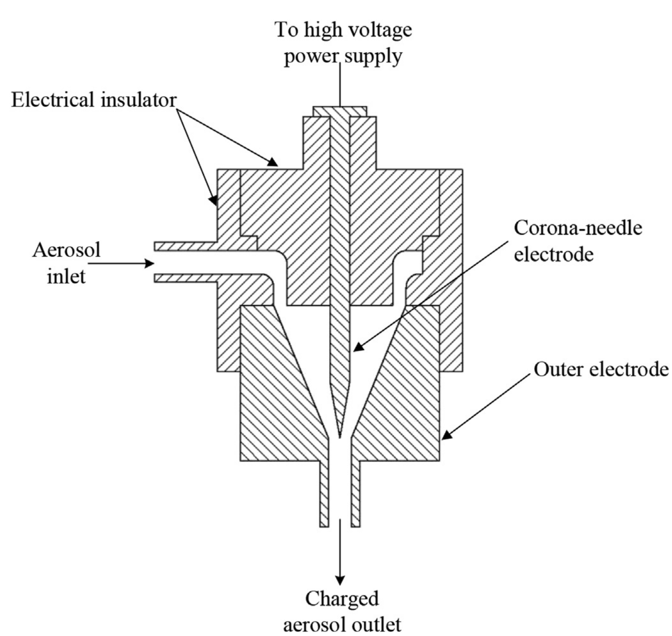


Fig. 1. Schematic diagram of the corona-needle charger.

radius, the charge carrier mobility in the drift region and other geometrical factors. Further, in 1980 Henson [21] theoretically developed a mathematical model for microscopic point-to-plane coronas in the steady-state regime, which was based on his work in liquid helium and expressed as

$$I = (2\pi K\varepsilon/\alpha)[F(\delta/\alpha)]^{-2}(V - V_o)^2 \quad (2)$$

where δ is the minimum corona glow radius, α is the distance between the needle tip and the plane, K is a dimensional constant and $F(\delta/\alpha)$ is a polynomial function of δ/α.

The value of the corona onset electric field strength, E_o, must be known, which has a strong dependence on the electrode tip radius and distance between needle electrode and nozzle [21]. Despite the experimental and theoretical efforts made to predict corona onset electric field accurately, its experimentally observed value varies under different conditions. The critical electric field strength, E_c, for the corona onset is given by the Peeks's equation [9].

$$E_c = m_v E_o \delta\left(1 + \frac{k}{\sqrt{\delta r}}\right) \quad (3)$$

where

$$\delta = \frac{P}{P_r}\cdot\frac{273 + T_r}{273 + T}, \quad (4)$$

m_v is the roughness coefficient of surface of conductor is 1 for smooth cylindrical electrodes, r is the radius of curvature of the needle tip, k is the empirical constant for cylindrical geometry, normally 0.308 $cm^{1/2}$, δ is the relative air density factor, T_r is the absolute temperature of room air, P_r is the normal atmosphere pressure, and T and P are the operating temperature and pressure of the air. For Peek equation, the standard reference atmospheric condition is adopted, i.e. $P_r = 101.3$ kPa and $T_r = 20$ °C. At normal temperature and pressure conditions, this electric field is around 15% larger for nitrogen than for air, i.e. $E_o(N_2) = 3.565 \times 10^6$ V/m. If space-charge effect is neglected, the corona onset voltage V_o can be approximated by

$$V_o = m_v E_o \delta\left(1 + \frac{k}{\sqrt{\delta r}}\right) r \ln\left(\frac{S}{r}\right) \quad (5)$$

where S is the distance between the needle electrode and nozzle.

