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ABSTRACT
In this paper, the electrical characteristics of both the dielectric barrier corona discharge and the usual ac corona discharge have been studied in parallel with the ozone generation under the same operating conditions. Therefore, the corona discharges were formed inside two identical reactors in the form of a coaxial wire-to-cylinder with and without a dielectric barrier covering the inner surface of the cylinder. The two reactors have been fed by constant flow rates from the dry air and the oxygen gas independently at the atmospheric pressure and the room temperature, in parallel with applying a sinusoidal ac voltage to the electrodes of the reactors. The electric power consumed in forming the corona discharges and the waveform of the discharge current as well as the ozone concentration generated in the flowing gases through the reactors have been studied versus the peak of the ac voltage that was applied to the reactors. The current-voltage oscillograms showed that the sequence of the dielectric barrier corona discharge modes in both the dry air and the oxygen gas is the same as the sequence of the usual ac corona discharge modes in the same gases. With the increase of the peak value of the ac voltage applied to the dielectric barrier corona discharge reactor, the peak of the discharge current increases linearly while the value of the electric charge accumulated on the surface of the dielectric barrier increases in the form of a power function. The ozone concentration generated by the dielectric barrier corona discharges is approximately equal to the ozone concentration generated by the usual ac corona discharges in both the dry air and the oxygen gas under the same operating conditions.

I. INTRODUCTION
The non-thermal plasmas are formed at the atmospheric pressure and the room temperature by using various types of the electric discharges under different experimental techniques. The corona discharge is one of the most common among the various types of the electric discharges. 1–8

The corona discharge is a partial breakdown of a gas at a relatively strong electric field. It is formed by applying a dc or ac high-voltage between two inhomogeneous electrodes such as a point-to-plate, a coaxial wire-to-cylinder, a wire or multi wires-to-plate or to-duct, …etc., where the electric field strength is high enough to ionize the gas molecules near the surface of the sharp electrode. 9–13

In the range of the overvoltage that is applied to the discharge gap, the corona discharge appears in several distinctive forms, such as glows, multiple spots, coronas, streamers, …etc., which are behind naming the phenomena by "the electrical coronas". It is also associated with a hissing sound. Sequence and properties of the corona discharge modes depend on the polarity of the voltage, the geometrical configuration of the electrodes and their dimensions, type of the gas and its pressure as well as the internal resistance of the high-voltage power supply. It is also influenced to some extent by the surface properties of the electrodes. 14–19

The corona discharges are used easily to form non-thermal plasmas over a wide range of the operating conditions. Most of the electric energy consumed in forming the corona discharge plasma is directed preferentially to produce energetic electrons, instead of heating the gas components. The average kinetic energy of the energetic electrons inside the corona discharge plasma is considerably higher than the kinetic energies of the other components of the
ambient gas. The minority of the gas molecules split to mono atoms during the collision processes with the energetic electrons. Some of these atoms convert to positive and negative ions, and some of them convert to the excited state, while the remaining atoms stay without convert to be free radicals. The free radicals react with the other components of the gas leading finally to synthesis or creation of new chemical species.\textsuperscript{24,25}

During the dc and the ac corona discharges, the volume of the non-thermal plasma that forms around the surface of the high electric field electrode is always very much smaller than the total internal volume confined between the electrodes.\textsuperscript{34–40} This phenomenon makes the dc and the ac corona discharges not efficient well when they are used in the applications of the volume plasma chemistry. However, they are used only in some of the commercial and the industrial applications that need small concentrations from the positive and the negative ions necessary to charge the electrically neutral particles during the adhesion process. These applications include the indoor air cleaning by using the electrostatic precipitators and the air-conditioning systems, coating the surfaces by using the spray systems, the electro-photocopying machines, the grain separation systems, the radiation detectors and the surface treatment of polymers.\textsuperscript{24–30}

