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Positive direct current corona discharges in single wire-duct electrostatic precipitators

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This paper is aimed to study the characteristics of the positive dc corona discharges in single wire-duct electrostatic precipitators. Therefore, the corona discharges were formed inside dry air fed single wire-duct reactor under positive dc voltage at the normal atmospheric conditions. The corona current-voltage characteristics curves have been measured in parallel with the ozone concentration generated inside the reactor under different discharge conditions. The corona current-voltage characteristics curves have agreed with a semi empirical equation derived from the previous studies. The experimental results of the ozone concentration generated inside the reactor were formulated in the form of an empirical equation included the different parameters that were studied experimentally. The obtained equations are valid to expect both the current-voltage characteristics curves and the corresponding ozone concentration that generates with the positive dc corona discharges inside single wire-duct electrostatic precipitators under any operating conditions in the same range of the present study. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). [http://dx.doi.org/10.1063/1.4951693]

I. INTRODUCTION

There are only two types of the electrical discharges that are being used in the literature to form non-thermal plasmas at the atmospheric pressure under different experimental techniques. These types are the corona discharges and the dielectric barrier discharges (DBDs).1–4

With the non-thermal plasmas that are formed by using the corona discharges, the mean electron energies are considerably higher than those of the components of the ambient gas. The majority of the electrical energy consume into the production of energetic electrons, rather than into heating of the gas. The energy lost in the plasma is thus directed preferentially to electron impact dissociation and ionization of the background gas to produce positive and negative ions as well as free radicals. The free radicals, in turn, lead to synthesis or creation of new chemical species.5 The main advantage of the corona discharges is that they can be used easily to form non-thermal plasmas with flexibility in the operating parameters. These parameters include the geometrical shape of the discharge electrodes and their dimensions, type of the gas and its mass flow rate through the electrodes as well as mode and polarity of the voltage that drives the discharge process.5 On the contrary, the disadvantage of the corona discharges is that the volume of the non-thermal plasma that forms around the high electric field electrode depends to a large extent on mode and polarity of the applied voltage. With the dc and ac corona discharges, the volume of the non-thermal plasma...
is always very much smaller than the total internal volume that is confined between the electrodes, while it is relatively large with the pulsed corona discharges.\textsuperscript{5–8} Therefore, the non-thermal plasmas formed by using the dc and ac corona discharges are suitable only for the industrial applications that need to small concentrations of positive and negative ions for charging particles. Typical examples are indoor air cleaning by using electrostatic precipitators, spray coating, electro-photography machines, drying separation systems, radiation detectors and surface treatment of polymers.\textsuperscript{11–13} On the other hand, the non-thermal plasmas that form by using the pulsed corona discharges are being used over a wide range to remove many kinds of the pollutants from the flue gases.\textsuperscript{14–16}

With the different applications of the corona discharges, the ozone gas is generated from the oxygen content in the atmospheric air. The mechanism of the ozone generation by using the corona discharges in air is known well.\textsuperscript{14} The ozone is a strong oxidizing agent, and for this reason it is used over a wide range in many of the important industrial applications.\textsuperscript{15,16} On the contrary, the ozone is a toxic gas to humans and animals, causes serious damage to the plant life, and produces damage in many materials. The dangerous effects for the ozone gas on health of humans are well recognized.\textsuperscript{17–19} This makes the ozone generation inside any device operates by using the corona discharges represents a great problem on the health of the users, especially inside the closed places. Therefore, the devices that are used in the real applications, where the air is inhaled by humans, animals and plants, and touches other materials, should be designed with adequate efficiency, but not so high to produce dangerous levels of the ozone concentration.\textsuperscript{20,21}

In order to design safe device operates by using the corona discharges in the various industrial applications that were mentioned previously, it is necessary to have trustworthy criteria for expecting the current-voltage characteristics in parallel with the ozone concentration that generates at the desired operating conditions. These criteria are significant for both the researchers and the designers to control the efficiency of the devices, and in order to avoid the risk of inhalation of the ozone gas that emits from these devices on the health of their users. Subsequently, two of the authors of this paper have studied previously the ozone generation with the corona discharges under different applications of the corona discharges, the ozone gas is generated from the different discharge conditions. This is aimed to find suitable criteria for calculating both the current-voltage characteristics curves and the ozone concentration that generates with the positive dc corona discharges in single wire-duct electrostatic precipitators. These criteria may be useful either in the future academic studies or in the technical applications.

