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The impingement of a kHz helium atmospheric pressure plasma jet on a dielectric surface

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Abstract

A parametric study of the impingement of a helium kHz atmospheric pressure plasma jet on a flat glass surface was performed by means of time-resolved intensified charge-coupled device imaging. The development of the plasma on the target is linked to the plasma evolution in the source and governed by the power supply. The glass surface takes part in the elongation of the plasma jet by the virtue of two mechanisms: the local enhancement of the electric field and the supply of pre-deposited charge. The evidence for the pre-deposited charge is the formation of a sheath on the glass surface, and the faint discharge formed on the glass surface during the negative voltage slope starting at the maximum of the negative current peak. The influence of the gas flow dynamics taking into account various gas flows, incident angles and distances is more important for the behaviour of the discharge on the surface than the voltage amplitude or the geometry of the source. The capacitance of the target strongly modifies the interaction with the plasma jet and increases the deposited surface charge density, featuring a streamer-like propagation mechanism in the case of high electric field enhancement at the surface.

Keywords: atmospheric pressure plasma jet, impingement, oblique dielectric surface, time resolved imaging, helium jet surface interaction, charge deposition, gas flow dynamics

(Some figures may appear in colour only in the online journal)

1. Introduction

Promising results have been obtained with atmospheric pressure plasma jets (APPJs) for material surface treatments as well as biomedical applications. The modification induced by APPJs on various surfaces is therefore the main motivation for studying these plasma sources. Nevertheless, the link between the main features of a given APPJ configuration and the resulting effect on the target is rarely described.

The characteristics of APPJs expanding freely in the surrounding atmosphere have been extensively investigated in different gases (Helium, Argon or Neon), with different electrode geometries as well as power excitation frequencies (single pulse, RF or kHz range sinusoidal power source) [1, 2]. Many parameters have been measured such as the electron

density [3], the electric field [4], the gas temperature [5], the gas dynamics [6] as well as the reactive species produced by APPJs whether metastables, radicals or molecules [7–10].

The modifications of various surfaces exposed to APPJs have also been widely investigated. Detailed studies describe the modification of the structure and hydrophobic properties of polymers, metals or even wood surfaces [11, 12]. Deposition with precursors added in the jet has also been investigated for thin film deposition such as SiO_x deposition [13]. In the frame of biomedical applications, APPJs were investigated for sterilization of surfaces [14], as well as for dentistry [15], disinfection or wound healing [16].

The link between APPJs expanding freely in surrounding gas and the modifications of various surfaces exposed to APPJs is not trivial to make as the presence of a target will

Figure 1. Experimental setup of the coaxial geometry used for generating the atmospheric pressure plasma jet and the glass target on which the jet is spreading. The iCCD camera can be placed in one of the 3 positions shown depending on the angle α between the target surface and the axis of the capillary.

in many cases change the electrical properties of the APPJ as well as the chemical composition of the plume. Consequently, the plume of an APPJ can reach the surface of a target and propagate over it exhibiting different properties than a jet propagating freely in gaseous surroundings.

Focusing of the interaction of the plasma plume with the surface of the target, its dynamics is more reproducible and easier to control if the exposed surface is conductive. It provides a way to stabilize different plasma regimes in the capillary and the plume because it gives a strong constraint on the configuration of the electric field in these two parts [17]. Gas flow dynamics has recently been studied with this type of configuration [18]. However most of materials to be treated with APPJs are dielectric, in which case the electric field in front of the propagating ionization wave is dependent on the surroundings of the setup as well as possible charge on the capillary and the surface of the target.

Several papers describe the interaction of the jet and a dielectric substrate. In [19] a comparison is made of the same APPJ impinging either on a copper or a glass surface. The plasma appears to be more homogeneous over the glass than the copper surface on photographs taken with a 1 ms exposure time. It has been shown that charge deposited on the surface depends on the capacitance of the target by Ito *et al* [20]. The geometry of the source can also play a role, for example in [21] the authors compare the maximum diameter of the point of contact between the jet and the substrate in three different electrodes configurations for an APPJ with the same 30 kHz power supply. The coaxial configuration with a high voltage electrode inside the capillary and an outer grounded ring is shown to produce a wider contact point on a glass plate than the two configurations with only one high voltage electrode.

Even within a given type of an APPJ source, many parameters can influence the interaction of the jet and a dielectric surface. One of the most commonly used APPJ configurations

is a coaxial electrode arrangement powered by a kHz range sinusoidal high voltage source. We have already reported a detailed electrical study of such an APPJ in [22] as well as the first surface electric field measurement obtained on a BSO crystal target [23].