With the various applications of the dc and the ac corona discharges, the ozone gas generates inside the devices from the oxygen content in the atmospheric air and diffuses into the surrounding air. The ozone is a toxic gas, and causes serious damage to the living organisms, whether the humans, or the animals, or the plants. The ozone gas reacts also with many of the substances and destroys them. The dangerous effects of the ozone gas on the health of humans are known well. These effects make the ozone gas generated inside the devices that operate by using the corona discharge systems represents a great danger on the health of their users, especially over the long-term of exposure to it. Therefore, the devices that operate by using the corona discharge systems in the various industrial applications should be designed so that the concentration of the generated ozone does not exceed the acceptable global limits as much as possible. According to the air quality guideline issued by the World Health Organization, the maximum global limit of the ozone concentration in the air allowable for the exposure is 0.05 ppm (0.1 mg/m\(^3\)) for 8-h daily maximum. Therefore, the ozone concentrations in the air that exceed this value are considered dangerous on the health of humans and cause many diseases according to their values and the term of exposure. The problem is that both the efficiency of the devices and the concentration of the generated ozone are directly proportional with the value of the electric power consumed in forming the corona discharges.\textsuperscript{31–35} This problem has stimulated the author and others to study the electrical characteristics of the dc and the ac corona discharges in parallel with the ozone generation under different operating conditions.\textsuperscript{34–40} On the other hand, the dielectric barrier corona discharges (DBCDs) have been studied in some of the previous papers, where the grounded electrodes were covered by dielectric layers.\textsuperscript{31–40} However, all these papers have concentrated on studying the electrical properties of the DBCDs only, and have not exposed to studying the generated ozone.

In this paper, the electrical characteristics of both the dielectric barrier corona discharges and the usual ac corona discharges have been studied in parallel with the concentration of the generated ozone under the same operating conditions. Therefore, the corona discharges were formed inside two identical reactors in the form of a coaxial wire-to-cylinder with and without a dielectric barrier covering the inner surface of the cylinder. The two reactors have been fed by constant flow rates from the dry air and the oxygen gas independently at the atmospheric pressure and the room temperature, in parallel with applying a sinusoidal ac voltage to the electrodes of the reactors. The electric power consumed in the corona discharges and the waveform of the discharge current as well as the ozone concentration generated in the flowing gases through the reactors have been studied versus the peak of the ac voltage that was applied to the reactors. The aim from that is studying the electrical characteristics in parallel with the ozone generation for both the dielectric barrier corona discharges (DBCDs) and the usual ac corona discharges (ACCDs) under the same operating conditions.

II. EXPERIMENTAL SETUP AND MEASURING TECHNIQUE

A. Experimental setup

Figure 1 shows a schematic diagram of the experimental setup that has been used in this study, and it was composed of the following.

1. High-voltage ac power supply

The high-voltage ac power supply consists of a step-up transformer (\(V_{\text{input}} = 0 \rightarrow 100 \text{ V}_{\text{rms}}, 60 \text{ Hz} \) and \(V_{\text{output}} = 0 \rightarrow 20 \text{ kV}_{\text{rms}}, 1 \text{ kW} \)) and a load resistor (500 k\(\Omega\), 250 kV, 200 W).

2. Corona discharge reactors

Two of the identical reactors in the form of a coaxial wire-to-cylinder with and without a dielectric barrier covering the inner surface of the cylinder have been used in the experimental measurements as follows.

The first reactor consists of an aluminum foil its thickness 0.2 mm wrapped around the external surface of a glass tube along a distance \(L = 0.15 \text{ m} \). The length of the glass tube is 0.30 m, its inner and outer radii are \(R_i = 8.8 \times 10^{-3} \text{ m} \) and \(R_o = 10 \times 10^{-3} \text{ m} \) respectively, while the relative permittivity of the glass is \(\varepsilon = 3.926 \times 10^{11} \text{ F/m} \). The discharge wire in the reactor is made of the stainless steel with a radius \(r_o = 5 \times 10^{-5} \text{ m} \). The wire has been tensioned along the axis of the glass tube between two silicone plugs, and they have been fixed into the ends of the tube. The two silicone plugs were provided with a system to adjust the wire along the axis of the tube and to allow for the gas to flow around the wire at inlet and outlet of the reactor.

The second reactor is similar to the first reactor, but the glass tube in the first reactor has been replaced with an aluminum tube in the second reactor. The length of the aluminum tube is \(L = 0.15 \text{ m} \) and its inner radius is equal to the outer radius of the glass tube (i.e., \(R_i = 0.01 \text{ m} \)). The two outer ends for the aluminum tube have been inserted into two Perspex tubes along 1 cm to install the silicone plugs. The length of the Perspex tubes was 10 cm, and the discharge wire was the same as in the first reactor.