II. CORONA DISCHARGES IN SINGLE WIRE-DUCT REACTORS

A single wire-duct reactor simply consists of a thin discharge wire taut well at the mid-distance between two parallel plates, as shown in Figure 1. When the length of the discharge gap on both sides of the wire \(d\) is smaller than the width of the two parallel plates \(W\) (i.e., \(d < W\)), the physical mechanism of the corona discharge in single wire-duct reactors is approximately the same as in coaxial wire-cylinder reactors.\textsuperscript{20} Therefore, the previous equations that identify the corona discharge parameters in coaxial wire-cylinder reactors can be modified to conform with the corona discharge in single wire-duct reactors, as follows.

With the positive dc corona discharges in coaxial wire-cylinder systems, the electric field strength \(E\) at any point along the discharge gap is given by the equation\textsuperscript{30}

\[
E = \sqrt{\frac{I}{2\pi \varepsilon_0 \mu L} \left[ 1 - \left( \frac{r_o}{r} \right)^2 \right] + \left[ \frac{V_o}{r \ln(R/r_o)} \right]^2}, \tag{1}
\]

where \(I\) is the corona current, \(\varepsilon_0\) is the permittivity of the free space (8.854 \times 10^{-12} \text{ F/m}), \(\mu\) is the mobility of the positive ions, \(L\) is the length of the cylinder and \(R\) is the internal radius, \(r_o\) is the
radius of the axial discharge wire, $V_o$ is the corona onset voltage, while $r$ is the radial coordinate (i.e., $r_o \leq r \leq R$).

According to Equation (1), when $R$ is replaced by the length of the discharge gap $d$ in single wire-duct reactor, the electric field strength at any point along the discharge gap in a direction perpendicular to the surfaces of the two parallel plates as shown in Figure 1 is

$$E = \sqrt{\frac{l}{2\pi e_o \mu L} \left[ 1 - \left( \frac{r_o}{r} \right)^2 \right] + \left( \frac{V_o}{r \ln(d/r_o)} \right)^2},$$

(2)

where $r_o \leq r \leq d$, and $L$ becomes the length of the two parallel plates in this case.

With the starting of the corona discharge inside the reactor, the value of the corona current is negligible (i.e., $I \approx 1 \times 10^{-6}$ A). Therefore, according to Equation (2), the electric field strength at the surface of the discharge wire where $r = r_o$ is

$$E_o = \frac{V_o}{r_o \ln(d/r_o)}.$$  

(3)

The electric field strength required to starting self-sustained positive dc corona discharges in the atmospheric air around the surfaces of the smooth and clean straight wires is determined by using Whitehead’s empirical formula 31

$$E_o = \left( 33.7\delta + 0.813 \sqrt{\frac{\delta}{r_o}} \right) \times 10^5.$$  

(4)

The air density factor $\delta$ in Equation (4) is given by the relation 31

$$\delta = 2.94 \times 10^{-3} (P/T),$$  

(5)

where $P$ and $T$ are pressure and temperature of the air inside the reactor, respectively. From Equations (3), (4), and (5), the onset voltage of the positive dc corona discharge inside air fed single
wire-duct reactors is determined by using the equation

\[ V_o = \left[ 9907.8(P/T) + \sqrt{1.943 \times 10^{7}(P/T)} r_o \ln \left( \frac{d}{r_o} \right) \right]. \tag{6} \]

As soon as the corona discharge starts inside the reactor, the air gap between the electrodes transforms to an ionization region of radius \( r_i \) covering the wire surface (i.e., sheath of non-thermal plasma) and a conduction region of length \( (d - r_i) \), as shown in Figure 1. The non-thermal plasma is formed only inside the ionization region, where the ionization coefficient \( \alpha \) is greater than the attachment coefficient \( \eta \). Because the physicochemical reaction processes take place inside the ionization region, the ozone molecules are generated inside this region only.\(^{23-25}\)

With the positive dc corona discharges in the atmospheric air at normal temperature and pressure, the volume of the non-thermal plasma \( V_{\text{plasma}} \) that forms around the thin wires is determined by using the equation\(^{25,32,33}\)

\[ V_{\text{plasma}} = \pi \left[ (0.562255 r_o^{0.78})^2 - r_o^2 \right] L. \tag{7} \]

When a sufficient value of the overvoltage (i.e., \( V - V_o \)) is applied to the reactor, the value of the corona current \( I \) in Equation (2) is relatively large. Moreover, the value of \( (r_o/d)^2 \) is much less than one with the practical dimensions for the electrodes of the reactor. Therefore, the value of the first term in the right hand side of Equation (2) becomes much greater than the value of the second term (i.e., \( \sqrt{I/2\pi \varepsilon_o \mu L} \gg [V_o/r \ln(d/r_o)] \)). Under these conditions, the net electric field strength applied to the discharge gap that has a length \( d \) is

\[ \frac{(V - V_o)}{d} = \sqrt{\frac{I}{2\pi \varepsilon_o \mu L}}. \tag{8} \]

