Properties of DBD Plasma Jets Using Powered Electrode With and Without Contact With the Plasma

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Abstract—An experimental investigation comparing the properties of plasma jets in dielectric barrier discharge (DBD) configurations using a powered electrode with and without a dielectric barrier, while keeping a second dielectric barrier over the grounded electrode, is reported in this work. For this purpose, two different power sources were used to produce the plasma jets, with one of them producing a pulsed high-voltage (HV) output and the other one producing a damped sine-wave HV output, which acts as a pulse-like power source. Measurements of plasma parameters were performed for both configurations using argon and helium as working gases. As a result, if the pulsed power source is used, significant differences were found in discharge power \( P_{\text{dis}} \) and rotational and vibrational temperatures \( T_r \) and \( T_v \), respectively when switching from one configuration to the other. On the other hand, using the pulse-like HV, only the \( P_{\text{dis}} \) parameter presented significant differences when switching the electrode’s configuration. For the pulsed source, it has been observed that despite the remarkable increase in \( P_{\text{dis}} \) when changing from the double barrier configuration to the single barrier one, the values obtained for \( T_r \) and \( T_v \) also increased, but not in the same proportion as the increase in \( P_{\text{dis}} \), which suggests a nonlinear dependence between temperatures and discharge power in the plasma jet. As an example for application of plasmas in both configurations, tests in an attempt to remove copper films deposited on alumina substrates were performed and, as a result, there was significant material removal only when the powered electrode was in contact with the plasma. As a general conclusion, if higher power is really required for applications that do not involve in vivo targets, it is better to use this configuration.

Index Terms—Atmospheric pressure plasma jets (APPJ), dielectric barrier discharge (DBD), DBD plasma, plasma jets, plasma properties.

I. INTRODUCTION

PLASMA plumes produced under atmospheric pressure and in open environment generally referred to as atmospheric pressure plasma jets (APPJs) have been extensively studied in recent years, and a large number of applications for these devices have been developed due to their versatility, easy operation, and low cost of implementation compared to low-pressure plasmas [1]–[4]. The APPJs applications can be in industry, biology, and medicine, with the last field receiving great attention, especially due to successful treatments of cancerous tissues and, more recently, for combating viruses, including the Sars-Cov-2, and the success in biological treatments using APPJs is strongly related to the reactive oxygen and nitrogen species produced in such gas discharges [5]–[17]. Dielectric barrier discharge (DBD) is a kind of electrodes arrangement commonly employed to produce APPJs. Its main characteristic is the presence of at least one insulating layer between metallic plates [1], [3]. Among the various DBD configurations, the cylindrical geometry is the most commonly employed because it naturally takes advantage of using the gas flow to produce a plasma jet [2]. Even though many studies on different APPJ arrangements have been carried out, yet there is no a particular configuration that can be considered ideal, even for specific applications [3], [4]. Therefore, research goes on and different geometry configurations and device variations have been explored. It has been a considerable challenge to control plasma jet properties as well as to establish a relationship between different plasma parameters.

Among different electrode arrangements in cylindrical APPJ reactors, those setups that present powered electrodes at the center of the reactor have been commonly employed. They can have such an electrode covered with a dielectric barrier or not, that is, with the powered electrode in contact with the working gas or not. Each configuration will produce a plasma jet with different temperatures, power, and/or density of reactive species that are created when the plasma interacts with the surrounding ambient air or with a surface [4], [18]. The first mentioned configuration (encapsulated powered electrode) presents higher electrical safety when compared to the other (a powered electrode without a dielectric barrier) and, for this reason, it is preferred for medical applications of plasma jets, especially when the treatments are in vivo.

Studies regarding the interaction between APPJs and different substrates have shown that the conductivity or dielectric properties of the substrate, as well as the distance from device output to the target surface, influence not only the treatment results but can also modify the characteristics of the plasma jet itself [19]–[24]. Works concerning differences in plasma jet properties when impinging on grounded or floating targets have been reported [25], [26]. To generate APPJs, most devices use sinusoidal voltages, ranging in frequencies from kilohertz to megahertz. Previous works of our group revealed that using conducting or dielectric targets (or sample holders) has an important effect not only on plasma jet properties but also...
on plasma treatment outcome [19], [27]. For instance, it was verified that better adhesion of polydimethylsiloxane (PDMS) samples was achieved after plasma treatment using a conductive sample holder [27].

