Experimental Study of Dielectric-Barrier-Discharge Reactor for Plasma-Assisted-Combustion

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Abstract—A cylindrical Dielectric Barrier Discharge (DBD) plasma reactor is analyzed and investigated at normal environmental conditions. The stressed voltage is varied up to 40 kV peak to peak with variable frequency from 60 up to 4 kHz. The reactor is filled with aluminum oxide pellets to decrease the onset voltage, to assist combustion and to reduce the input electrical power. An equivalent configuration is proposed to model the region of alumina pellets inside the reactor and to calculate the corresponding equivalent capacitances of the reactor. A plasma-assisted combustion (PAC) application is studied experimentally with the reactor. The plasma causes an increase in the flame propagation rate, attributed to the production of reactive radicals and fragmentation of fuel molecules in the plasma. The experimental study includes the reactor operation at different fuel-air ratio by controlling the flow rate of propane and oxygen to achieve lean combustion. The effect of plasma on the flame propagation and intensity is evaluated. The capability of plasma to enhance combustion has significant practical implications.

Keywords—DBD, discharge power, micro-discharge, plasma-assisted-combustion

I. INTRODUCTION

Corona and DBD are non-thermal plasmas under standard operating conditions for pressure and temperature. DBDs are superior to corona discharges in terms of plasma chemical processing [1] due to higher energy density. For the applications of volume plasma chemistry, therefore, the silent discharges are useful. The flexibility of DBDs with respect to geometrical configuration, operating medium, and operating parameters is very high compared with corona discharges. The conditions optimized in laboratory experiments can be scaled up to large industrial installations. Therefore, DBDs appear in many industrial applications, such as ozone generation [2], surface treatment [3], deposition [4], sterilization [5], toxic gas decontamination [6], and so on. DBDs have also been used for UV excimer lamp, plasma display panel, surface modification and biomedical applications for the past twenty years [7].

These industrial applications of DBD owe to the easy formation of stable plasmas and its scalability, effectiveness and low operational cost [8-10]. Researchers tried to model DBDs to facilitate determination of the optimum parameters, reactor configuration and operating conditions. These models can be divided into physical models [11-13] and electrical models [6, 7, 14-17]. The physical models are based on fluid equations involved with movements of charges and boundary conditions. However, physical models include various gas ionization processes, and the related simulation and calculation are complicated and time-consuming to calculate, whereas electrical model is relatively convenient and simple, as the discharge plasmas are usually regarded as an equivalent electrical circuit representing the relationship between the reactor configuration and electrical parameters [7].

In Plasma-Assisted Combustion (PAC), a sufficient electric field is applied to a fuel/air mixture, which enables ionization of the gas mixture to generate plasma. The plasma increases the temperature of free electrons and ions and hence helps combustion by forming active species such as free radicals. Moreover, plasma dissociates the fuel molecules into smaller and easier combustible fragments. Non-thermal plasmas (NTP) reported in literature [18-23] were DBD since it is easily operated at standard conditions of atmospheric pressure and temperature under a wide range of frequencies. NTPs have been directly applied to a flame region or to a fuel/air, pre-flame mixtures. Sometimes the plasma is applied to the fuel only for cracking whereas the oxidizing air is mixed with the fuel gas after it is activated by plasma [23].

In this paper, the authors extend the work published in [24] to study the DBD reactor for plasma-assisted combustion. A laboratory model was set up and tested under different operating conditions of varying the applied voltage and frequency.

The provided experimental work includes two phases; the first phase shows the temporal waveforms of the voltage and discharge current at different applied voltages and frequencies and the corresponding discharge power is calculated. The second phase is the plasma-assisted combustion application by applying different flow rates of propane and oxygen to achieve lean combustion and provide their effects on the flame propagation and intensity. The plasma causes an increase in the flame propagation rate, attributed to the production of reactive radicals and fuel fragments in the plasma.