By squaring both sides of Equation (8), the relationship of corona current-voltage characteristics in single wire-duct reactors takes the form

\[ I = \frac{2\pi \varepsilon_o \mu L (V - V_o)^2}{d^2}. \tag{9} \]

Certainly, the lines of the electric field inside single wire-duct reactor are not distributed regularly around the surface of the discharge wire as in the case of coaxial wire-cylinder reactor. This makes the value of \( (V - V_o)^2 \) that produces a certain value of the corona current varies from a reactor to another, according to the geometrical configuration for the electrodes and their dimensions. In addition to that, the temperature of the air and the relative humidity vary also from an experiment to another. In order to overcome this difficulty, Equation (9) can be generalized on the following form

\[ I = \left( \frac{2\pi \varepsilon_o \mu L}{d^2} \right) (V - V_o)^n, \tag{10} \]

where the value of the exponent \( n \) is determined experimentally, as it will be discussed later.

With the open systems of single wire-duct reactors, the residence time \( t_r \) of the flowing air inside the reactor is determined by using the relation\(^{34,25}\)

\[ t_r = \frac{V_{\text{reactor}}}{Q}, \tag{11} \]

where \( V_{\text{reactor}} \) is the internal volume of the duct that is confined between the two parallel plates, and \( Q \) is the magnitude of the air flow rate through the reactor.

**III. EXPERIMENTAL SETUP AND MEASURING TECHNIQUE**

**A. Experimental setup**

Figure 2 shows a schematic diagram of the experimental setup used in this study. The setup was composed of the following.
1. **High-voltage dc power supply**

The high-voltage dc power supply consisted of a step-up transformer \( V_{\text{input}} = 0 \rightarrow 100 \text{ V}_{\text{rms}}, \) 60 Hz and \( V_{\text{output}} = 0 \rightarrow 20 \text{ kV}_{\text{rms}}, 1 \text{ kW} \), a rectification diode (100 kV, 20 mA, 100 kΩ), a charging capacitor (64 nF, 40 kV) and a load resistor (500 kΩ, 250 kV, 200 W).

2. **Single wire-duct reactor**

The outer frame of the reactor was on the shape of a box its walls made from a transparent Perspex sheet with a thickness \( 5 \times 10^{-3} \) m. The internal dimensions of this box were 0.30 m length, 0.03 m width and 0.05 m depth. Two stainless steel plates have been pasted face to face on the internal walls of the box as shown in Figure 2, and the surface area of each plate was \( 0.20 \times 0.05 \text{ m}^2 \) with a thickness \( 5 \times 10^{-3} \) m. The plate-to-plate spacing of the duct was 0.02 m, and a stainless steel wire has been tightened at the mid-distance between them along the length of the box. The radius of the wire was changed in the range of \( 2.5 \times 10^{-5} \leq r_o \leq 20 \times 10^{-5} \) m. With this arrangement, the length of single wire-duct electrodes inside the reactor was 0.20 m (i.e., \( L = 0.20 \) m), while the length of the discharge gap on both sides of the wire was 0.01 m (i.e., \( d = 0.01 \) m).

The air flowing through the reactor was distributed regularly in a direction perpendicular to the discharge wire as shown in Figure 2 through two lines of the opposite holes that were opened on both sides of the box, 20 holes on each side.

3. **Gas flow system**

The reactor was fed by dry air from high-pressure cylinder provided with flowmeter.
B. Measuring technique

The reactor has been connected to both the high-voltage dc power supply and the gas flow system as shown in Figure 2. The magnitude of the air flow through the reactor has been regulated with a constant rate in the range of $0.83 \times 10^{-5} \leq Q \leq 13.33 \times 10^{-5} \text{ m}^3/\text{s}$ at the atmospheric pressure and the room temperature. The electric power input into the setup was adjusted by using a regulating transformer (100 $V_{\text{rms}}$, 500 W). The output positive dc voltage was applied to the discharge wire of the reactor, and measured by using a 1000:1 high-voltage probe (Tektronix P6015A, 75 MHz) on the display screen of two channels digital real-time memory oscilloscope (SONY-TDS360P, 200 MHz). The two plates of the duct in the reactor were connected with the ground in one cable through a digital multimeter (IWATSUM-7411) for measuring the corona current $I$. The air flowing from outlet of the reactor has been passed through a quartz cell installed in UV-VIS spectrophotometer (SHIMADZU-1200), where the absorbance of the ozone was recorded at a wavelength of 253.7 nm. The ozone concentration $[O_3]$ in the flowing air was calculated from the absorbance measurements by using Beer-Lambert law. The average room temperature during the experimental measurements was about 288 K. Every point of the experimental results represents the mean of three independent readings under the same operating conditions.