It was clear from Equation (5) that V_o is independent of air humidity because of Peek's consideration that air humidity does not influence the occurrence of the corona when there is no dewdrop on surface of conductor. In order to take into account the effect of air humidity, the Peek equation was modified with a correction function by Xu et al. [13], and is given by

$$V_o = m_v E_o \delta\left(1 + \frac{k}{\sqrt{\delta r}}\right) r \ln\left(\frac{S}{r}\right) f(H) \quad (6)$$

where $f(H)$ is the correction function of the air humidity and H is the air humidity. The correction function of the air humidity can be calculated by Ref. [13].

$$f(H) = 1 + \left(5.76 - \frac{1.63}{0.69\sqrt{\delta r} + 0.21}\right)\cdot\frac{P_w}{P}\cdot H \quad (7)$$

where P_w is the partial pressure of saturated water vapor can be calculated by using the following equation [22]:

$$P_w = 611 \times 10^{7.5T/(237.3+T)} \quad (8)$$

Substituting Equation (7) into (6), the modified Peek equation which takes into account the air humidity around conductor is given as

$$V_o = m_v E_o \delta\left(1 + \frac{k}{\sqrt{\delta r}}\right) r \ln\left(\frac{S}{r}\right)\left[1 + \left(5.76 - \frac{1.63}{0.69\sqrt{\delta r} + 0.21}\right)\cdot\frac{P_w}{P}\cdot H\right] \quad (9)$$

4. Experimental setup

The experimental setup for relative humidity and air flow effects on positive and negative corona discharges in a corona-needle charger is shown in Fig. 2. It consisted of a corona-needle charger, an adjustable DC high voltage power supply, an electrometer, a high efficiency particulate-free air (HEPA) filter, a Dwyer mass flow controller, a humid air supply, a silica gel dryer, an air compressor pump, and a vacuum pump. The air flow through the charger was regulated and controlled by a mass flow meter and controller (Dwyer model GFC-1111) with a vacuum pump located at the end of the experimental equipment train, typically between 5 and 15 L/min. Air samples were filtered through a Pall HEPA capsule filter (model 12144) before and after the charger in order to remove any particles. The positive and negative high voltage differences on the corona-needle electrode of the charger were applied by an adjustable commercial DC high voltage power supply (Leybold Didactic model 521721), in the range between 0 and 3.1 kV with a maximum load current of 0.5 mA, and the ripple voltage of 3% of maximum value. The discharge current from the outer electrode of the charger was directly measured by the Keithley 6517A electrometer with an input bias current of <3 fA with just 0.75 fA p–p (peak-to-peak) noise, <20 μV burden voltage on the lowest range, and the current measurement range of 1 fA to 20 mA. As shown in Fig. 2, the experiments are carried out inside a closed cylindrical glass vessel with 600 mm in length and 300 mm in diameter filled with clean air. In this study, the effect of the relative humidity of the inlet air, in the range between 20 and 90% RH, is the only parameter taking into account because of the effect of temperature and pressure on the electrical behavior of a corona discharge has been examined extensively in the literature. The operating temperature of 25 °C and the operating pressure of 101.3 kPa inside the test chamber are controlled during each experiment. The relative humidity of the ambient air varies between 20 and 90%. It was reduced by introducing a dry clean air, a diffusion dryer by silica gel drying chamber was used to remove any remaining water for RH less than 10% RH, coming from a vacuum pump and or increased by adding water vapor resulting from the humid air supply after a period of relaxation in a container, during 15 min. The RH of the air inside the test chamber is monitored with the multifunction Fluke 975 AirMeter™, accuracy of about ±2% RH (10% RH–90% RH). It should be noted that the measurements of the discharge current was repeated at least three times for each set of operating conditions. Table 1 gives the ranges and values of variables investigated.