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II. MATHEMATICAL MODEL OF THE DBD REACTOR

The studied DBD reactor is a cylindrical type that consists of a circular stainless steel rod with radius \( r_p \), a dielectric barrier of quartz glass with an inner and outer radii of \( r_d \) and \( r_o \), and a ground mesh from stainless steel as the ground electrode, as shown in Fig. 1(a). The annulus region between the rod and dielectric barrier is filled with aluminum oxide (Al\(_2\)O\(_3\)) pellets of 2 mm in diameter. The alumina pellets are added here for plasma-assisted combustion application. Adding alumina pellets decreases the onset voltage, enhances the reactor operation, provides intensive plasmas and increases the time of the micro-discharge.

In order to facilitate the calculation of the reactor equivalent capacitances, an equivalent dielectric material having the same dielectric constant and filling a region near to the rod, as shown in Fig. 1(b), replaces these dielectric alumina pellets. This equivalent region of alumina is calculated based on the total weight of the pellets and their density. The accumulated volume of air between pellets is represented by the annulus region between the alumina and dielectric barrier region, Fig. 1(b). It is found from the simulation study that letting the alumina region beside the dielectric barrier gives almost the same effects and results. For the reactor configuration and operation conditions, provides intensive plasmas and increases the time of the micro-discharge.

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Using the above equation, the equivalent volume of the pellets and the corresponding outer radius of the pellets region, \( r_p \) and \( r_c \), is estimated. If the air region is assumed located near to the dielectric barrier, as shown in Fig. 1(b), the equivalent volume of the air region, \( \nu_{air} \), is calculated from the rest of the annulus volume as [24]:

\[
\nu_{pellet} = \frac{w_p}{\rho} = \pi L (r_p^2 - r_c^2) \tag{1}
\]

where, \( \nu_{pellet}, w_p, \rho \) are the volume, weight and density of the pellets, \( r_p \) and \( r_c \) is the radii of the pellets' region and rod, respectively and \( L \) is the reactor effective length.

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\[
\nu_{air} = \pi L (r_d^2 - r_c^2) - \nu_{pellet} = \pi L (r_p^2 - r_c^2) \tag{2}
\]

Referring to the equivalent configuration of Fig. 1(b), the equivalent electrical model of the DBD reactor consists of three capacitors connected in series. One represents the capacitance of the aluminum oxide pellets (\( C_p \)), the second represents the capacitance of the equivalent volume of air gaps (\( C_g \)) and the last represents the capacitance of the dielectric barrier (\( C_d \)). The equivalent capacitances are calculated taking into account the topology of the coaxial capacitor with three different materials; aluminum oxide, free-space and quartz glass of the dielectric barrier. The equivalent capacitances are calculated as [24]:

\[
C_p = \frac{2\pi \varepsilon_0 \varepsilon_r L}{\ln(r_p/r_c)} \quad C_g = \frac{2\pi \varepsilon_0 L}{\ln(r_d/r_p)} \quad C_d = \frac{2\pi \varepsilon_0 \varepsilon_r L}{\ln(r_d/r_d)} \tag{3}
\]
and $C_d$ are determined, and that $i_d(t)$ is controlled by the applied voltage and strongly related to $i(t)$. In this case, the current controlled source follows the multitude and attenuation of the micro-discharges according to the slope of the applied voltage and hence, represents the dynamic state in the air gap annulus layer. It is well known that the micro-discharges will not take place unless the applied voltage exceeds the breakdown or onset voltage of the reactor. The onset voltage depends on the source frequency, relative permittivity of the dielectric materials and the physical dimensions of the reactor. If the applied AC voltage on the reactor is in the form:

$$v_s(t) = V_m \sin(\omega t)$$  \hspace{1cm} (4)

where, $\omega$ is the angular frequency of the applied voltage, $V_m$ is its amplitude. The ignition and extinction times; $t_1$ and $t_2$ during the positive half cycle of the applied voltage are [6, 7, 24]:

$$t_1 = \frac{1}{\omega} \sin^{-1}\left(\frac{V_o}{V_m}\right), \quad t_2 = \frac{\pi}{2\omega}$$  \hspace{1cm} (5)

where, $V_o$ is the onset voltage of micro-discharges inside the reactor.