In this work, we studied the behavior of three main parameters of an APPJ: rotational and vibrational temperatures ($T_r$ and $T_v$, respectively) and mean discharge power ($P_{dis}$) in a DBD device in two distinct configurations. The first one employed is more often reported in the literature, in which a plasma jet is produced between two dielectric barriers, one enveloping the powered electrode and the other covering the grounded one. In the second configuration, the dielectric on the powered electrode was partly removed, while the one covering the grounded electrode was kept. This last configuration was not extensively explored yet, mainly due to safety issues appearing in medical applications of APPJs. Some works using microwave, sinusoidal, and pulsed power sources have been reported using it but with no mention of measurements of plasma power, vibrational or rotational temperatures, or comparison for different working gases [28]–[36]. Since some applications may not require the safe operating conditions provided by the dielectric barrier over the powered electrode, these can take advantage of the higher plasma power and other jet properties that can be achieved when the dielectric barrier is removed.

II. MATERIALS AND METHODS

A schematic layout of the experimental setup is shown in Fig. 1. In order to produce the plasma jets using the pulsed power source, high-voltage (HV) pulses of 20-kV amplitude and $\sim$250-ns width (at half peak voltage value) with positive polarity followed by a negative polarity pulse with $\sim$12-kV amplitude and $\sim$170-ns width, with 60-Hz repetition rate, were applied to a pin electrode covered with a glass tube with one of its ends closed (covered tip) or open (exposed tip), for the double- (DB) and the single-barrier (SB) configurations, respectively. Details about the pulsed power source can be found in [37]. A biaxially oriented polyethylene terephthalate (BoPET) foil, 500 $\mu$m thick and 10 cm sided, was placed on the top of a grounded electrode and acted as a common dielectric barrier (the dielectric plate in Fig. 1) in both cases. The distance $d$ between the end of the dielectric enclosure (a polyvinyl chloride tube) and the dielectric plate was kept constant and equal to 10 mm. Argon (Ar) and helium (He), both with 99.99% purity, were used as working gases at the same flow rate of 3.0 l/min. The damped sine-wave power source consists of an HV supply whose output presents a damped sine waveform with an oscillation frequency of $\sim$150 kHz and 60-Hz repetition rate. This power source acts as a pulse-like one due to the small duration of the voltage waveform when compared to its repetition rate. The maximum positive voltage peak provided by this power source is $\sim$15 kV. The other parameters used in the experiment with the damped sine-wave power source are the same as those mentioned for the pulsed one.

The light emitted by the plasma was collected using an optical fiber with 600 $\mu$m core diameter and numerical aperture of 0.22, providing an acceptance angle of 25.4°. The optical fiber was placed at the center of the plasma column, in both horizontal and vertical directions. The distance $L$ between the end tip of the optical fiber and the center of plasma device was kept unchanged in all experiments and equal to 10 mm. The spectroscopic measurements were performed using a portable multichannel spectrometer from OceanOptics (model HR4000), with a spectral resolution [full-width at half-maximum (FWHM)] equal to $(0.545 \pm 0.007)$ nm, measured at 632.8 nm.
In order to obtain the rotational and vibrational temperatures of $N_2$ molecules, we use spectroscopic emissions from the $N_2$ second positive system, $C^\,2\Sigma_g^+,\nu'=B^\,2\Pi_g,\nu''$ (referred as $N_2(C \rightarrow B)$ hereafter), with $\Delta \nu = \nu' - \nu'' = -2$ in the wavelength range from 360 to 385 nm [38]–[41]. Then, comparisons between measured and simulated spectra are performed and the $T_r$ and $T_v$ pair of temperature values is determined by those that generate simulated curves that best fit to the experimental spectra, providing the lowest chi-squared value in the temperature ranges used to obtain the simulated curves. The spectral resolution value provided by the spectrometer is not enough to resolve rotational levels of the $N_2$ molecules and obtain accurate values for the $T_r$ parameter. However, there is a direct relationship between the shape and broadening of the $N_2$ vibrational bands and the variation of the $T_r$ values, being that the higher $T_r$, the larger the broadening, and also the higher the intensity of the rotational lines in the vibrational bands. Both effects cause a change in the shape of the vibrational bands in that part that degrades to violet, causing it to become higher and wider, allowing the estimation of the $T_r$ values by using low-resolution spectrometers. Thus, even if not very accurate, the $T_r$ values obtained can be good enough to show the trend of that parameter. The spectra simulations were performed using data from the SpecAir software [42]. We defined the uncertainties in the temperature measurements as