For a deeper understanding of the interaction of a plasma jet with a target, a systematic parametric study of the dynamics of the propagation of the plasma over different dielectric surfaces is performed by means of fast imaging using the same APPJ source as in [22, 23]. After the description of the dynamics of discharges developing in the source, the capillary and the jet prior to the impact on the target, the relative influence of gas flow characteristics, voltage amplitude and source dimensions is evaluated and compared to the influence of the properties of the target on the propagation dynamics.

2. Experimental setup

The plasma jet source used for this work has already been described in [22, 23]. It is a coaxial geometry APPJ with a metallic capillary as high voltage electrode inserted inside a Pyrex capillary with 2 mm inner diameter and 4 mm outer diameter. The grounded electrode is a ring on the outer side of the capillary with a length (L_{gr}) of 3, 5.5 or 8 mm. The gap length (L_{gap}) between the high voltage electrode and the beginning of the grounded ring can vary from 0 to 15 mm. The length of the capillary after the ground ($L_{capillary}$) varies from 17.5 mm to 22.5 mm depending on L_{gr} . Figure 1 shows the schematics of the source. The high voltage electrode is powered with a 30 kHz sinusoidal power supply with voltage amplitude (U_a) up to 4 kV. The current is monitored at the grounded electrode over a 1 k Ω resistor. The helium gas flow (ϕ) in the capillary varies from 100 to 1000 SCCM. The jet is operated in horizontal position.

Figure 2. Time averaged images of the plasma in the source, the capillary and the jet part obtained in the reference conditions (see section 2) except for the impact angle ($\alpha = 90^\circ$) and the jet length ($d = 3$ mm). Camera in position 2 with gate of $12 \mu\text{s}$ opened either during the whole positive voltage slope (a) or the whole negative voltage slope (b) and (b') as shown with the dotted vertical lines. The contrast of images (a) and (b) is the same while it is enhanced on image (b'). The right part of the figure shows the corresponding applied voltage (U_a) and current measured at the ground (I_{meas}) signals as well as the calculation of the voltage across the gas gap (U_{gas}).

Table 1. set of parameter used for the measurements. The first row in bold gives the values used as reference conditions.

U_a (kV)	Φ (SCCM)	L_{gap} (mm)	L_{gr} (mm)	$L_{\text{capillary}}$ (mm)	d (mm)	α ($^\circ$)	Δ (mm)
2	700	5	5.5	20	5	45	2
1–4	400–1000	0–15	3–8	10–25	2–10	30–90	1–4

Note: the second row gives the variation range for each parameter.

For clarity the system is divided in four parts, referred to as ‘source’, ‘capillary’, ‘jet’ and ‘target’, as illustrated in figure 2. The plasma is initiated in the ‘source’ between the high voltage and the grounded electrode. If the energy dissipated in the source is high enough, an ‘ionization wave’ (also referred in literature as ‘guided streamer’, ionization front, ‘plasma bullet’, or ‘plasma stream’) forms and propagates away from the source inside the ‘capillary’ following the gas flow. The ‘jet’ is the plasma outside the capillary in atmospheric air, also known in literature as ‘plume’.

The power dissipated in the system as a function of applied voltage and other parameters has been reported in [22] for the conditions used in this work, the power dissipated has been measured to be varying from 0.2 to 0.5 W.

Glass ($\epsilon_r = 4$) disks with different thicknesses ($\Delta = 1, 2$ or 4 mm) are used as target to study the spreading of the plasma jet. Each disk has a very large diameter of 120 mm so that He flow is contained on one side of the disk. The distance d between the capillary and the target surface varies from 2 to 10 mm. The angle α between the axis of the capillary and the plane of the target varies from 30° to 90° . Each parameter is varied individually from a set of conditions chosen as the reference conditions given in table 1

These reference conditions are chosen because of the possible variation range of each parameter but also in accordance with the results of the electrical measurements performed with the same APPJ source in [22]. It has been shown that two different regimes occur in the source depending on the

applied voltage amplitude. Below $U_a = 2.5$ kV a very stable regime is obtained generating one single ionization wave at the maximum of the current peak during the positive voltage slope. Above $U_a = 2.5$ kV, microdischarges occur around the grounded electrode and the ionization wave emitted during the positive voltage slope exhibits large jitter of few μs from one period to another.