5. Results and discussion

Fig. 3 shows the current–voltage characteristics of the corona-needle charger for positive and negative coronas at different relative humidity. In this experimentation, the corona voltage was maintained to the charger in the range of 0–3.1 kV, the relative humidity was about 20–90%, and the air flow rate was about 5 L/min. As shown in Fig. 3, both positive and negative discharge currents monotonically increase with the applied voltage when it

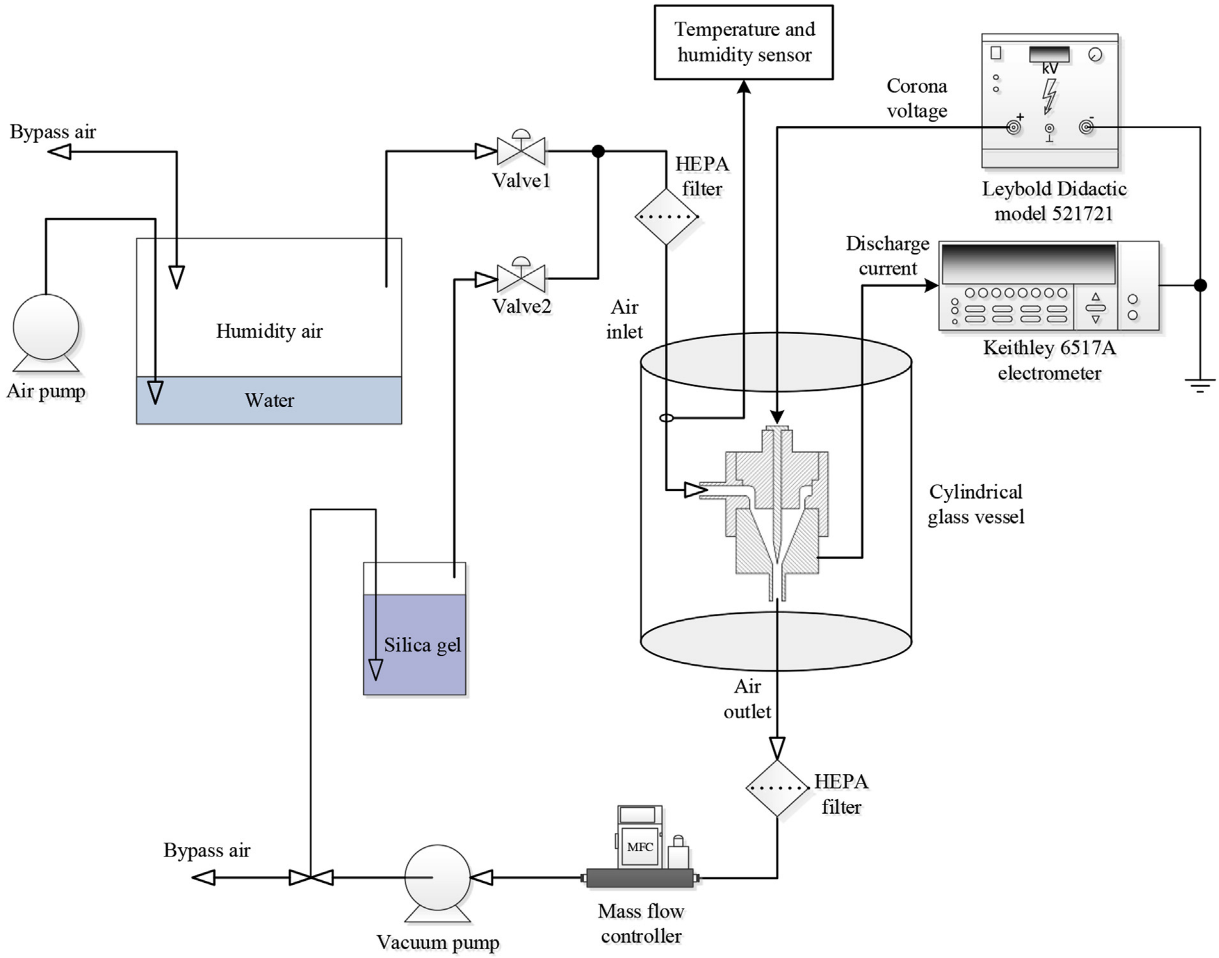


Fig. 2. Experimental setup for relative humidity and air flow effects in a corona-needle charger.