IV. RESULTS AND DISCUSSION

A. The current-voltage characteristics

Table I shows experimental and calculated results for the corona onset voltage inside the reactor $V_o$, when the radius of the discharge wire is changed in the range of $2.5 \times 10^{-5} \leq r_o \leq 20 \times 10^{-5}$ m. The calculated results have been obtained by introducing the values of the operating conditions (i.e., $P$, $T$, $r_o$, and $d$) into Equation (6). In general, the values of the experimental results agree with the values of the calculated results, whatever the value of the radius of the discharge wire. This indicates that the surfaces of the discharge electrodes for the reactor were smooth and clean during the experimental measurements. The results in Table I show also that the value of the corona onset voltage $V_o$ increases with increasing the radius of the discharge wire $r_o$. This behavior has been explained in previous studies.

The different symbols in Figure 3 represent experimental results for the current-voltage characteristics curves of the corona discharges inside the reactor, when the radius of the discharge wire is changed in the range of $2.5 \times 10^{-5} \leq r_o \leq 20 \times 10^{-5}$ m. During the measuring of these results, the magnitude of the air flow rate through the reactor has been changed also in the range of $0.83 \times 10^{-5} \leq Q \leq 13.33 \times 10^{-5} \text{ m}^3/\text{s}$ with the different radii of the discharge wire $r_o$, independently. However, the behavior of the current-voltage characteristics curves that are shown in Figure 3 does not change with the variation of the magnitude of $Q$ in this range.

In order to check the validity of Equation (10) versus the experimental results, Equation (10) is written on the form

$$\ln I = n \ln (V - V_o) + \ln \left[ \frac{2\pi e_o \mu L}{d^2} \right].$$

By applying Equation (12) on the experimental results of the current-voltage characteristics curves that are shown in Figure 3, the values of $\ln I$ versus the values of $\ln (V-V_o)$ are linear relationships

| $r_o$ (m) | $V_o$ (V) [Exp. Results] | $V_o$ (V) [Cal. Results, Eq. (6)] |
|----------|---------------------------|----------------------------------|
| $2.5 \times 10^{-5}$ | 3150 | 3032 |
| $5.0 \times 10^{-5}$ | 4200 | 4067 |
| $10 \times 10^{-5}$ | 5500 | 5478 |
| $20 \times 10^{-5}$ | 7350 | 7394 |
FIG. 3. Experimental and calculated results (i.e., the different symbols and the solid curves respectively) show the current-voltage characteristics curves of the corona discharges inside the reactor for different radii of the discharge wire $r_o$.

with the different radii of the discharge wire $r_o$ as shown in Figure 4. This behavior agrees well with the linear formula of Equation (12). Because the straight lines that show the values of $\ln I$ versus the values of $\ln (V-V_o)$ are very close to each other, Figure 4 includes only the values that show the straight lines of the smallest and the largest radius of the discharge wire. The values of the exponent $n$ in Equation (10) were determined from the slope of the straight lines with the different radii of the discharge wire $r_o$, whether that appear in Figure 4 or that did not appear. The obtained values of $n$ were plotted versus the different values of $r_o$, and they show a linear relationship as shown in

FIG. 4. Experimental results show logarithm of the corona current $\ln I$ versus logarithm of the overvoltage that is applied to the reactor $\ln (V-V_o)$ for the smallest and the largest radius of the discharge wire $r_o$. 
FIG. 5. Results show the value of the exponent $n$ as a function of the radius of the discharge wire $r_o$.

Figure 5 (with a correlation factor of $R = 0.99995$) on the following form

$$n = 2.0565 + 578.43 r_o.$$  \hspace{1cm} (13)

By equating the value where the straight lines cut the axis of $\ln I$ in Figure 4 (i.e., the intercept $= -24.89$ A) with $\ln[2\pi\varepsilon_0\mu L/d^2]$, the mobility of the positive ions $\mu$ inside the reactor is about $1.4 \times 10^{-4}$ m$^2$/Vs. This value of $\mu$ agrees well with the previous studies.\textsuperscript{34–36}

By introducing Equation (13) into Equation (10), the current-voltage characteristics curves of the positive dc corona discharges inside the reactor are calculated by using the following equation

$$I = \frac{2\pi\varepsilon_0\mu L}{d^2}(V - V_o)^{(2.0565+578.43 r_o)}.$$  \hspace{1cm} (14)

The solid curves in Figure 3 represent the results of the current-voltage characteristics that have been calculated by using Equation (14). In general, the solid curves are consistent with the experimental results (i.e., the different symbols). Both the experimental and the calculated results in Figure 3 show the following.