The dynamics of the propagation of ionization waves in air and on dielectric surfaces is monitored with an ANDOR iCCD camera with a 1024×1024 px chip, placed at different positions relative to the target. For the reference conditions with $\alpha = 45^\circ$ the camera is placed at position 1 shown in figure 1 so that camera is facing the surface. For $\alpha = 90^\circ$ the camera is placed at position 2 and the focal distance of the lenses used is adapted in order to monitor either the whole system from the source to the target or only the plume. The position 3 is used only for $\alpha = 60^\circ$. The spatial resolution used for following the dynamics of the propagation on the surface is $10 \mu\text{m}/\text{pixel}$.

3. Time resolved plasma development in the APPJ and the influence of the target

This section describes the time resolved plasma development in the APPJ in the presence of a glass disk used as treated surface (the target). It will be shown that the only part influenced by the presence of the target is the plasma plume and the dynamics of the ionization wave in it.

Figure 3. Light emission from the plasma in the source, the capillary and the jet parts as a function of time over one full cycle of the applied voltage. Each vertical line correspond to 1 image obtained with a camera gate of 50 ns. The jet is generated with the reference conditions except $\alpha = 90^\circ$ and camera in position 2 (see section 2). Contrast is adjusted for showing the structure of the plasma in each part. The electrical signals under the image are plotted with the same time scale to give the corresponding timing of voltage and current.

3.1. Plasmas in the source and the capillary

Figure 2 shows the discharge development during the positive (image (a)) and the negative voltage slope (image (b)) as well as the corresponding voltage/current signals. The images were obtained by iCCD photography and integrated over 12 μs .

The discharge exhibits the typical current voltage characteristics of atmospheric pressure glow like discharge (APGD) as described in [24, 25]. The source can be described by electrical circuit schematics representing DBD discharges [22, 25] considering the gas gap and the dielectric as two capacitances C_g and C_{die} in series. When the plasma is ignited, a resistor is added in parallel with the gas capacitance C_g . Following this description the voltage across the gas gap U_{gas} (shown in figure 2) can be calculated as follows:

$$U_{\text{gas}} = U_a - \frac{1}{C_{\text{die}}} \int I_{\text{meas}}(t) dt \quad (1)$$

U_a is the voltage applied between the two electrodes and $I_{\text{meas}}(t)$ is the current measured at the grounded electrode. This equation does not take into account the current carried by the ionization wave in the capillary. However that current has been shown to be small compared to the current required for charging C_{die} in our previous paper [22] by comparing current at the output of the power source and current at the ground electrode. C_{die} is estimated equal to 2.2 pF by considering a cylindrical capacitor with the length of the ground electrode and the thickness of the glass capillary.

During the positive half-period of the voltage cycle when the voltage across the gas gap reaches about 1 kV a streamer DBD discharge forms in the source as reported in [26, 27]. The discharge in the source develops faster than the resolution time in our experiments, and remains constant in time and space for 1.8 μs , as can be seen in figure 3 showing the light emission along the axis of the capillary as a function of time over a full voltage cycle. The figure was obtained from 660 photographs with a camera gate of 50 ns and 30 accumulations per photograph. Each photograph is reduced to a vertical line by summing all the pixels perpendicularly to the capillary axis. The contrast is kept constant for each part but it is adjusted between positive and negative voltage slope in order to exhibit the structures of the weak light emitted during negative voltage slope. The measurements are performed with the reference conditions except for the impact angle ($\alpha = 90^\circ$).

Upon the formation of the discharge in the source the current recorded at the grounded electrode increases enough to cause U_{gas} to fall to a low and almost constant value similarly to what is observed in APGD. The maximum of current is reached during the decay of U_{gas} and coincides with the beginning of the ionization wave propagation in the capillary. The ionization wave is the result of the accumulation of charge deposited on the capacitance C_{die} in the section of the dielectric capillary facing the grounded electrode. The intensity of the light emitted by the ionization wave is about 10 times lower than that emitted from the source. In this configuration and conditions an ionization wave propagates inside the

capillary only during the positive slope of the high voltage cycle as can be seen on image (a) in figure 2, with constant velocity around 10 km s^{-1} (phase B on figure 3).

During the negative slope of the voltage (images (b) and (b') in 2 and 3), the light intensity in the source is weaker than during positive voltage slope and located mostly at the tip of the cathode. Ionization waves are not observed in the capillary. The calculation of U_{gas} shows that after the ignition of the plasma in the source, the voltage remains almost constant at -0.9 kV across the gas gap. The negative current peak amplitude is lower than for the positive one, but it lasts about $8 \mu\text{s}$.