$$\sigma T = \sqrt{(\Delta T/2)^2 + [(1 - R^2)T]^2}$$  \hspace{1cm} (1)$$

where $R^2$ is the coefficient of determination obtained in the comparison between experimental and simulated spectra, $T$ is the temperature value obtained for $T_r$ or $T_v$, and $\Delta T$ is the temperature step used in the simulations, being that: for $T_r$, $\Delta T$ is 25 K, and for $T_v$, $\Delta T$ = 200 K. Therefore, the uncertainty calculated using (1) considers both the temperature steps and the fittings quality when the experimental and simulated curves are compared.

The mean discharge power ($P_{\text{dis}}$) was calculated by measuring simultaneously the voltage applied on the powered electrode (point $P_1$ in Fig. 1) and the voltage drop across a serial resistor $R = 47 \, \Omega$ (point $P_2$ of Fig. 1), which is used to calculate the current that flows through the plasma. In order to measure the applied voltage at $P_1$, a 1000:1 voltage probe (Tektronix model P6015A) was used, and the voltage measurement at $P_2$ was performed using a 100:1 voltage probe. The signal waveforms were recorded using a 100-MHz oscilloscope from Tektronix (model TBS1104B). Then, the $P_{\text{dis}}$ value is obtained through the integration of the product between voltage $[V(t)]$ and current $[i(t)]$ signals during the time of plasma pulse duration multiplied by the pulse repetition rate ($f$), that is [43]–[46]

$$P_{\text{dis}} = f \int_{t_0}^{t_1} V(t)i(t)dt.$$  \hspace{1cm} (2)$$

It is interesting to notice that $i(t)$ is composed by the discharge current itself and the displacement current in the gas gap [46].

Another important parameter that correlates optical measurements with an electrical quantity in APPJs is the reduced electric field strength $E_n = E/n$, where $E$ is the electric field strength and $n$ is the gas number density. The $E_n$ value can be estimated using the ratio between intensity emissions from $N_2^+$ ions and excited $N_2$ ($I_{N_2^+}/I_{N_2}$), and variations in this ratio indicate the change in $E_n$, being that the higher the ratio $I_{N_2^+}/I_{N_2}$, the higher the $E_n$ value, that is, $E_n \propto I_{N_2^+}/I_{N_2}$ [36], [47], [48]. The determination of $E/n$ using the line ratio method may not consider quenching reactions for excited and ionized states of molecular nitrogen when noble gases containing metastable states with high energy levels, such as helium and neon, are used as the working gas because, in this case, the Penning ionization reactions play a dominant role in the ionization and excitation processes in the plasma jet, making the quenching reactions being of less importance.

Usually, the emission from the first negative system of $N_2^+$ from the band $(B \, \Sigma_g^+, \nu' = 0 \rightarrow X \, \Sigma_g^+, \nu'' = 0)$, emitting at $\lambda = 391.4$ nm, together with an $N_2(C \rightarrow B)$ emission coming from $N_2(C)$ energy level with $\nu' = 0$ or $2 = 0.95$ is used to calculate the $I_{N_2^+}/I_{N_2}$ ratio and obtain $E_n$. We choose using $N_2(C, \nu' = 0 \rightarrow B, \nu'' = 2)$, emitting at $\lambda = 380.49$ nm to obtain $I_{N_2}$ (referred as $I_{\text{850}}$ hereafter) as well as the usual $N_2^+$ emission at $\lambda = 391.4$ nm to obtain $I_{N_2^+}$ (referred as $I_{\text{951}}$ hereafter). However, the $I_{\text{951}}/I_{\text{850}}$ ratios were not chosen to obtain $E_n$ values in the APPJs in this work, but were only used to evaluate possible changes in plasma jet behaviors when switching from the DB to the SB configuration.