With the same value of the voltage applied to the reactor, the value of the corona current increases with the decrease of the value of the wire radius. Moreover, the maximum value of the overvoltage (i.e., $V_{\text{max}} - V_o$) that is applied to the reactor increases also with the decrease of the value of the wire radius. Therefore, it is recommended to use thin discharge wires in the design of the electrostatic precipitators in order to improve the efficiency of the charging process.

According to Equation (13), when the value of the wire radius increases in the range of $2.5 \times 10^{-5} \leq r_o \leq 20 \times 10^{-5}$ m, the value of the exponent that makes Equation (10) agrees with the experimental results in Figure 3 increases also in the range of $2.07 \leq n \leq 2.17$. This is due to the decrease of the value of the electric field strength at the surface of the discharge wire with the increase of the radius as Equation (4) indicates. Therefore, with the same value of the corona current $I$, the value of the overvoltage $(V - V_o)$ that is applied to the reactor increases with decreasing the value of the wire radius $r_o$ as shown in Figure 3. The result is the value of the exponent $n$ that makes the value of the corona current remains constant in Equation (10) increases with increasing the value of wire radius.
Some of the researchers have got on a general empirical formula for the current-voltage characteristics of the corona discharge in point-plate system on the form\cite{37}

\[ I = K(V - V_o)^n, \]

where \( K \) is a dimensional constant, and the value of the exponent \( n \) varies in the range 1.5 - 2.0 according to the point radius. In another experimental study, it was found that the value of \( n \) is 1.6 with the positive dc corona discharge in the same electrodes system.\cite{38}

Other researchers found that the current-voltage characteristics of the positive dc corona discharges in 1 to 8 wire-duct electrostatic precipitator system agree also with Equation (15). This in addition to the value of \( n \) increases in the range 1.5 - 1.7 with the increase of the number of the discharge wires.\cite{39} In the case of 1 wire-duct electrostatic precipitator system, the operating conditions in their experiment were as follows: \( L = 0.20 \) m, \( d = 0.05 \) m, \( r_o = 20 \times 10^{-5} \) m, \( P = 1.014 \times 10^5 \) Pa, \( T = 302 \) K and RH = 65\%. By introducing these values into Equations (6) and (10), it was found that the calculated results agree also with the current-voltage characteristics curve that is shown in Figure 2 of their study, when the value of \( n \) is about 1.96 only. This value is slightly less than the value of \( n \) that was obtained in the present study with the same value of the radius of the discharge wire (i.e., \( n = 2.17 \)). The difference of the value of \( n \) produces certainly from the variation of the operating conditions between the previous study and the present study, especially the variation in the values of both \( T \) and RH.

In general, Equation (15) is the same as Equation (10), but the difference between them is that the dimensional constant \( K \) is unknown in Equation (15), and it is determined experimentally. However, more experimental studies should be conducted in order to identify accurate values for the exponent \( n \) in Equation (10) over a wide range of the operating conditions.

B. The ozone generation inside the reactor

The different symbols in Figures 6-9 show experimental results for the ozone concentration \([O_3]\) generated inside the reactor as a function of the corona current \( I \). With these Figures, the value of the radius of the discharge wire \( r_o \) is \( 2.5 \times 10^{-5}, 5 \times 10^{-5}, 10 \times 10^{-5} \) and \( 20 \times 10^{-5} \) m,
FIG. 7. Experimental and calculated results (i.e., the different symbols and the solid curves respectively) show the ozone concentration $[O_3]$ generated inside the reactor as a function of the corona current $I$, when the radius of the discharge wire is $r_o = 5 \times 10^{-5}$ m and the magnitude of the air flow rate is variable in the range of $0.83 \times 10^{-5} \leq Q \leq 13.3 \times 10^{-5}$ m$^3$/s.

respectively. The magnitude of the air flow rate through the reactor is changed in the range of $0.83 \times 10^{-5} \leq Q \leq 13.33 \times 10^{-5}$ m$^3$/s with each value for the wire radius.

In order to derive an empirical equation for calculating the ozone concentration inside the reactor, the steps that were followed in our previous studies$^{24,25}$ have been applied on the experimental results that are shown in Figures 6-9. By applying these steps, the ozone concentration that

FIG. 8. Experimental and calculated results (i.e., the different symbols and the solid curves respectively) show the ozone concentration $[O_3]$ generated inside the reactor as a function of the corona current $I$, when the radius of the discharge wire is $r_o = 10 \times 10^{-5}$ m and the magnitude of the air flow rate is variable in the range of $0.83 \times 10^{-5} \leq Q \leq 13.3 \times 10^{-5}$ m$^3$/s.
FIG. 9. Experimental and calculated results (i.e., the different symbols and the solid curves respectively) show the ozone concentration \([O_3]\) generated inside the reactor as a function of the corona current \(I\), when the radius of the discharge wire is \(r_o = 20 \times 10^{-5} \text{ m}\) and the magnitude of the air flow rate is variable in the range of \(0.83 \times 10^{-5} \leq Q \leq 13.3 \times 10^{-5} \text{ m}^3/\text{s}\).