The presence of the target in front of the jet does not influence the current measured at the ground, the light emission in the source nor the ionization wave dynamics in the capillary. The real influence of the target on the discharge in the capillary is shown in images (b) and (b') in figures 2—during the negative voltage slope weak light emission is present at the target that extends into the capillary.

3.2. The dynamics of the jet (plume) and the appearance of a sheath

Upon reaching the end of the capillary, the ionization front slows down to a stop, presumably because of the change of the geometry in the capillary, causing an increase in capacitance. Similarly to the process at the grounded electrode, after the capacitance at the end of the capillary is charged, another ionization wave is initiated and emitted into the surrounding air. This part of the discharge in the surrounding atmosphere is called the 'jet' or 'plume' in this paper.

The velocity of the ionization front in the jet is 30 km s^{-1} at its initiation (20 km s^{-1} higher than inside the capillary) and it falls to 15 km s^{-1} in the first 4 mm of propagation. As shown in figures 2 and 3 the light intensity increases when approaching the target surface and it reaches a peak 4 times more intense at the impact point at the surface of the target than in the capillary. This is also shown in figure 4 depicting in detail the dynamics of the ionization front approaching the target surface. The plasma was obtained at reference conditions (except for $\alpha = 90^\circ$) and has been imaged with 5 ns camera gate starting from $t_0 = 7.9 \mu\text{s}$ for the positive voltage slope, and 20 ns camera gate starting from $t_0 = 16.5 \mu\text{s}$ for the negative voltage slope.

Close to the exit of the capillary (images at 5 and 45 ns) the jet still has a ring shape that has been seen with camera in position 3. This ring shape disappears with the reduction of the diameter of the front at 2.5 mm from the target (image at 85 ns). When the ionization wave is about 1 mm away from the surface of the target (between 125 ns and 130 ns on figure 4) light is emitted from the surface of the target. This is a consequence of the field enhancement between the surface and the ionization front as shown in [28]. The field enhancement becomes high enough to detach electrons from the pre-charged surface and ionize the gas between the jet and the target. The ionization wave then expands over the surface of the glass target symmetrically around the axis of the capillary with a maximum radius of 2 mm , as shown in figure 2(a).

Figure 4. Time resolved imaging of the gap between the end of the capillary and the target glass plate. The left column shows images obtained with camera gates of 5 ns for different delays after a trigger corresponding to $7.9 \mu\text{s}$ on current trace from figure 2. The right column shows images obtained with camera gates of 100 ns for different delays after a trigger corresponding to $16.5 \mu\text{s}$ on current trace from figure 2. Each image is an accumulation of 30 images. Plasma jet obtained with reference conditions except $\alpha = 90^\circ$, camera in position 2.

The light emitted by the jet is more intense in the vicinity of the target than at the exit of the capillary, predicted in [28] as a consequence of the field enhancement caused by the presence of the target. However, the maximum of light intensity is about $200 \mu\text{m}$ away from the surface, with a dark space just at the target surface. This sheath structure appears between 135 and 140 ns , before any radial expansion of the discharge over the surface. The explanation for this can again be found in [28]: the ionization wave reaching the target deposits positive charge on the surface, causing the maximum of electric field a few tens of μm above the surface.

The sheath structure remains visible above the target surface for more than $3 \mu\text{s}$ (phase C on figure 3). Above it light is emitted at a constant intensity until the applied voltage at the source reaches its maximum and the current recorded at the grounded electrode crosses zero (end of phase C on figure 3). This behaviour suggests that the dynamics of the discharge on the target on figure 4 is imposed by the power supply, and it can be explained if the channel left behind the ionization front is still conductive enough to carry at least partially the potential of the source all along the propagation length, what is named plasma stream in [29].

The charge deposition on the surface has been shown to be responsible for the appearance of the sheath during the positive voltage slope but it also induces a plasma during the negative

Figure 5. Radius of plasma jet along the gap between the capillary and the target for 5 different helium flows. The corresponding image obtained with camera gate of $12 \mu\text{s}$ during positive period are shown on the left (reference conditions except $\alpha = 90^\circ$, camera position 2). The measured radius are obtained by taking into account any pixel with intensity higher than 1.1 time the background level. The solid line correspond to profile of constant He/Air mixing obtained for Reynolds number 40 and 70 calculated for helium flow surrounded by air without plasma in [32].

voltage slope. As can be seen on figures 2(b) and (b'), figure 3 and on the right column of figure 4, a weak light is emitted from the impact point on the surface and expands towards the capillary during several μs . It also expands on the surface of the target and reaches the same maximum radius as during the positive voltage slope. At $5 \mu\text{s}$ a clear ring shape can be seen on the target, the impact point being dark. It is possible that the discharge on the target surface during the negative voltage slope is the result of charge neutralization processes.