It is worthy to mention that the geometrical dimensions of the metallic electrodes in the two reactors are equal, but the first reactor has been provided with a dielectric barrier covering the inner surface of the outer tube that was formed from the aluminum foil.
3. Gas flow system

The reactor under study has been fed by either the dry air or the oxygen gas with a constant flow rate from high-pressure cylinders connected to it through gas flow meters as shown in Figure 1.

B. Measuring technique

The reactor under study has been connected to both the high-voltage ac power supply and the gas flow system as shown in Figure 1. The electric power input to the high-voltage ac power supply was controlled by using a regulating transformer (0 → 100 Vrms, 60 Hz, 500 W), and its value was measured through an automatic digital power meter (Yokogawa-2534). The output of the high-voltage ac power supply was connected to the discharge wire of the reactor, and the wave of the sinusoidal ac voltage was displayed on the screen of two channels digital real-time memory oscilloscope (SONY-TDS360P, 200 MHz) by using 1000:1 high-voltage probe (Tektronix P6015A, 75 MHz). The outer tube of the reactor has been grounded through either an automatic digital multimeter (IWATSU-7411) or a resistor $R = 10 \, \text{k}\Omega$. The digital multimeter was used for measuring the discharge current, while the resistor was used to display the waveform of the discharge current on the screen of the oscilloscope as shown in Figure 1. The total value of the electric power consumed in the experimental setup, the value and the waveform of the discharge current as well as the ozone concentration generated in the flowing gas through the reactor have been studied versus the peak of the ac voltage applied to the reactor.

The value of the electric power consumed in forming the corona discharges (i.e., the discharge power $P$) and the ozone concentration generated in the flowing gases through the reactors $\text{C}[\text{O}_3]$ have been measured by using the same experimental techniques that were explained in previous papers.34–40

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. The electrical characteristics of the dielectric barrier corona discharges

1. Formation of the corona discharge modes

With the dielectric barrier corona discharge (DBCD) in the dry air, Figure 2 shows successive oscillograms for the waveform of the discharge current versus the sinusoidal wave of the ac voltage that was applied to the first reactor. The successive current-voltage oscillograms in this figure show the following.

When the peak value of the ac voltage $V_F$ applied to the reactor reaches to or exceeds slightly the value of the corona onset voltage $V_o$, the discharge starts in the positive voltage half cycle in the form of a uniform stable glow with a pulseless current, while starts in the
Successive current-voltage oscillograms for the dielectric barrier corona discharge (DBCD) in the dry air show the waveform of the discharge current versus the sinusoidal wave of the ac voltage that was applied to the first reactor when the value of $Q = 1.66 \times 10^{-5}$ m$^3$/s. The oscillograms (a), (b), (c), (d) and (i) reproduced with permission from Abdel-Salam et al. J. Phys. D: Appl. Phys. 36, 252 (2003). Copyright 2003 IOP Publishing Ltd.

When the peak voltage increases to the value of $V_P = 6000$ V, the value of the stable glow current increases more in the positive voltage half cycle, while the number and the amplitude of the onset streamers increase in the negative voltage half cycle as shown in Figure 2(b). Furthermore, at the peak of the ac voltage in both the positive and the negative half cycle where $(dV_P/dt) = 0$, the flow of discharge current from the reactor does not stop like the case of the dielectric barrier discharges (DBDs) inside the gaps of the uniform electric field, but it continues in the flow from the reactor with the decrease of the voltage until reaches to the value of $V_o$ again.

With increasing the value of the peak voltage gradually in the range of $8000 \leq V_P \leq 20000$ V, the value of the stable glow current increases continuously in the positive voltage half cycle, while the onset streamers disappear gradually in the negative voltage half cycle to form a stable glow with a steady negative current as shown in Figure 2 (from c to i). In addition to that, the wave of the discharge current shifts gradually to the left side in the direction of beginning the complete cycle of the ac voltage, as it would be explained later.

Figure 3 shows also successive oscillograms for the waveform of the discharge current versus the sinusoidal wave of the ac voltage that was applied also to the first reactor with the dielectric barrier corona discharge (DBCD) in the oxygen gas. The successive current-voltage oscillograms in this figure show the following.

At the corona onset voltage ($V_o$), the discharge starts in the form of onset streamers in both the positive and the negative half cycle as shown in Figure 3(a). When the value of the peak voltage increases in the range of $6000 \leq V_P \leq 10000$ V, the repetition rate of the onset streamers increases in the positive voltage half cycle up to a critical value at which the negative space charge created in the ionization region chokes off this mode of the discharge. After that, the onset streamers disappear gradually and followed by a stable glow mode as shown in Figure 3 (from b to d).