The ozone concentration inside the reactor is determined by using the equation

\[
[O_3] = \left( \frac{711.255 r_o^{0.626875}}{Q} \right) I \left[ 1 - \left( \frac{7.5}{Q^{0.28}} \right) I \right].
\]  
(16)

The solid curves in Figures 6-9 indicate the results that were calculated by using Equation (16). In general, the solid curves agree with the experimental results over range of the parameters that were studied experimentally. This behavior confirms that Equation (16) can be used for expecting the ozone concentration inside the reactor under any operating conditions in the same range of the parameters \(r_o\), \(Q\) and \(I\).

Equation (16) can be rewritten on the form

\[
[O_3] = \left( \frac{711.255 r_o^{0.626875}}{Q} \right) I - \left( \frac{5334.4125 r_o^{0.626875}}{Q^{1.28}} \right) I^2,
\]  
(17)

and it is equivalent the formula

\[
[O_3] = \left( \frac{K_f}{Q} \right) I - (K_d),
\]  
(18)

where \(K_f = \left( \frac{711.255 r_o^{0.626875}}{Q} \right) I\) while \(K_d = \left( \frac{5334.4125 r_o^{0.626875}}{Q^{1.28}} \right) I^2\), and they are usually called the ozone formation and destruction coefficients inside the corona discharge reactor, respectively.\(^{6,20}\) The Equations (17) and (18) show the following.

The ozone formation and destruction coefficients, \(K_f\) and \(K_d\), inside the reactor are directly proportional with the radius of the discharge wire through the relation of \(r_o^{0.626875}\). This is due to the increase of the volume of the sheath of the non-thermal plasma \(V_{\text{plasma}}\) around the wire surface with increasing the value of its radius \(r_o\), as shown in Table II. With increasing the volume of the non-thermal plasma around the surface of the discharge wire, the number of the gas molecules that are involved in the physicochemical reaction processes for generation and destruction of the ozone increases also. The result is that the values of both \(K_f\) and \(K_d\) increase in parallel with increasing the value of the wire radius through the relation of \(r_o^{0.626875}\). This explains why the ozone concentration \([O_3]\) generated inside the reactor increases significantly with increasing the value of the wire radius.
Calculated results show the value of the volume of the sheath of the non-thermal plasma \( V_{\text{plasma}} \) that forms around the surface of the discharge wire versus the radius \( r_o \).

| \( r_o \) (m) | \( V_{\text{plasma}} \) (m\(^3\)) [Eq. (7)] |
|----------|-------------------------------|
| 2.5 \times 10^{-5} | 1.28 \times 10^{-8} |
| 5.0 \times 10^{-5} | 3.72 \times 10^{-8} |
| 10 \times 10^{-5} | 10.8 \times 10^{-8} |
| 20 \times 10^{-5} | 31.2 \times 10^{-8} |

\( r_o \), when the values of the other parameters are constant (i.e., \( I \) and \( Q \)) as shown in Figures 6-9. Therefore, the discharge electrodes in the devices that operate by using the corona discharges with the various industrial applications should be designed from thin wires in order to reduce the levels of the ozone concentration as much as possible.

The value of the residence time \( t_r \) of the flowing gas molecules inside the sheath of the non-thermal plasma decreases with increasing the magnitude of the air flow rate through the reactor \( Q \), as shown in Table III. On the other hand, the amount of the electric energy that consumes in the physicochemical reaction processes decreases with decreasing the value of the residence time of the gas molecules inside the sheath of the non-thermal plasma, where the electric energy \( = I \, V \, t_r \). Therefore, the number of the ozone molecules that generate inside the sheath of the non-thermal plasma decreases significantly with increasing the magnitude of the air flow rate through the reactor \( Q \). This explains why the ozone concentration \([O_3]\) increases inside the reactor with decreasing the value of \( Q \), when the values of both \( r_o \) and \( I \) are constant as shown in Figures 6-9. This explains also why the ozone concentration \([O_3]\) is inversely proportional with the magnitude of the air flow rate through the reactor \( Q \) in Equation (18).