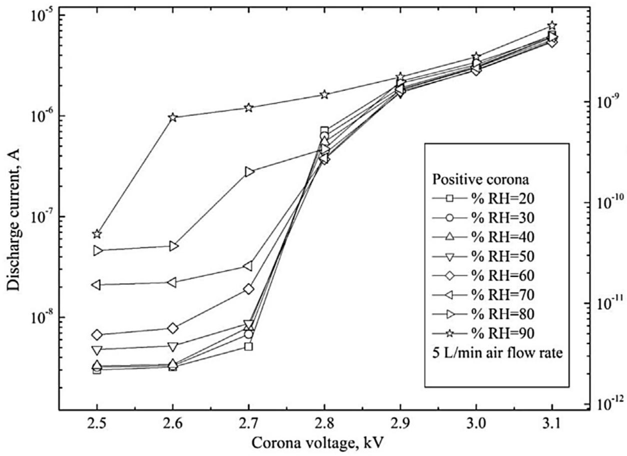
Table 1
Ranges and values of variables investigated.

Variable	Range
Corona voltage	0–3.1 kV
Ion generated	Positive ion (+), Negative ion (−)
Ionized gas	Air
Relative humidity	20–90% RH
Flow rate	5, 10 and 15 L/min
Temperature	25 °C
Pressure	101.3 kPa

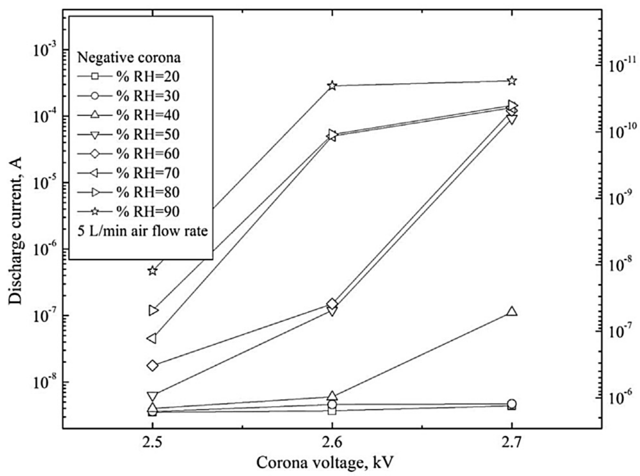
exceeds the corona onset voltage until breakdown voltage. At RH value of 60%, the corona onset voltage was found to be about 2.7 and 2.5 kV for positive and negative coronas, respectively, and the breakdown voltage was found to be about 3.2 and 2.8 kV for positive and negative coronas, respectively. At a given voltage, the discharge current is higher with the negative polarity, which is explained by the difference between the apparent mass and electrical mobility of negative charge carriers compared to positive ones. Ionic electrical mobility was inversely proportional to its mass. Generally, values of electrical mobility for positive and negative ions differ by approximately 19.30%. Reischl et al. [23] quote averages for ionic electrical motility as $Z^{+}_{ion} = 1.15 \times 10^{-4}$ m^2/V s and $Z^{-}_{ion} = 1.425 \times 10^{-4}$ m^2/V s, respectively. Additionally, a positive corona has much lower density of free electrons compared to a negative corona; a thousandth of the electron density, and a hundredth of the total number of electrons. However, the electrons in a positive corona are concentrated close to the surface of the curved electrode, in a region of high potential gradient, and therefore the electrons have a high energy, whereas in a negative corona many of the electrons are in the outer, lower-field areas. Therefore, if electrons are to be used in an application which requires a high activation energy, positive coronas may support a greater reaction constants than corresponding negative coronas; though the total number of electrons may be lower, the number of a very high energy electrons may be higher. The RH effect on the positive and negative discharge currents is different depending on the applied voltage.