During the negative half cycle of the applied voltage, the ignition of micro-discharges occurs at the negative onset value at time $t_3$ and the extinction time will be at $t_4$ as:

$$t_3 = \frac{1}{\omega} \sin^{-1}\left(-\frac{V_o}{V_m}\right), \quad t_4 = \frac{3\pi}{2\omega}$$  \hspace{1cm} (6)

The discharge power, $P_D$, in generating micro-discharges is given by the following formula [1, 7, 24, 25, 27, 28] taking into account that there are two capacitors connected in series with the air gap capacitance $C_g$; that are equivalent pellet capacitance, $C_p$, and the dielectric barrier capacitance, $C_d$:

$$P_D = 4f \left(\frac{C_p d^2}{C_p + C_d}\right) V_o (V_m - V_o)$$  \hspace{1cm} (7)

III. EXPERIMENTAL ANALYSIS

The schematic diagram of the experimental setup is shown in Fig. 3. It consists of a regulating transformer, high voltage AC power supply and the plasma reactor, in addition to, the measuring probes and the digital oscilloscope (OSC). The capacitor ($C = 68$ nF) shown in the figure is connected when $Q$-$V$ measurements are conducted where the current probe is replaced by another voltage probe across the capacitor to measure its voltage. Note that all the devices are connected to one ground point. The applied voltage to the plasma reactor is varied along with its frequency and the corresponding measurements are recorded.

A. Experimental Results without Combustion

The applied voltage of the AC power supply to the DBD plasma reactor is varied at different operating frequencies and the corresponding voltage and current waveforms are recorded with the OSC and re-drawn as shown in Figs. 4 and 5. The amplitude of the applied voltage is fixed at 30 kV$_{pp}$ and the frequency is changed from 1 kHz to 4 kHz. As the frequency of the applied voltage increases, the discharge current inside the reactor increases with increasing the number of micro-discharges. At the same applied voltage of 30 kV$_{pp}$, the voltage across the capacitor ($V_s$) and voltage of the applied voltage ($V_t$) are recorded and plotted on $xy$ mode of the OSC. The frequency is varied from 50 Hz to 4 kHz as
shown in Fig. 6. Increasing the frequency, the discharge current increases and hence the voltage across the capacitor which equals to the time integration of the current increases. When the parallelogram area increases, the discharge power proportionally increases. The discharge power can be expressed in terms of the area of parallelogram (S) as \[ P_D = \frac{1}{T} \int_0^T V I \, dt = \frac{C}{T} \int_0^T V \, d\phi \, dt = fC \phi V d\phi = fCS \] (8)

The applied voltage magnitude varies from the onset voltage until 40 kV\(_{pp}\) with varying its frequency and at each time, the discharge power is calculated as shown in Fig. 7. It is clear that increasing the applied voltage magnitude or its frequency results in an increase of the discharge power of the plasma DBD reactor.

B. Experimental Results with Combustion

To burn one mole of propane (C\(_3\)H\(_8\)) completely at stoichiometric conditions, one needs 5 moles of oxygen (O\(_2\)) as shown in the following reaction:

\[ C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \] (9)

To determine the combustion conditions according to the air and fuel ratios, an equivalence ratio \( \lambda \) is calculated as:

\[ \lambda = \frac{AFR}{AFR_{stoich}} \] (10)

where \( AFR \) is the air-to-fuel ratio and \( AFR_{stoich} \) is the ratio at stoichiometric conditions.

When the value of \( \lambda \) is greater than unity, it means that the combustion is lean (using less fuel in excess of air) whereas when it is less than unity it means rich combustion (combusting more fuels). The deterministic case when \( \lambda \) equals unity demonstrates the stoichiometric mixture. For the plasma-assisted combustion, many configurations for the reactor arrangement are considered. One of these configurations is shown in Fig. 8 where the high voltage is connected to the inner tube where the air flows and the outside mesh is connected to the ground. The alumina fills the inner volume of the quartz glass of the dielectric barrier where the propane flows through its pellets. The ground mesh electrode and the alumina pellets are in the same level as shown while the high voltage inner tube where air flows inside is higher by the length of \( L_2 \) and the quartz glass is taller than that by \( L_1 \). The length of the mesh electrode is \( L_3 \).
The other reactor dimensions and their values are listed in Table I.