With the small values of the corona current \( I \), the value of the first term in the right hand side of Equation (17) is much greater than the value of the second term with the same values of both \( r_o \) and \( Q \) [i.e., \((711.255 r_o^{-0.626875} Q)/Q = (5334.4125 r_o^{-0.626875}/Q^{1.28})I^2\)]. Therefore, the ozone concentration \([O_3]\) generated inside the reactor increases linearly in the relatively low range of the corona current \( I \) according to the equation

\[
[O_3] = \left( \frac{711.255r_o^{-0.626875}}{Q} \right) I. \tag{19}
\]

The dotted curves in Figures 6-9 show the end of the linear relationship between the ozone concentration \([O_3]\) and the corona current \( I \). The coordinates of the dotted curves have been determined analytically by subtracting Equation (17) from Equation (19), and equating the output of the subtraction to 1 ppm only. According to this method, the dotted curves intersect with the solid curves in the coordinates of \( I = \sqrt{(Q^{1.28})(5334.4125 r_o^{-0.626875})} \) and \([O_3] = \sqrt{(94.834r_o^{-0.626875}/Q^{0.72})}\). In general, the length of the linear range from the \([O_3] - I \) characteristics curves is short in comparison with the full range as shown in Figures 6-9, and varies according to the values of both the radius of the discharge wire \( r_o \), and the magnitude of the air flow rate through the reactor \( Q \). This indicates that the volume of the sheath of the non-thermal plasma that forms around the surface of the discharge wire

TABLE III. Calculated results show the value of the residence time \( t_r \) of the air molecules inside the reactor for different magnitudes of the air flow rate \( Q \).

| \( Q \) (m\(^3\)/s) | \( t_r \) (s) [Eq. (11)] |
|---------|-----------------|
| 0.83 \times 10^{-5} | 24 |
| 1.66 \times 10^{-5} | 12 |
| 3.33 \times 10^{-5} | 6 |
| 6.66 \times 10^{-5} | 3 |
| 13.3 \times 10^{-5} | 1.5 |
and the residence time of the gas inside it are the main variables that control the ozone generation inside the reactor.

The linear behavior of the $[O_3] - I$ characteristics curves in the range that locates down the dotted curves in Figures 6-9 confirms that the ozone destruction processes inside the reactor are approximately negligible (i.e., $K_d = 0$). Moreover, the value of the discharge power $P$ that dissipates inside the reactor in the form of heat energy is not sufficient to heat the gas to the temperature $T$ required to decompose the ozone molecules, where $P = IV$ and $TeaP$. In this case, almost all the oxygen atoms that are created inside the sheath of the non-thermal plasma turn into ozone molecules according to the reactions\textsuperscript{23-25}

\[
\text{O} + \text{O}_2 + \text{O}_2 \rightarrow \text{O}_3 + \text{O}_2 \\
k = 6 \times 10^{-34} (T/300)^{-2.8}
\]

\[
\text{O} + \text{O}_2 + \text{N}_2 \rightarrow \text{O}_3 + \text{N}_2 \\
k = 5.6 \times 10^{-34} (T/300)^{-2.8}
\]

In addition to that, the excited nitrogen molecules and the nitrogen atoms provide additional oxygen atoms that in turn convert to ozone molecules according to the reactions

\[
\text{N}_2^* + \text{O}_2 \rightarrow \text{N}_2 + 2\text{O} \\
k = 3 \times 10^{-12} (T/300)^{0.55}
\]

\[
\text{N}_2^* + \text{O}_2 \rightarrow \text{N}_2\text{O} + \text{O} \\
k = 6 \times 10^{-14} (T/300)^{0.55}
\]

\[
\text{N} + \text{O}_2 \rightarrow \text{NO} + \text{O} \\
k = 1.5 \times 10^{-11} \exp(-3600/T)
\]

\[
\text{N} + \text{NO} \rightarrow \text{N}_2 + \text{O} \\
k = 2.1 \times 10^{-11} \exp(100/T)
\]

This explains why the $[O_3] - I$ characteristics curves that are shown in Figures 6-9 take the form of linear relationships in the relatively low range of the corona current $I$, whatever the values of both $r_o$ and $Q$.

With increasing the value of the corona current in the range of $I \geq \sqrt{(Q^{1.28})/(5334.4125 r_o^{0.626875})}$, the value of the second term in the right hand side of Equation (17) increases gradually in parallel with the value of the first term, whatever the values of both $r_o$ and $Q$. Therefore, the $[O_3] - I$ characteristics curves deviate from the linear behavior in the current range that locates up the dotted curves that are shown in Figures 6-9. The ozone concentration $[O_3]$ generated inside the reactor increases slowly in the high range of the corona current $I$, especially with the low magnitudes of the air flow rate of $Q \leq 1.66 \times 10^{-5}$ m$^3$/s as shown in Figures 6-9. This behavior confirms that the temperature of the gas inside the sheath of the non-thermal plasma increases gradually with increasing the value of the corona current in the range of $I \geq \sqrt{(Q^{1.28})/(5334.4125 r_o^{0.626875})}$. With the gradual increase of the gas temperature $T$ inside the sheath of the non-thermal plasma, the rate of the ozone formation of the two reactions (20) and (21) decreases while the rate of the ozone decomposition of the reaction