Fig. 4 shows the theoretical and experimental comparison of corona onset voltage for positive and negative coronas at different relative humidity and air flow rate. It was showed that both positive and negative corona onset voltages decrease with increasing relative humidity for those air flow rate. It should be noted that negative corona discharges appear as discrete points or tufts along the electrode in contrast to the uniform positive corona discharge. At voltages near the corona onset voltage, only a few tufts appear. They are irregularly spaced along the electrode and preferentially appear at imperfections on the surface. As the voltage is increased, the number of tufts increases and the distribution of tufts becomes more uniform [24]. The corona onset voltages with different relative humidity at different air flow rate were approximated by the modified Peek equation, Equation (9), and were in reasonable and systematical agreement with the experiments.

Fig. 5 shows the variation of the discharge current with the



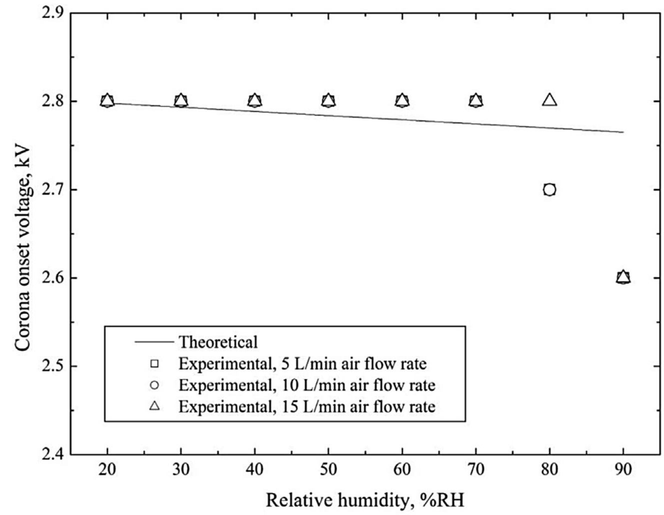
(a) Positive corona



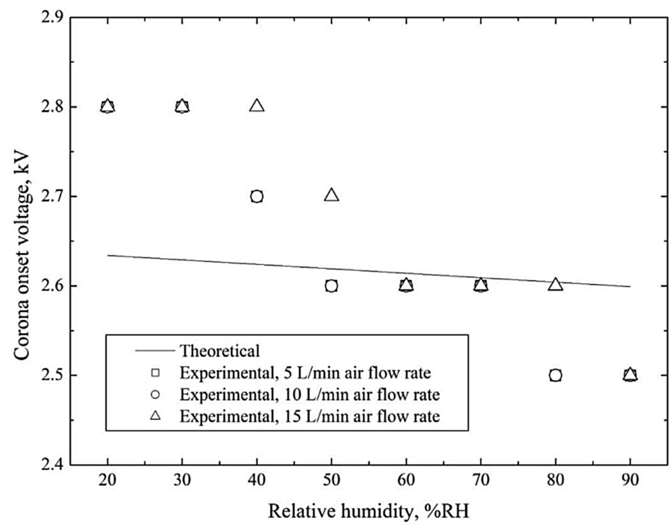
(b) Negative corona

Fig. 3. Current–voltage characteristics of the corona-needle charger for positive and negative coronas at different relative humidity.

relative humidity at different positive and negative corona voltages. The discharge currents of the charger of both positive and negative coronas were evaluated for the RH of 20–90%, the air flow rate of 5 L/min, and the corona voltage of 2.5–3.1 kV. At the same corona voltage, an increasing RH value in the range of 20–90% resulted in increased the positive discharge current for the corona voltage between 2.5 and 2.7 kV. In case of the corona voltage between 2.8 and 3.1 kV, it was shown that the positive discharge current decreased with increasing RH value at RH values below 60% and increased with increasing RH value at RH value above 60% in the same corona voltage. The negative discharge current was found to be stable with increasing RH value at RH values below 40% and increased with increasing RH value at RH value above 40% in the same corona voltage. In the negative corona, RH effect is unstable and more complex. This effect is due to the water vapor present in the air affects the corona initiation field strength [5,7,8,10,15], the mobility of charge carriers [16,17], and the plasma chemistry [18]. At higher % RH, the discharge current might be increased with RH due to the electric conductivity enhancement. At lower % RH, the discharge current might be decreased with increasing RH due to the decreases of apparent mobility of ions, resulting from their combination with water molecules. Table 2 shows the ratio of the discharge currents between 20 and 90% RH to the 60% RH discharge current in case of the positive corona voltage of about 2.9 kV and