With increasing the value of the peak voltage gradually in the range of $12000 \leq V_P \leq 20000$ V, both the value of the stable glow current and the repetition rate of the streamers increase continuously in the positive and the negative half cycle respectively as shown in Figure 3 (from e to i).

In a previous paper, the author and others have studied the development of the ac corona discharge (ACCD) modes in both the atmospheric air and the oxygen gas. The corona discharges have been formed inside a wire-to-duct reactor without dielectric layers, with the flow of the gases through it by a constant rate of $1.67 \times 10^{-5}$ m$^3$/s and applying a sinusoidal ac voltage to the electrodes of the reactor. Figures 3 and 4 in the previous paper show the successive current-voltage oscillograms that have been recorded with the ac corona discharges in both the air and the oxygen gas respectively. By comparing the current-voltage oscillograms in the present study versus those present in the previous paper, one can note easily the following.

(i) The behavior of the dielectric barrier corona discharge modes in both the dry air and the oxygen gas shown in Figures 2 and 3 of the present study is the same as the behavior of the usual ac corona discharge modes in the same gases shown in Figures 3 and 4 of the previous paper respectively.

FIG. 2. Successive current-voltage oscillograms for the dielectric barrier corona discharge (DBCD) in the dry air show the waveform of the discharge current versus the sinusoidal wave of the ac voltage that was applied to the first reactor when the value of $Q = 1.66 \times 10^{-5}$ m$^3$/s. The oscillograms (a), (b), (c), (d) and (i) reproduced with permission from Abdel-Salam et al. J. Phys. D: Appl. Phys. 36, 252 (2003). Copyright 2003 IOP Publishing Ltd.
FIG. 3. Successive current-voltage oscillograms for the dielectric barrier corona discharge (DBCD) in the oxygen gas show the waveform of the discharge current versus the sinusoidal wave of the ac voltage that was applied to the first reactor when the value of $Q = 1.66 \times 10^{-5}$ m$^3$/s.

(ii) In the current-voltage oscillograms shown in Figures 3 and 4 of the previous paper, the wave of the discharge current does not shift to the left side with increasing the peak value of the ac voltage applied to the reactor. In other words, the peak of the discharge current $I_P$ coincides with the peak of the ac voltage $V_P$ along the range of the overvoltage that was applied to the reactor. Simply, because the surfaces of the duct in the reactor were not covered with dielectric layers.

(iii) In general, Figures 2 and 3 in the present study as well as Figures 3 and 4 in the previous paper indicate that the sequence of the ac corona discharge modes during the positive and the negative half cycle of the ac voltage is the same as the sequence of the positive and the negative dc corona discharge modes respectively with the same wires.

2. The current-voltage characteristics

Figure 4 shows the current-voltage characteristics of the dielectric barrier corona discharges (DBCDs) and the usual ac corona discharges (ACCDs) in both the dry air and the oxygen gas. Because the values of the experimental results are close to each other, they have been plotted in Figure 4 without using symbols. Therefore, the blue and the red curves indicate the $I_P - V_P$ characteristics of the ACCDs in the dry air and the oxygen gas respectively, while the blue and the red straight lines indicate the $I_P - V_P$ characteristics of the DBCDs in the dry air and the oxygen gas respectively. The $I_P - V_P$ characteristics in Figure 4 show the following.

The value of the onset voltage ($V_o$) of the ACCDs is equal to the value of the onset voltage of the DBCDs whether in the dry air or in the oxygen gas. This behavior is explained by the fact that the practical values of the breakdown voltage for the discharge gaps bounded by one or two of the dielectric barriers are equal to the values of the breakdown voltage for the same discharge gaps when they are confined between metal electrodes only under the same conditions.

The value of $V_o$ for both the ACCD and the DBCD in the dry air agrees with the value that was calculated by using Peek’s equation at the experimental operating conditions.

The value of $V_o$ for both the ACCDs and the DBCDs in the oxygen gas is higher than the value of $V_o$ in the dry air. Therefore, the values of $I_P$ in the dry air are higher than the values of $I_P$ in the oxygen gas for the same values of $V_P$ that are applied to the reactors as shown in Figure 4.