A digital camera is supported to record the flame images for different operating conditions of the applied voltage, frequency and flow rates. The ends of the electrodes and the end of the quartz tube were separated by a $L_1$ mixing region. By using a relatively long mixing region, we were able to eliminate any effects of the electric field on the flame. The photographs are taken with a Nikon digital camera with ISO640, a focal length of 10 mm, and exposure time of 5 s. The images focus on the mixing region above the alumina pellets as well as above the quartz tube.

The effects on the combustion flame due to a progressively AC high voltage with a frequency of 1 kHz applied to the DBD reactor electrodes are shown in Fig. 9. The airflow rate is 4 L/min while the propane flow rate is 95 mL/min leading to an equivalence ratio of 1.762. This value of $\lambda > 1$ ensures lean combustion condition. Fig. 9(a) shows a propane-air flame without plasma condition. Applying a 30 kV, 1 kHz on the electrodes initiates the plasma which cracks the propane molecules into smaller pieces and increases the micro-discharge to help the combustion as shown in Fig. 9(b)-(d). Increasing the applied high voltage to 35 kV in Fig. 9(c) and to 40 kV in Fig. 9(d) lengthens the flame and improves the flame symmetry indicating increasing stability of the flame. In Fig. 9(d) where 40 kV is applied to the electrodes, the flame extended and propagated into the mixing region where excess of plasma exists. The changes in the flame’s ability to propagate downward suggest that the flame propagation rate increases with plasma power. The flame propagates more quickly because it is igniting and burning faster. This combustion enhancement may result from the improved cracking of propane, the creation of reactive radicals, or hydrogen generation [23].

With the same applied voltages but at different flow rate, the images are shown in Fig. 10. The equivalence ratio is increased to 2.203: (a) combustion without plasma, others with plasma at; (b) 30 kV, (c) 35 kV, and (d) 40 kV.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
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<td>45</td>
<td>$D_1$</td>
<td>21</td>
</tr>
<tr>
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<td>21</td>
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<td>62.5</td>
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Fig. 8. Reactor configuration and dimensions during PAC experiment.

Fig. 9. Effects of plasma applying voltage on the combustion at 1 kHz and equivalence ratio $\lambda = 1.762$: (a) combustion without plasma, others with plasma at; (b) 30 kV, (c) 35 kV, and (d) 40 kV.

Fig. 10. Effects of plasma applying voltage on the combustion at 1 kHz and equivalence ratio $\lambda = 2.203$: (a) combustion without plasma, others with plasma at; (b) 30 kV, (c) 35 kV, and (d) 40 kV.
flame indicates non-complete combustion of the propane due to excessive air. At the maximum of the applied voltage of 40 kV, the plasma helps the combustion and hence the red parts disappear as shown in Fig. 10(d).

In lean conditions, where the fuel amount compared to the used oxygen or air is less than that at stoichiometric or complete combustion. Without external assistance, the flame is weak and will not last for long times. The application of an AC high frequency voltage to the electrodes of the DBD reactor initiates the plasma inside the reactor. The plasma cracks the propane molecules into smaller pieces and increases the micro-discharge time to help the combustion and the flame will last for longer periods.

IV. CONCLUSION

Under different applied AC voltages and frequencies, the dielectric-barrier discharge (DBD) plasma reactor is studied at normal environmental conditions. The DBD plasma reactor study includes both theoretical and experimental analyses. Filling the DBD reactor with the alumina pellets enhances its performance due to the decrease of the onset voltage value and the intense generated plasma inside the reactor. Replacing the pellets of alumina by an equivalent uniform volume simplifies the analysis of the DBD reactor.

A plasma-assisted combustion (PAC) application is verified experimentally on the designed reactor. The plasma causes an increase in the flame propagation rate, attributed to the production of reactive radicals and fuel fragments in the plasma. The capability of plasma to enhance combustion has significant practical implications. At an equivalence ratio of 1.762 (propane flow of 0.95 L/min, airflow of 4.0 L/min) and a mixing region 45mm long, the propane flame-flashback phenomenon is observed when the propane is activated by a DBD prior to being mixed with air and burned. A stronger propagation happens with a more lean combustion of an equivalence ratio of 2.203 (propane flow of 0.95 L/min, airflow of 5.0 L/min).

REFERENCES