(a) Positive corona



(b) Negative corona

Fig. 4. Theoretical and experimental comparison of corona onset voltage for positive and negative coronas at different relative humidity and air flow rate.

the negative corona voltages of about 2.7 kV, respectively. At 20% RH, the positive and negative discharge currents were found about 1.20 and 3.64×10^{-5} times higher than the positive and negative discharge currents at 60% RH, respectively. At 90% RH, the positive and negative discharge currents were also found about 1.39 and 2.81 times higher than the positive and negative discharge currents at 60% RH, respectively.

Fig. 6 shows the variation of the discharge current with the air flow rate at different relative humidity for positive and negative coronas. The resultant discharge currents of the charger of both positive and negative coronas were evaluated for the air flow rate of 5, 10, and 15 L/min, and the corona voltage of 0–3.1 kV. At RH value below 90%, the positive discharge current was found to slightly decrease when the air flow rate increased. This is because the ions can be transported from the charger more easily by faster flowing air. At RH value of 90%, the positive discharge current was found to increase with the air flow rate due to high electrical conductivity enhancement. For the negative corona, the discharge current was found to slightly decrease when the air flow rate increased. It should be noted that the discharge current of negative ions was

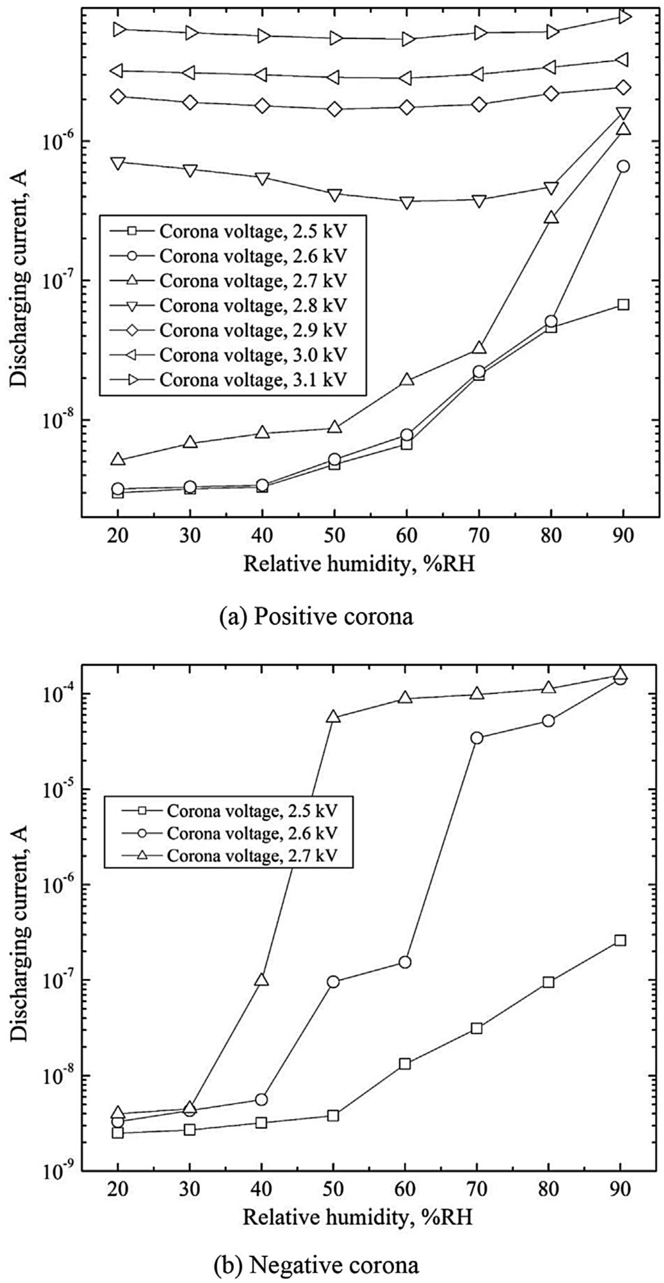


Fig. 5. Variation of the discharge current with the relative humidity at different positive and negative corona voltages.