\[
\text{O} + \text{O}_3 \rightarrow 2\text{O}_2 \\
k = 8 \times 10^{-12} \exp(-2060/T)
\]

increases. In this case, all the oxygen atoms are not converted to ozone molecules, and some of them may take part in the destruction of the ozone molecules that previously generated or may recombine to re-form an oxygen molecule. This explains why the commercial ozone generators need to efficient cooling systems\textsuperscript{1}. Moreover, when the concentration of the nitrogen oxides (NO$_x$) reaches certain levels; two reaction cycles decrease the ozone formation inside the reactor, the first
cycle is

\[
O + NO + M \rightarrow NO_2 + M \\
k = 1 \times 10^{-31} (T/300)^{-1.6}[N_2] \\
O + NO_2 \rightarrow NO + O_2 \\
k = 5.6 \times 10^{-12} \exp(180/T)
\]

\[
O + O \rightarrow O_2 
\]

(27)

and the second cycle is

\[
NO + O_3 \rightarrow NO_2 + O_2 \\
k = 3 \times 10^{-12} \exp(-1500/T) \\
O + NO_2 \rightarrow NO + O_2 \\
k = 5.6 \times 10^{-12} \exp(180/T)
\]

\[
O + O_3 \rightarrow 2O_2 
\]

(28)

The nitrogen compounds that are produced in the two cycles (27) and (28) react again fast with some of the ozone molecules according to the reactions

\[
NO + O_3 \rightarrow NO_2 + O_2 \\
k = 3 \times 10^{-12} \exp(-1500/T)
\]

(29)

\[
NO_2 + O_3 \rightarrow NO_3 + O_2 \\
k = 1.4 \times 10^{-13} \exp(-2470/T)
\]

(30)

\[
NO_2 + NO_3 + N_2 \rightarrow N_2O_5 + N_2 \\
k = 2.8 \times 10^{-30}(T/300)^{3.5}
\]

(31)

The resultant ozone concentration inside the reactor under these discharge conditions is approximately the difference between the ozone that generates by the reactions (20)-(25) and the ozone that destroys by the reactions (26)-(31). This explains why the ozone concentration \([O_3] \) generated inside the reactor increases slowly in the high range of the corona current \(I \), especially with the low magnitudes of the air flow rate of \(Q \leq 1.66 \times 10^{-5} \, \text{m}^3/\text{s} \), as shown in Figures 6-9.

With increasing the magnitude of the air flow rate through the reactor in the range of \(Q \geq 3.33 \times 10^{-5} \, \text{m}^3/\text{s} \), most of the heat energy that dissipates inside the reactor is removed quickly. This makes the temperature of the flowing gas does not change significantly in the high range of the corona current. In this case, the rate of the ozone formation of the two reactions (20) and (21) remains approximately constant, while the rate of the ozone decomposition of the reaction (26) increases slowly. Most of the ozone molecules are drifting quickly to outside the reactor without destruction. This explains why the ozone concentration \([O_3] \) decreases slowly along the high range of the corona current of \(I \geq 0.001 \, \text{A} \), when the magnitude of the air flow rate is in the range of \(Q \geq 3.33 \times 10^{-5} \, \text{m}^3/\text{s} \), as shown in Figures 6-9.

By introducing the corona current from Equation (10) into Equation (16), the ozone concentration generated inside the reactor as a function of the corona discharge parameters is given by the equation

\[
[O_3] = \left[ \frac{2\pi\varepsilon_o \mu L (711.255 \varepsilon_o^{0.626875} (V - V_o)^n)}{Q_d^2} \right] \left[ 1 - \frac{15\pi\varepsilon_o \mu L (V - V_o)^n}{Q^{0.35} d^2} \right],
\]

(32)

where the value of \(n \) is determined from Equation (13).

The physical quantities of the Equations (1)-(19) and (20) are in the International System of Units (SI), except the unit of the ozone concentration \([O_3] \) is ppm. The unit of the rate coefficients of the chemical reactions (20)-(31) is cm³ mol⁻¹ s⁻¹.
V. CONCLUSIONS

According to the experimental and the calculated results that were presented in this paper, one may conclude the following.

(i) The experimental results of the corona current-voltage characteristics curves agree with Equation (10), where the value of the exponent $n$ is determined by using Equation (13).

(ii) The ozone concentration generated inside the reactor is determined by using Equation (16) under any operating conditions in the same range of the present study.

(iii) The thin discharge wires produce high currents in parallel with low ozone concentrations under the same operating conditions.

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