In order to perform the tests attempting to remove copper (Cu) films deposited onto a 99.9% purity polished alumina ($\text{Al}_2\text{O}_3$) substrate, a 1-in-sided square sample was used. The thickness of the Cu film is approximately 500 nm. The plasma application was performed statically, that is, the sample was positioned under the plasma jet and was not moved during the entire application time interval, which was equal to 5 min in each case. This part of the work was performed using only the pulsed power source to produce the plasma jets since preliminary tests did not revealed significant removal of Cu film when using the damped sine wave power source.

III. RESULTS

A. Electrical Measurements

Fig. 2 shows the current waveforms obtained using the pulsed source with Ar and He as working gases for the DB configuration and the SB one. Typical HV waveforms obtained in each case, which have good repeatability, are also shown in Fig. 2. The values of the current measured in the SB configuration are notably higher, which is in agreement with what is expected to happen without an insulating barrier, justifying the choice of a double dielectric barrier configuration for applications that require electrical safety. The values obtained for the power in the DB configuration were 0.62 W when using Ar as the working gas and 0.64 W when using He. For the SB configuration, the power values were 2.98 W using Ar and 3.29 W using He. By changing the device configuration from DB to SB, the $P_{\text{dis}}$ values increased dramatically by approximately five times for both working gases, which is a great advantage for applications that require higher discharge power.

An interesting feature about the current waveforms shown in Fig. 2 is observed when operating in the DB configuration, the current signals for Ar and He gas (blue solid and red dashed curves, respectively) are almost equal, whereas in the
SB configuration, the current curves obtained for different gases do not behave in the same way, which suggests that different regimes are taking place depending on the working gas for the latter case. It can also be noticed that in the SB case, despite the $P_{\text{dis}}$ values being close, the current signal measured with Ar ($I_{\text{Ar}}$) presents a very high peak value ($\sim 80 \text{ A}$) at the beginning of the discharge, that is, nearly four times higher than the peak value of the current obtained with He ($I_{\text{He}}$). Also, the temporal behavior of $I_{\text{Ar}}$ is not as smooth as that observed for $I_{\text{He}}$, being that $I_{\text{Ar}}$ presents a lot of oscillations as time evolves, which is another indication that the regime of the plasma jet using Ar as the working gas changes when the barrier over the powered electrode is removed. However, the same does not seem to happen when He is used as the working gas, which exhibits quite similar current behavior in both configurations.

In Fig. 2, we can also see that in the SB configuration, the discharge currents start increasing earlier in the time interval between 100 and 150 ns, while using the DB, the current peaks begin growing between 150 and 200 ns. In other words, as expected, lower voltage values are required to ignite the discharge in the SB case due to the powered electrode being in contact with the working gas and thus releasing more electrons from the metal to the plasma. Moreover, when the first dielectric barrier is removed from the powered electrode, the associated capacitance between the powered electrode and the discharge gap is removed too, and this also contributes to the early ignition of the plasma discharge. Those findings can also be the reasons for the more extended duration of the plasma discharge, depicted by the wider current pulses observed comparing Fig. 2(a) and (b).

Fig. 3 shows the voltage and current waveforms measured in DB configuration for Ar and He and in SB mode for Ar and He using the pulse-like voltage source. Notice that the time scales are in nanosecond in Fig. 2 and in $\mu$s in Fig. 3. A point that is noteworthy when comparing DB and SB configurations using the same gas (Ar or He) is that, unlike the pulsed power source, when the damped sine-wave source is used, significant voltage drops, from 10–12 to $\sim 8–9 \text{ kV}$ for the first positive peaks, are observed when changing the configuration. The appearance of that voltage drop is due to the fact that the pulse-like source is more sensitive to impedance matching. The change in the impedance caused by the removal of the first dielectric barrier also results in a change in the oscillating frequency of the damped sine-wave power source from 150 kHz in the DB configuration to 110–120 kHz in the single one, as a consequence of the increase in the total capacitance of the system.