The exact dynamics is as follows. Light emission at the surface starts at $23 \mu\text{s}$ precisely when the negative current peak reaches its maximum amplitude, at the end of the negative plateau in U_{gas} , and at the beginning of light intensity decay in the source (see figure 3). On the target surface a low intensity light-emitting plasma spreads from the impact point along the target surface and simultaneously toward the capillary. The maximum of light intensity moves towards the capillary at 2.5 km s^{-1} and enters slightly inside the capillary (figure 3). Its propagation further inside the capillary can be seen on figure 2 (b') but is not intense enough to be detected during the time resolved imaging. Along the target surface the propagation velocity is constant at 0.2 km s^{-1} . In conclusion, the discharge behaviour on the target surface that has been described in this section during the positive voltage slope is strongly related to the dynamics of the voltage provided by the power supply, possibly because of the conductivity of the residual discharge channel as suggested in [29]. The behaviour during the negative voltage slope exhibits discharges different from 'back discharges' observed in DBD configurations that are caused

by electrons previously adsorbed on the dielectric barrier that are detached when the polarity is reversed [30]. In this case, the plasma propagates slower than a streamer mechanism and simultaneously in two opposite directions toward the capillary and along the surface. The faint discharges during the negative voltage slope are most likely electrons avalanches induced in the vicinity of positive surface charge when the potential of the source is redistributed all along the inner wall of the capillary as suggested in [31]. The appearance of a sheath on the target surface has already been predicted by [28], however its properties are most likely governed by the gas flow at the target as well as deposited charge.

4. Influence of gas flow and the dynamics of the sheath

4.1. Jet impinging at 90° relative to the surface

The length of the jet (often called 'plume length') has been shown to be driven by the gas mixing for various reactor geometries and carrier gases both experimentally [33–36] and using modeling [37]. However, the plasma jet can also modify the gas flow dynamics as a consequence of gas heating or ion wind [38, 39].

The light emission profiles between the capillary and the target obtained for 5 different helium flows at reference conditions are shown on figure 5. Three different regions are usually defined for laminar flows: the *free jet* region where the target has no influence, the *stagnation region* where the direction

Figure 6. Images of the plasma on the target surface for 3 incident angles ($\alpha = 60, 45$ and 30°), and 3 helium flows ($\phi = 500, 700$ and 1000 SCCM) during positive or negative voltage slope of the voltage. Other parameters are applied according to the reference conditions. Camera position 1, gate = $12 \mu\text{s}$, 30 accumulations.

of gas flow transits from perpendicular into parallel relative to the target surface, and the region of *radial flow* along the target surface [40].

In the *free jet* region, the plasma jet follows the profile predicted by fluid simulations of a buoyant helium flow expanding in higher density air surrounding. On figure 5 the solid lines gives the profiles of constant He/Air mixing ratio calculated by Satti *et al* for a 31.8 mm diameter capillary [32]. The results are scaled to the APPJ used in this paper by using the scaling parameters r/D and z/D where r is the radius of jet axis (radius of the capillary), and z the distance along the jet axis. For $z < 3.5$ mm the plasma jet follows the profile of the 80% He/Air mixing ratio for the two Reynolds numbers, $\text{Re} = 70$ and $\text{Re} = 40$ given in [32]. The discrepancy observed for $\text{Re} = 40$ just at the exit of the capillary is probably a consequence of the stronger back diffusion of air inside the pipe obtained in with a larger capillary in [32]. The agreement between the He/air mixing profile and the emitted light confirms that the plasma jet in the *free jet* region expands following the helium channel as reported in the literature [37].

For $z > 3.5$ mm the plasma jet enters the *stagnation region*. A usual estimate for the thickness of the stagnation region is about 1.2 times the diameter of the capillary [40] but the very low Reynolds number ($\text{Re} = 40$ to 100 for gas flows from 400 to 1000 SCCM) and the contraction of a helium flow in air could explain a thinner stagnation region.

The length of the plasma jet grows from 3.5 mm to 5 mm when the gas flow increases from 450 SCCM to 460 SCCM. This very sharp transition shows a clear influence of the target surface, as already shown in figure 4. At all flows high enough to have the plasma jet reaching the target the light intensity is higher in the vicinity of the surface (*stagnation region*) than in the *free jet* region. Both effects are consistent with the enhancement of the electric field caused by the surface [28].