The values of the $I_P - V_P$ characteristics of the ACCDs in both the dry air and the oxygen gas indicated by the blue and the red curves in Figure 4 follow Townsend’s general equation of the dc corona discharges in the form of

$$I_P = KV_P(V_P - V_o), \quad (1)$$

where $K$ is a constant and its experimental value depends on the geometrical dimensions of the coaxial wire-to-cylinder electrodes and the physical properties of the gas (i.e., type of the gas and its pressure).  39

With the DBCDs in both the dry air and the oxygen gas, the values of the $I_P - V_P$ characteristics fit a linear equation (with a correlation factor $R = 0.9995$) in the form of

$$I_P = K(V_P - V_o), \quad (2)$$
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FIG. 4. The current-voltage characteristics of the ac corona discharges (ACCDs) and the dielectric barrier corona discharges (DBCDs) in both the dry air and the oxygen gas when the value of \( Q = 1.66 \times 10^{-5} \) m\(^3\)/s.

where the experimental value of \( K = 1.418 \times 10^{-7} \) and \( 1.413 \times 10^{-7} \) A/V (or \( \Omega^{-1} \)) in both the dry air and the oxygen gas respectively.

With the DBCDs in both the dry air and the oxygen gas, the value of the peak voltage \( V_P \) that was applied to the first reactor has been increased up to 20000 V without forming an electric arc inside the discharge gap of the reactor. This is the advantage of the presence of the dielectric barrier inside the first reactor. On the other side, with the ACCDs in both the dry air and the oxygen gas, the value of the peak voltage \( V_P \) that was applied to the second reactor has been increased up to 12000 V only. This value was less than the value of the sparkover voltage directly. This explains why the range of the overvoltage (i.e., \( V_{P \max} - V_o \)) that was applied with the DBCDs in the first reactor is longer two times than the range of the overvoltage that was applied with the ACCDs in the second reactor as shown in Figure 4.

Figure 5 shows the values of the discharge power \( P \) consumed in forming the ACCDs and the DBCDs in both the dry air and the oxygen gas as a function of the peak values of the ac voltage \( V_P \) that was applied to the reactors. The \( P - V_P \) characteristics curves in this figure show the following.

The general behavior of the \( P - V_P \) characteristics curves shown in Figure 5 is similar to the behavior of the \( I_P - V_P \) characteristics shown in Figure 4. The reason for this similarity is that the value of \( P \) is directly proportional to the value of \( I_P \) when the value of \( V_P \) applied to the reactors is constant.

The maximum values of \( P \) with the ACCDs are higher than the maximum values of \( P \) with the DBCDs by about 67% and 42% in both the dry air and the oxygen gas respectively as the results indicate in Figure 5. This is the disadvantage that results from the presence of the dielectric barrier on the inner surface of the outer tube in the first reactor. Therefore, to increase the value of the electric power consumed in forming the non-thermal plasma inside the discharge gaps that are bounded by one or two of the dielectric barriers, the discharge mechanism is operated by using different waveforms of the high-frequency voltage in the range of kHz to MHz, as in the case of the ozone generators.\(^{1,2,7,51,52}\)

3. The electric charge accumulated on the surface of the dielectric barrier in the first reactor

The current-voltage oscillograms that were recorded in Figure 2 with the DBCD in the dry air indicate also the following.

When the active discharge mode \( t_d \) inside the reactor during the positive or the negative half cycle of the ac voltage increases with increasing the peak value of the ac voltage \( V_P \) according to the relation

\[
t_d = \frac{T}{2} - 2\left(\frac{1}{\omega}\right)\sin^{-1}\left(\frac{V_0}{V_P}\right),
\]

where \( T \) and \( \omega \) are the periodic time and the angular frequency of the ac voltage respectively. The experimental values of \( t_d \) that have been determined from the current-voltage oscillograms in Figure 2 versus the values of \( V_P \) agree with the values of \( t_d \) that were calculated by using Equation (3) as shown in Figure 6.

When the active discharge mode starts in the positive (or in the negative) half cycle of the ac voltage, the positive (or the negative) ions that are created inside the ionization region drift to the conduction region. When these ions reach to the dielectric barrier, they accumulate homogeneously on the surface and form a positive (or a negative) electric charge \( q \). This electric charge creates an induced...
electric field inside the discharge gap in a direction opposite to the electric field that produces from the ac voltage applied to the reactor. But the electric field strength resulting from the ac voltage at the wire surface is much higher than that at the inner surface of the dielectric barrier because $E = V_P/r\ln(R/r_o)$ where $r_o \leq r \leq R$. Therefore, the induced electric field strength that arises at the inner surface of the dielectric barrier is not enough to stop the discharge mechanism inside the reactor. This explains why the discharge current flows from the reactor at the peaks of the positive and the negative half cycles of the ac voltage although $(dV_P/dt) = 0$, as the current-voltage oscillograms show in Figure 2.