The values obtained for $P_{\text{dis}}$ calculated using data presented in Fig. 3 were 0.27 W when using Ar as the working gas, 0.23 W when using He in the DB configuration, and 0.49 W using Ar and 0.48 W using He in the SB mode. Despite the voltage drop observed when changing the DB configuration to the single one, the observed values for the power increased in the second case. However, the increase was only $\sim 1.8$ times using Ar and $\sim 2.1$ times using He.

### B. Spectroscopic Measurements

An overview of the emission spectra in all conditions studied in this work is shown in Fig. 4, for the pulsed source, and in Fig. 5 for the damped sine wave one. All atomic emissions shown in Figs. 4 and 5 are from neutral species in excited states. Squares indicate superposed emissions from Ar and N, triangles indicate superposition of O and N lines, and diamonds indicate an emission from the first positive system of $N_{2} \left( B ^{3} \Pi, \nu' = 4 \rightarrow A ^{3} \Sigma, \nu'' = 2 \right)$ [49]. The most intense atomic nitrogen lines come from multiplet systems and were observed at peak wavelengths 598.6, 649.2, 699.4, and 738.9 nm [50]. The right side of Figs. 4 and 5 is also shown photographs of the corresponding plasma jets produced in each configuration/working gas. The detailed views of the $N_{2}(C \rightarrow B)$ emission band used to calculate $T_{e}$ and $T_{v}$ are shown in Fig. 6 for the pulsed power source, and the results
Fig. 4. Emission spectra obtained using the pulsed power source with argon as the working gas in (a) and (b) for the DB and SB configurations, respectively, and the same for using helium in (c) and (d). (a’)-(d’) Corresponding photos of plasma jets. The ellipses indicate reflections.

Fig. 5. Emission spectra obtained using the damped sine-wave power source with argon as the working gas in (a) and (b) for the DB and SB configurations, respectively, and the same for using helium in (c) and (d). (a’)-(d’) Corresponding photographs of plasma jets. The ellipses indicate reflections.

Obtained for $T_r$ and $T_v$ using the pulse-like power source are shown in Table I.

Comparing the spectra in Fig. 4 obtained in the case of pulsed source with DB or SB for each gas, the noticeable differences are that the intensities of the atomic and molecular emissions are more intense when the plasma jet is operated using a single-dielectric barrier, which is in agreement with the apparent higher luminosities shown in the corresponding photographs. Furthermore, the change from DB to SB plasma jet configuration does not result in any new excited species nor species emitting radiation in other wavelengths, that is, no new excitation levels were observed after the change. It is interesting to notice that the relative intensities of atomic species remain almost the same in the different configurations. However, even though there are no significant changes in the relative emissions intensities of different species, the fact that they have increased in absolute values when changing from the DB to the SB configuration indicates the production of more excited reactive species. This observation is associated with the higher discharge power values observed when changing from the DB to the SB configuration indicates the production of more excited reactive species. This observation is associated with the higher discharge power values observed when changing from the DB to the SB configuration indicates the production of more excited reactive species. This observation is associated with the higher discharge power values observed when changing from the DB to the SB configuration indicates the production of more excited reactive species. However, even though there are no significant changes in the relative emissions intensities of different species, the fact that they have increased in absolute values when changing from the DB to the SB configuration indicates the production of more excited reactive species. This observation is associated with the higher discharge power values observed when changing from the DB to the SB configuration indicates the production of more excited reactive species. This observation is associated with the higher discharge power values observed when changing from the DB to the SB configuration indicates the production of more excited reactive species.

Contrary to what happened with the pulsed source when switching from the DB to the SB configuration, when using the pulse-like power source, it was observed an increase in the intensity of the emissions from atoms and molecules only when He was used as the working gas. An interesting...
observation can be made on the appearance of an emission line whose peak was detected at 678.29 nm in Fig. 5(d), which is possibly an emission from neutral Cu atoms \( \lambda_{\text{Cu}} \approx 677.57 \) nm [50]. However, since there are no other line emissions from Cu in the observed spectrum, further investigation will be required in order to confirm this information.