Table 2
Ratio of discharge currents between 20 and 90% RH to 60% RH discharge current.

Relative humidity (%)	Ratio of 20–90% RH discharge currents to discharge current at 60% RH	
	Positive corona +2.9 kV	Negative corona −2.7 kV
20	1.20	3.64×10^{-5}
30	1.09	3.88×10^{-5}
40	1.03	9.26×10^{-4}
50	0.97	0.76
60	1.00	1.00
70	1.05	1.11
80	1.26	1.20
90	1.39	2.81

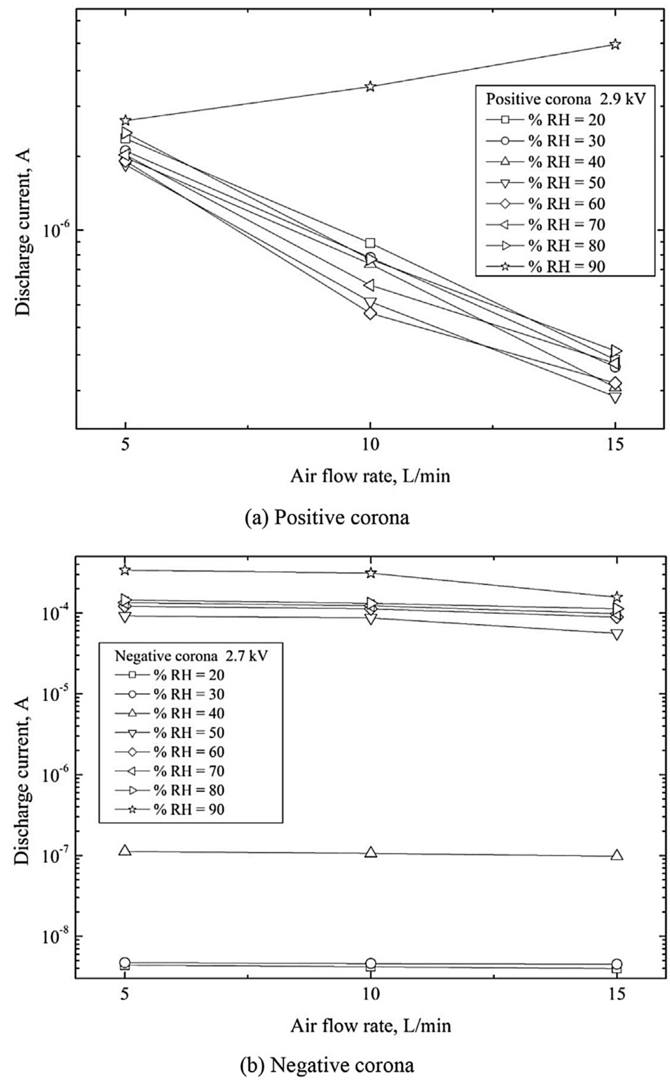


Fig. 6. Variation of the discharge current with the air flow rate at different relative humidity for positive and negative coronas.

found to be slightly higher than positive ions due to high electrical mobility of negative ion. This negative ion was more likely to impact and deposit on the outer electrode wall of the charger due to the electrostatic force resulted in higher discharge current. Fig. 7 shows the variation of the discharge current with the air flow rate at different positive and negative coronas for 90% relative humidity. It was shown that the discharge current increased with increasing the air flow rate for positive corona but decrease in negative corona. It seems that the electrical mobility of negative ions decreases with the RH and increase with RH for positive ion, which can be explained by the gas/liquid phase transition inducing the formation of ions of water [7].