The sheath structure already discussed in section 3 can be seen in the *stagnation region* and in the *radial flow* region. Sheath thickness (δ) can be defined as the distance between the target surface and the maximum of light intensity above

it. δ_{impact} measured at the impact point increases with the gas flow from 50 to $130 \mu\text{m}$; this can be a consequence of both higher surface charge density on the target and higher over pressure at the stagnation point.

Sheath thickness δ_{edges} measured at the maximum radial extension of the jet (for instance $r = 0.8$ mm for $\phi = 1000$ SCCM) grows faster than δ_{impact} with the increase in gas flow and can reach up to $200 \mu\text{m}$. As the surface charge is expected to decrease radially [28], the increase of δ_{edges} is more likely to be a consequence of the flow dynamics in the *radial flow* region as described in [40].

The target surface influences the plasma by both field enhancement attracting the jet towards the surface and charge accumulation influencing the observed sheath. However, it is the dynamics of the helium gas flow impinging on the surface including the angle of impingement that is an essential parameter driving the spreading of the plasma over the target.

4.2. Jet impinging at variable incident angles

Figure 6 shows the light emission of the jet on the glass target for 3 different flows, during positive and negative voltage slope and with 3 different incident angles ($\alpha = 30^\circ, 45^\circ$ and 60°) between the jet axis and the glass surface (measurements have been done for 9 different flows but figure 6 shows representative examples). The distance (d) between the capillary and the target surface along the capillary axis is kept constant at 5 mm and all the other parameters were at the reference conditions.

The pattern of the discharge formed during the negative voltage slope always follows the pattern formed during the positive voltage slope signifying that the pattern formed during the negative voltage slope is a good image of the positive surface charge distribution.

A distinction can be made between the ‘impact region’ and the ‘tail region’. The ‘impact region’ is shaped like a disk (oval for small α) and corresponds to the footprint of the jet when it reaches the surface. After the impact, if the helium

Figure 7. Propagation of the plasma jet on the target surface for $\phi = 700$ and 1000 SCCM. The time in the middle column is the delay after the first contact on the target happening at $t_0 = 7.9 \mu\text{s}$ for 700 SCCM and $t_0 = 8 \mu\text{s}$ for 1000 SCCM. The jet is run with the reference conditions including $\alpha = 45^\circ$. Camera position 1, gate = 20 ns, 30 accumulations.

flow is high enough and/or the angle is small enough, the plasma can spread over the surface, forming the ‘tail region’. The motivation for distinguishing these two regions can be seen on figure 7 which shows images of the jet impact with incident angle of 45° , with 20 ns camera gate and delay from 0 to 460 ns after the impact. For the two flows shown on figure 7 the jet keeps an oval shape at the impact point, however 40 ns later a crescent-shaped ionization front starts propagating on the surface along the general direction of the He flow.

The pattern of the plasma jet over the dielectric surface takes different shapes depending on the incident angle (α) and the gas flow (ϕ). The main tendencies shown through the examples of figure 6 can be summarized as follows:

- (i) the ‘impact region’ becomes extended for small α in both the direction of He flow and in the opposite direction. Its surface grows with the increase in the flow rate and changes from a disk into a ring shape during the negative voltage slope,
- (ii) in the ‘tail region’ the reduction of α increases the plasma length and decreases the opening angle (β on figure 6),
- (iii) the end of the ‘tail region’ always tends to converge towards the impingement axis (green arrows on figure 6),
- (iv) at small α and high ϕ , two crescent-shaped ionization fronts form instead of one as can be seen on figure 7.

Several of these features can be explained by the dynamics of the He flow across the surface. Gas flows impinging at an oblique angle are usually studied at much higher Reynolds numbers in hot gas [41–44] but the described structure appears to be similar to what is described in this paper.