The value of the electric charge $q$ that accumulates on the surface of the dielectric barrier during the positive (or the negative) half cycle of the ac voltage increases regularly with increasing the values of both $V_P$ and $I_P$. Therefore, the induced electric field strength that arises inside the discharge gap at the end of the negative half cycle increases also by the same rate with increasing the value of $V_P$, and supports the electric field resulting from the ac voltage applied to the reactor at beginning of the next positive half cycle, and vice versa in the next half cycle of the ac voltage. The result is that the wave of the discharge current shifts gradually to the left side in the direction of beginning the complete cycle of the ac voltage applied to the reactor with increasing the value of $V_P$, as the current-voltage oscillograms in Figure 2 indicate.

With the gradual shift for the wave of the discharge current, the values of the time interval confined between the peak of the ac voltage $V_P$ and the peak of the discharge current $I_P$ [i.e., $t(V_P) - t(I_P)$ as indicated in Figure 2(c)] have been determined from the current-voltage oscillograms shown in Figure 2 versus the values of $V_P$. Moreover, the values of the ac voltage that corresponds to the peak of the discharge current $I_P$ in the current-voltage oscillograms [i.e., $V(I_P)$ as indicated also in Figure 2(c)] have been calculated by using the relation

$$V(I_P) = V_P \sin \left[ \frac{T}{4} - \frac{1}{2} \left\{ t(V_P) - t(I_P) \right\} \right].$$

Figure 7 shows the values of both $[t(V_P) - t(I_P)]$ and $V(I_P)$ that were obtained versus the values of $V_P$.

![FIG. 6. Experimental and calculated results (the red circles and the blue curve respectively) for the time of the active discharge mode ($t_d$) inside the first reactor versus the peak value of the ac voltage ($V_P$).](image)

![FIG. 7. The values of both $[t(V_P) - t(I_P)]$ and $V(I_P)$ versus the peak value of the ac voltage ($V_P$).](image)

![FIG. 8. The maximum value of the electric charge ($q_{max}$) accumulated on the surface of the dielectric barrier as a function of the peak value of the ac voltage ($V_P$).](image)
The maximum value of the electric charge that accumulates on the surface of the dielectric barrier during the active discharge mode in the positive (or the negative) half cycle of the ac voltage applied to the first reactor has been calculated by using the equation

$$q_{\text{max}} = \frac{2 \pi \varepsilon L}{\ln(R_0/R_i)} [V_p - V(I_p)],$$  \hspace{1cm} (5)

where $L$, $R_i$, $R_0$, and $\varepsilon$ are the specifications of the glass tube inside the first reactor as mentioned in Sec. II A 2. Figure 8 shows the values of $q_{\text{max}}$ that have been calculated by using Equation (5) versus the values of $V_p$. The equation of the curve fit in Figure 8 shows that the value of $q_{\text{max}}$ increases gradually with increasing the value of $V_p$ in the form of the power function

$$q_{\text{max}} = 3.45014 \times 10^{-18} (V_p)^{2.94557},$$  \hspace{1cm} (6)

with a correlation factor $R = 0.99996$.

It is worthy to mention that the previous method is applicable also on the current-voltage oscillograms of the DBCD in the oxygen gas shown in Figure 3.

### B. The ozone generation in the flowing gases through the reactors

Figure 9 shows the ozone concentration $C[O_3]$ generated by both the ACCDs and the DBCDs in the dry as a function of the discharge power $P$ for different rates of the air flow through the reactors $Q$. Figure 10 is similar to Figure 9, but it includes the $C[O_3]$ - $P$ curves of both the ACCD and the DBCD in the oxygen gas.

The $C[O_3]$ - $P$ curves of the ACCDs and the DBCDs in both the dry air and the oxygen gas in Figures 9 and 10 respectively show the following.