From the spectra shown in Fig. 4, obtained from the plasmas produced using the pulsed power source, one can see that it is possible to calculate the \( I_{380}/I_{391} \) ratios only when He is used as the working gas because \( N_{\text{Cu}}^+ \) emissions are not present in the spectra obtained using Ar to generate the plasma jets. From Fig. 4(c) and (d), the \( I_{391}/I_{380} \) ratios for the DB and SB configurations are 0.786 and 0.811, respectively, which corresponds to an increase of \( \sim 3\% \) in the \( E_{\text{ns}} \) value when switching from the DB to the SB configuration. In other words, \( E_{\text{ns}} \) remains almost constant when switching the device configuration, which means that the observed increase in the number of emitting species shown in Fig. 4 is mainly caused by the increase in the number of electrons released to the plasma, coming from the metallic electrode in contact with the plasma, which participates strongly in the ionization and excitation processes. Since \( E_{\text{ns}} \) is almost constant when we switch from the DB configuration to the single one, it suggests that there are no changes in the operating plasma regime associated with the change in the device configuration when He is used as the working gas. It was not possible to perform the same analysis using the pulse-like power source due to the low-intensity emission from \( N_{\text{Cu}}^+ \) measured using the DB configuration.

From the photographs shown in Figs. 4(a’)-(d’) and 5(a’)-(d’), one can notice that the plasma jets produced using the SB configuration tend to spread further on the impinged surface than those produced in the DB configuration (compare a’ with b’ and c’ with d’). These differences in the size of plasma jets spreading on the surface are related to the different electrical potentials (higher without the barrier on the powered electrode and smaller when the second dielectric barrier is used) that are being applied to the plasma in each condition. Therefore, in the SB APPJ configuration, the potential difference between the grounded electrode and the plasma is higher, producing higher current as well with a greater probability for the plasma plume to reach the target. From the photographs in Figs. 4(a’)-(d’) and 5(a’)-(d’), it can also be seen that the plasma jets are not homogeneous along the plasma column. Therefore, one can expect to observe some differences in the values of line intensity ratios, \( T_{\text{v}} \) and \( T_{\text{g}} \), when they are measured in different regions of the plasma column, specially when comparing the plasma channel region, where the spectroscopic measurements were performed, with the plasma located near the surface of the second dielectric barrier.

From Fig. 6, we can see that when the pulsed power source is used, both \( T_{\text{v}} \) and \( T_{\text{g}} \) values change when switching from the DB configuration to the single one, for both working gases used. Usually, in APPJs, the \( T_{\text{v}} \) value is considered to be very close to the gas temperature \( T_{\text{gas}} \) when the gas is in the plasma state, that is, \( T_{\text{v}} \approx T_{\text{gas}} \). Therefore, regarding the obtained small variations in \( T_{\text{v}} \) values, 50 K for both gases, it is a good finding since plasma jets as cold as possible are desirable in order to avoid possible thermal damages on samples subjected to APPJ treatment. In relation to the increment in \( T_{\text{v}} \) values for the SB plasma jet, 400 K for both gases, it is a very good result because one wants to produce APPJs with \( T_{\text{v}} \) values as high as possible due to the relationship between this parameter and chemical reaction rates. Thus, plasma jets with higher \( T_{\text{v}} \) values are able to induce higher degree of surface activation [53]–[55].

On the other hand, as shown in Table I, the temperature variations obtained using the pulse-like source cannot be considered significant since the uncertainties in the temperature values are higher than 15% of the measured ones in all cases. However, the increase in \( T_{\text{v}} \) and \( T_{\text{g}} \) values obtained using He when switching from the double to the SB configuration can be considered as a trend.

C. Applications on Removal of Copper Films Deposited Onto Alumina Substrates

In order to verify some effects related to the choice of powered electrode covered or not with a dielectric material, we applied the plasma jets on a copper (Cu) film deposited onto an alumina \( (\text{Al}_2\text{O}_3) \) surface using the pulsed power source. A consideration that should be considered before analyzing the results is that the sample is a conducting material. Thus, it acts as a floating electrode when the plasma jet is applied to it, and when using the powered electrode without the dielectric barrier, the discharge plasma regime cannot be considered a DBD discharge, that is, the change in the target conductivity modifies drastically the nature of the discharge in the SB configuration. However, since the grounded electrode still covered with a dielectric, it is a valid experiment concerning the use of a powered electrode covered or not with a dielectric material. The sample used to perform the tests is shown in Fig. 7(a). Fig. 7(b) shows the visual effects on the Cu film after applying plasma jets for 5 min for each of the configurations studied in Sections III-A and III-B. The regions where the plasma jets were applied using Ar or He as working gases in DB or SB configurations are shown in Fig. 7(c).