- (i) For instance it is known that stagnation region moves towards the capillary for higher gas flow with an increase of the overpressure at the impact point [41, 44], which means that the apparent elongation of the impact point of the jet can be related to the movement of the stagnation region.
- (ii) The opening angle of the tail (β) can also be explained by the opening angle of the gas flow. Most of the momentum in the gas flow is transferred to the surrounding air for opening angles smaller than the incident angle α [44]. Therefore the surrounding air can be efficiently repelled above the surface for $\beta \leq \alpha$, a high He/air mixing ratio is kept along a narrower and longer channel when α is small and a small angle is therefore favorable to a longer propagation. The length of the plasma jet impinging the target is, however, not driven only by He gas flow dynamics. The jet length along the target surface can be twice longer than the free jet in the same conditions. This elongation is the result of the field enhancement on the surface [28] similarly to what is known is surface DBD [30] or flashover configurations [45, 46].
- (iii) The appearance of two ionization fronts as well as their convergence at the end of the tail can be a consequence of gas flow dynamics as well as electric charge repulsion: if the maximum of light emission is obtained for a given He/air mixing ratio because of high electron energy due to collisions with He and the lower ionization potential of nitrogen, then the highest light emission will be present on the edge of the He flow. On the other hand, if the charge density is very high at the impact, Coulomb repulsion can force the ionization front to split in two. The tendency of the discharge to converge to a single front at the end of the propagation gives an argument in favour of the first option.

This is corroborated in figure 8 that shows the plasma expansion on the target surface as a function of the distance between the capillary and the target, for $d = 3, 5, 7$ and 9 mm. With the increasing distance the area on the target surface covered by the discharge decreases and the two fronts get closer to each other. The main difference in conditions in the four images is the He/air mixture at the target surface and the directly induced difference in charge density of the associated ionization wave.

5. The relative role of the high voltage amplitude

The peak voltage at the source is the easiest adjustable parameter of the APPJ. It has been shown in section 3 that the time evolution of the voltage applied at the source has a direct influence on the plasma development on the target. However this does not necessarily imply that the amplitude of the applied voltage is equally important. In this section the impingement on the target is studied for voltage amplitudes from 1.25 to 3.1 kV, keeping all other parameters at reference conditions. As discussed in the previous section, the jet behavior on the target is very sensitive to the gas flow dynamics. In order to exhibit the influence of the voltage amplitude without being

Figure 8. Plasma over the target surface during negative voltage slope obtained with the reference conditions except $\Phi=1000$ SCCM and variable distances between the capillary and the target surface ($d = 3, 5, 7$ and 9 mm) Camera position 1, camera gate = $12 \mu\text{s}$.

Figure 9. Characteristics of the plasma jet over the target obtained for 45 conditions of applied voltage amplitude ($U_a = 1.25$ to 3.1 kV) and helium flow ($\Phi = 400$ to 1000 SCCM) The data are obtained from images obtained with camera position 1 and gate = $12 \mu\text{s}$ during positive or negative voltage slope of the voltage. (a) maximum extension length (mm), (b) maximum width (mm), (c) area of the jet footprint on the target (mm^2), (d) mean light intensity during positive voltage slope (a.u.), (e) mean light intensity during negative voltage slope (a.u.), and (f) angle of the tail region (β in degree).

deceived by the role of the gas flow, for each value of the applied voltage, the gas flow rate is also varied from 400 to 1000 SCCM. The incident angle is been kept constant at

$\alpha = 45^\circ$. Images of the jet on the target are taken with camera in position 1 with gate opening of $12 \mu\text{s}$ for 45 different conditions of applied voltage and gas flow (U_a, Φ) and for positive

Figure 10. Image of jet ran with the reference conditions on different target surfaces during negative voltage slope. Four different glass plates are used as targets with thicknesses of 1, 2 or 4 mm and 2 mm with a copper sheet at the back connected to the ground. $\Phi = 500, 700$ or 1000 SCCM, $\alpha = 45^\circ$, camera position 1, gate = 12 μ s.

and negative voltage slope. Figure 9 shows the results obtained at these 90 conditions. The shape of the footprint of the jet on the target is the same for the positive and the negative voltage slope. However with a 12 μ s camera gate the light emitted by the jet before the impact can not be distinguished from the light emitted from the target surface, making the edge of impact point more difficult to determine during positive half period. Therefore the geometric dimensions (length, width, area and angle) are calculated using the negative voltage slope images.

The footprint of the jet on the target surface is slightly narrower and longer when the voltage amplitude increases, but the total area and the light intensity during the positive voltage slope remain mostly unchanged with the increase of the voltage amplitude (figures 9(a)–(c)). This result suggests that the amplitude of the applied voltage does not determine the properties of the discharge in the jet, i.e. the properties of ionization waves propagating between the capillary and the target.

A small decrease of the area is observed only for voltage amplitudes higher than 2.5 kV, which is the voltage amplitude level at which micro discharges around the ground electrode appear [22]. The appearance of micro discharges has been shown to contribute to higher power and heat dissipation, while reducing the length of the plume. The area of the surface covered by the plasma is much more influenced by the He flow rate than by the high voltage amplitude.