In general, the ozone concentration generated by both the ACCDs and the DBCDs in the low range for the value of the discharge power (i.e., $P \leq 2$ W) increases with a higher rate than the ozone concentration generated in the high range for the value of the discharge power (i.e., $P \geq 10$ W), whatever type of the gas and its flow rate through the reactors, as shown in Figures 9 and 10. This behavior has been explained previously in the light of mechanisms of formation and destruction of the ozone by the physicochemical reaction processes that take place inside the corona discharge plasma.

The ozone concentration generated by the DBCDs is equal to the ozone concentration generated by the ACCDs under the same operating conditions (i.e., the same type of the flowing gas through the reactors and the same values of both $P$ and $Q$). This equality confirms that the successive modes of the DBCDs are the same as the modes of the ACCDs, as it was explained previously. Therefore, the physicochemical reaction processes that take place inside the DBCD plasma repeat by the same style inside the ACCD plasma under the same operating conditions mentioned before. Because the ozone gas is generated mainly inside the sheath of the corona discharge plasma surrounding the wire surface (i.e., the ionization region).

With both the ACCDs and the DBCDs, the ozone concentration generated in the oxygen gas shown in Figure 10 is equal on the average twice the ozone concentration generated in the dry air shown in Figure 9 for the same values of $P$ and $Q$. This behavior agrees well with previous experimental results.

Although the percentage of the oxygen gas in the dry air is 20.95% only by volume, however the ozone concentration generated by using the dc and the ac corona discharges as well as the dielectric
barrier discharges (DBDs) in the dry air is half the ozone concentration generated in the pure oxygen gas under the same operating conditions. This means that the ozone concentration generated in the dry air is higher than that would be expected from the percentage of oxygen in the air. This fact has been explained previously in the light of the physicochemical reaction processes that take place inside the electrical discharges in both the dry air and the oxygen gas.

When the value of the discharge power $P$ consumed inside the reactors is constant, the ozone concentration generated by the ACCDs and the DBDs in the dry air and the oxygen gases decreases with increasing the value of the gases flow rate through the reactors $Q$, as shown in Figures 9 and 10. With the open systems of the coaxial wire-to-cylinder reactors, the residence time of the flowing gas molecules inside the reactor $t_r$ equals the internal volume of the reactor $V_r$ divided by the gas flow rate through it $Q$ (i.e., $t_r = V_r/Q$). Because the value of $V_r$ is constant for both of two reactors, the value of $t_r$ decreases with increasing the value of $Q$. Therefore, the residence time of the flowing gas molecules inside the region of the corona discharge plasma decreases also with increasing the value of $Q$, where the physicochemical reaction processes take place and the ozone gas is generated. The result is that the ozone concentration decreases in parallel with the decrease of the time of exposure of the gas molecules to the physicochemical reaction processes. This explains why the value of $C_{[O_3]}$ decreases with increasing the value of $Q$ when the value of $P$ is constant, as shown in Figures 9 and 10.

IV. CONCLUSION

The experimental and the calculated results that were presented in section III of this paper have been summarized in the following.

(i) The sequence of appearing the DBCD modes in both the dry air and the oxygen gas is the same as the sequence of appearing the ACCD modes in the same gases under the same operating conditions.

(ii) The current-voltage characteristics of the DBCDs in both the dry air and the oxygen gas take the form of linear relationships.

(iii) The range of the overvoltage that can be applied to the reactor with the DBCDs is at least twice the range of the overvoltage that can be applied to the reactor with the ACCDs.

(iv) The maximum value of the electric power consumed with the ACCDs is much higher than the maximum value consumed with the DBCDs when the reactors are fed by the same flowing gas.

(v) With the DBCDs in the coaxial wire-to-cylinder reactor, the value of the electric charge accumulated on the surface of the dielectric barrier that covers the inner wall of the cylinder increases regularly with increasing the peak value of the ac voltage in the form of a power function. With increasing the value of the electric charge on the surface of the dielectric barrier, the wave of the discharge current shifts gradually to the direction of beginning the complete cycle of the sinusoidal ac voltage that is applied to the reactor.

(vi) The ozone concentration generated by the DBCDs is equal to the ozone concentration generated by the ACCDs inside the identical reactors when are fed by constant flow rate from the same gas and constant value of the electric power.

(vii) In general, the ozone concentrations generated by both the ACCDs and the DBCDs in the gases flowing through the reactors under the operating conditions present in this paper are much higher than the maximum global limit of the ozone concentration allowable for the exposure.

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