Comparing the photographs in Fig. 7(a) and (b), it can be seen that evident visual effects are observed only when the SB configuration was used, operating with both Ar and He gases. The rounded marks in the sample, highlighted in blue in Fig. 7(b), correspond to the regions where there was significant removal of Cu film, while in the regions highlighted in green, the removal of film was less significant. In preliminary tests, we had found that the use of Ar in the SB configuration promoted greater removal of Cu films. Thus, we chose to apply plasma to the sample in the following order: Ar-SB, He-SB, Ar-DB, and He-DB. Thus, the possible effects of plasmas applied in one region to affect the other would favor greater removal of Cu film with less potent plasma conditions. However, this precaution is a redundancy, because when impinging the surface of the Cu film, the plasma does not spread through it as it would happen with an insulating target. The observed change in copper color before and after applying plasma is only due to the differences in lighting used to take the photographs.

From Fig. 7(b), we can also verify that in the SB configuration, the use of Ar as the working gas was able to remove the Cu film over an area larger than when using He. This result may be related to the higher peak current that occurs when using Ar.
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IV. DISCUSSION AND CONCLUSION

The experimental results obtained in this work using the pulsed power source are summarized in Table II, whereas the results obtained using the damped sine-wave source are summarized in Table III.

Table II shows that the values of all measured parameters increase when changing from the DB configuration to the single one, using Ar or He as working gases. As shown in Table II, the $T_r$ and $T_v$ values presented differences not so far from the measurements uncertainties (especially for $T_r$). On the other hand, changing from DB to SB configuration, the $P_{\text{dis}}$ values increased about 4.8 and 5.1 times when using Ar and He gases, respectively. This last result was expected because when the powered electrode is in contact with the working gas, a higher electric current will flow through the plasma jet, a result that is confirmed by the current waveforms measured for Ar and He using the DB or the SB configurations.

Concerning the different $T_r$ and $T_v$ values obtained in the two DBD configurations, one can conclude that it would be beneficial to use the SB one since $T_r$ does not change significantly, while $T_v$ is higher compared to the DB case. However, due to the higher current and power values obtained for the SB jet, it is not readily suitable for applications that require electrical safety for the device operator or the target impinged by the plasma jet, as in in vivo applications. Besides that, the SB configuration combined with HV values is not suitable for applications on in vivo targets due to the risk of arc discharges between the HV electrode and the target. On the other hand, for this purpose, high discharge power values can be achieved using the DB configuration by using pulsed power sources with higher pulse repetition rates. Nevertheless, the SB configuration is quite attractive for treatments of materials that require more powerful plasma to achieve an adequate degree of surface activation or higher interaction between the plasma and the target. An example of that is the application reported by Gazeli et al. [26], where it was verified that a more powerful plasma jet is more efficient in the removal of resistant bibenzyl deposits formed on glass surfaces. In the present work, we have shown another example, verifying that the efficiency in the removal of a Cu film deposited onto an Al$_2$O$_3$ substrate was higher when more powerful plasma jets were used, noticing that the nature of the discharge has changed drastically due to the use of a conductive target.

In Table III, we can see that when the damped sine-wave power source was used, only the $P_{\text{dis}}$ parameter changed significantly when switching the configuration from the DB to the single one. However, the observed increase in $P_{\text{dis}}$ did not occur in the same proportion as $P_{\text{dis}}$. This can be attributed partially to the voltage drop that occurred due to the change in electrode configuration and partially to the reduction of the observed frequency in the damped-sine waveform. Nevertheless, we can speculate that a pulsed voltage presents a more effective way for energy transfer from the power source to the plasma when operating in the SB mode.
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