6. Conclusion

The effects of inlet air RH and air flow rate on positive and negative corona discharges in a corona-needle charger have been experimentally studied and discussed in this paper. The corona discharge characterizations of the charger in terms of current-to-voltage relationships of the corona-needle charger on the effects of inlet air RH and air flow rate were evaluated at applied corona voltages between 0 and 3.1 kV, an air flow rates between 5 and 15 L/

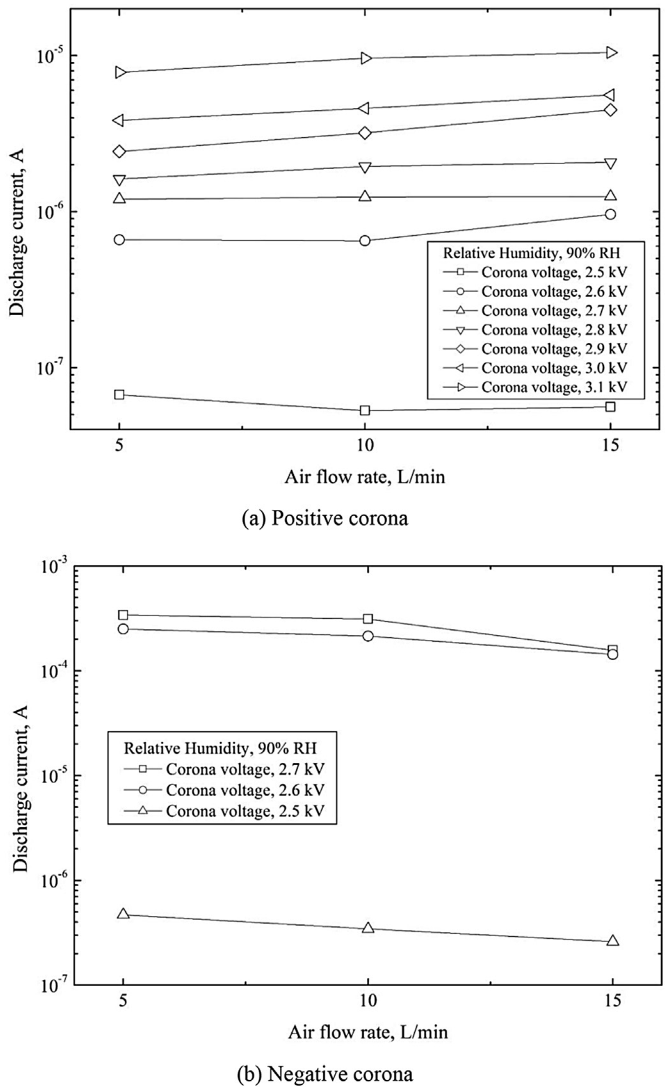


Fig. 7. Variation of the discharge current with the air flow rate at different positive and negative coronas for 90% relative humidity.

min, a relative humidity between 20 and 90%, and an operating pressure of about 101.3 kPa. It was shown that both positive and negative discharge currents monotonically increase with the applied voltage when it exceeds the corona onset voltage until breakdown voltage. As experimental results shown, the discharge current is strongly affected by the RH level of the inlet air. Both positive and negative corona onset voltages were decreased with increasing relative humidity for different air flow rate. The positive discharge current was found to be decreased with increasing RH value at RH values below 60% and increased with increasing RH value at RH value above 60% in the same corona voltage. The negative discharge current was found to be stable with increasing RH value at RH values below 40% and increased with increasing RH value at RH value above 40% in the same corona voltage. This effect is due to the water vapor present in the air affects the corona initiation field strength, the mobility of charge carriers, and the plasma chemistry. For the air flow rate effects, the positive discharge current was found to slightly decrease when the air flow rate increased at RH value below 90% and to increase with the air flow rate at RH value of 90%. For the negative corona, the discharge current was also found to monotonically decrease when the air flow rate increased. Finally, research is in progress on the RH effects on the charging efficiency of the corona-needle charger.

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