The change of the voltage amplitude has a consequence on the angle at the end of the tail region (figure 9 (f)). As seen in section 4, at high gas flows two ionization fronts are formed on the target surface instead of one. For instance, the angle at the end of the tail is about 50° for $\alpha = 45^\circ$, $U_a = 2$ kV and $\Phi = 1000$ SCCM as can be seen also on figure 6. At higher voltage amplitude the two fronts propagate over a longer distance and at the end converge, which corresponds to the negative values of angles for low gas flows and high

voltage amplitudes. The shape at the end of the propagation of the jet in the ‘tail region’ changes similarly with the applied voltage amplitude or a small incident angle. The increase in both voltage amplitude and He flow rate extend the plasma footprint on the surface.

The voltage amplitude has a minor influence on the jet impingement compared to the gas flow but there is still a link between the potential in the source and the target surface, as illustrated by the light intensity during the negative voltage slope (figure 9(e)). The source geometry, like the voltage amplitude, play a minor role on the jet impingement. The gap length (L_{gap}) and the ground length (L_{gr}) have also been varied from 0 to 15 mm and from 3 to 5.5 mm respectively but only minor changes in the shape of the jet on the target have been observed, similarly to the results obtained by varying the voltage amplitude.

6. The influence of target capacitance

APPJs are mostly studied for surface modifications, however, depending on the target material, the target surface can modify the plasma jet development. Figure 10 shows the footprint of the plasma jet on the target surface at reference conditions during the negative voltage slope (the shape is the same during positive voltage slope) on 4 different targets. The targets are all glass disks of 120 mm diameter but the thickness (Δ) is 1, 2 or 4 mm. The fourth target is a glass disk of $\Delta = 2$ mm with a grounded copper sheet on the back. The distance between the capillary and the surface of all the targets is always 5 mm.

The area of the footprint of the jet on the target decreases with the glass thickness Δ and the mean light intensity over this area increases. Ito *et al* [20] have shown that the total charge deposited increases with the capacitance of the target. A decrease of the footprint area and an increase of the total charge deposited results in a higher surface charge density

with the increasing thickness and therefore the capacitance of the target. The observed increase of the mean light intensity by a factor 4 between the target with $\Delta = 1$ mm and the one with $\Delta = 4$ mm can be linked to this increase of the surface charge density.

The images obtained with the target of $\Delta = 2$ mm with a grounded copper sheet on the back show a very strong influence of the proximity of the ground and therefore higher potential gradient. Especially at 1000 SCCM the propagation of the jet exceeds the usual expansion surface by forming long and narrow plasma channels with direction changing from one period of the applied voltage to another. The velocity of these discharges are too high to be temporally resolved in our experiments. The ground at the back of the target increases the capacitance of the target and consequently causes higher charge density to be deposited on the surface. It also enhances the electric field at the surface, which is strong enough to trigger the propagation of a new ionization front at distances where the He/Air mixing ratio is low. On the image for $\delta = 4$ mm and $\Phi = 1000$ SCCM the beginnings of this filamentation process appear at the edge of the plasma.

7. Conclusions

The development of a helium kHz plasma jet on a glass surface chosen as a model dielectric target depends mainly on the gas flow dynamics over the surface and the capacitance of the target. The amplitude of the applied voltage and the source geometry plays a minor role on the jet impingement. However the plasma dynamics on the target is still linked to the time evolution of the plasma in the source, suggesting that the electric potential given by the power supply is the determining factor in the discharge dynamics on the target surface.

The amplitude of the applied voltage does not seem to determine the properties of the discharge in the jet, i.e. the properties of ionization waves propagating between the capillary and the target, when microdischarges around the grounded electrode are not present.

Using the APPJ source studied in this work, an ionization wave reaches the surface only during the positive voltage slope of the voltage cycle. The footprint of the positive charge deposited induces a low light-emitting plasma during the negative voltage slope when the plasma in the source starts vanishing.

At high gas flow rates two ionization fronts develop on the target, probably corresponding to He/air mixing ratio favorable for intense light emission.

A higher capacitance of the target leads to a more localized charge deposition from the plasma jet. If the electric field at the surface is strong enough because of high surface charge density, new discharges are initiated at much higher propagation velocities resembling the streamer discharge mechanism.

Studies on APPJs are mostly motivated by surface modification applications. The tuning parameter used for controlling the surface processes is often the power dissipated in the source. However this work shows that the results on the targeted surface varies strongly with the gas flow dynamics and substrate properties.

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