Characterization of an atmospheric pressure plasma jet and its application for treatment of non-woven textiles

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Abstract: Atmospheric pressure plasma jets are well-known in the plasma chemistry community because of their novel applications. However, in spite of a large amount of publications, the physical chemistry of plasma jet/surface interactions is still unknown. In this work, an atmospheric pressure plasma jet (APPJ) in pure argon will be used to modify the surface of PET non-woven textiles. In a first part of the paper, the plasma jet will be characterized using current-voltage waveforms, time resolved ICCD images and optical emission spectroscopy. Afterwards, the influence of water vapor addition on these plasma characteristics will be briefly mentioned. In a second part of this work, one layer and several textile layers will be modified using the APPJ in pure argon. These surface modification results clearly show that the APPJ in argon can effectively enhance the hydrophilicity of several textile layers and can thus modify the inner surface of porous materials.

Keywords: atmospheric pressure plasma jet, argon, surface modification, non-woven textile

1. Introduction

Atmospheric pressure plasma jets (APPJs) at low temperature can play an important role in different technological applications. The high electron temperature enhances the plasma chemistry processes while the plasma gas remains close to room temperature [1]. In this way, APPJs are very attractive tools for the surface modification of temperature-sensitive materials. APPJs are not confined by electrodes and can be adjusted from a few cm down to the sub-mm region. These small plasma dimensions in combination with the ability to penetrate into narrow gaps and porous structures [2,3] makes APPJs particularly interesting for the treatment of textiles and 3-D objects with complex geometries [4].

In this contribution, an APPJ will be used to modify the surface of non-woven textiles. The pre-treatment and finishing of textiles by plasma technologies becomes more and more applied as a surface modification technique since it possesses several advantages over conventional chemical processes [5]. It does not use water or chemicals resulting in an environmentally friendly technique. Moreover, it is a versatile technique, where a large variety of chemically active functional groups can be incorporated into the textile surface. Possible applications are an improved wettability, adhesion of coatings, printability, induced hydrophobic properties, etc.

Plasma treatment changes the outermost layer of a polymer film without affecting the bulk properties. However, textiles are porous structures with a total thickness up to several millimeters. In some cases, applications make a homogeneous treatment throughout the entire textile volume necessary and to guarantee this effect, the plasma species that are chemically active should penetrate through the textile material without losing their modifying ability [6]. In a first part of the paper, the plasma jet will be characterized by voltage-current waveforms, time resolved ICCD images and optical emission spectroscopy. Also the influence of water addition to the plasma jet will be discussed. In a second part, plasma penetration in different textile layers will be studied by applying the APPJ on different sheets of polyethylene terephtalate (PET) non-wovens.

2. Experimental set-up and plasma jet characterization

A schematic diagram of the dielectric barrier discharge (DBD) plasma jet is shown in figure 1 and has been previously described in detail in [7]. High purity argon is used for plasma generation with a flow rate of 2.0 standard litres per minute (slm). The plasma jet is generated by an AC voltage with a fixed frequency of 71 kHz.

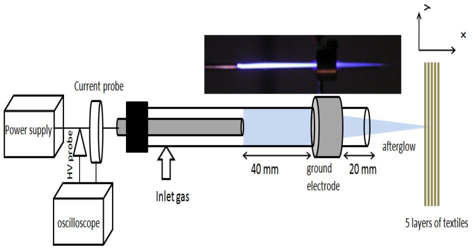

Figure 1. Schematic diagram of the APPJ

The applied voltage for all measurements is fixed to 12.2 kV (peak-to-peak), resulting into a plasma power of 12.8 W for the pure argon discharge. Figure 2 shows the voltage-current waveforms of the plasma jet in pure argon.

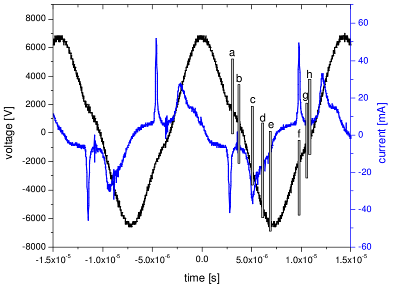

Figure 2. V-I characteristic of the DBD plasma jet in pure argon (Labels a to h show the position of ICCD triggering time)

From figure 2, it can be observed that at least two current peaks appear every half period of the applied voltage with duration of the pulses up to 2.8 µs. To study the dynamics of the plasma jet, time resolved ICCD images of the afterglow region were taken. The exposition time of the ICCD images was fixed to 100 ns and only single shot images (no accumulation) were recorded and analyzed. A pulsed generator triggered by signal from the high voltage (HV) probe has been used to synchronize the ICCD gate unit and to adjust delay time between initial signals and triggering of the camera. The time resolved ICCD images of the plasma jet in pure argon are presented in Figure 3 along with the voltage-current waveform and notation of gating time for each ICCD image (Figure 2). As can be seen from Figure 3, a discharge in filamentary mode is generated. Using current density measurements, the electron density in the filaments is estimated to be 1.5×10^{13} cm^{-3}. A detail explanation of this electron current density measurement can be found in an earlier published article [7].

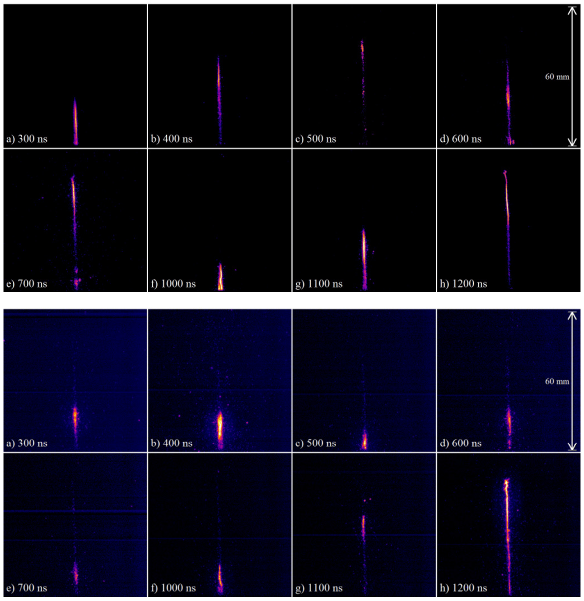

Figure 3. Time resolved ICCD images of the DBD plasma jet in pure argon (upper image) and argon/0.31% H_2O (lower image)

3. Optical characterization of the plasma jet

Space resolved optical emission spectroscopy (OES, resolution: 1 mm) has been performed to characterize the plasma species present in the discharge and Figure 4 shows the axial emission spectrum of the pure argon plasma jet.

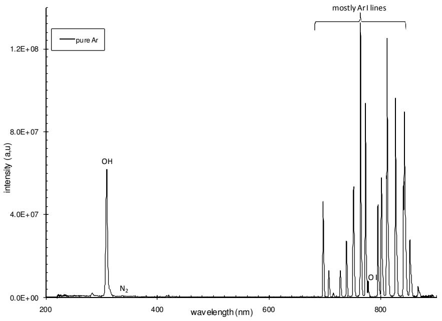

Figure 4. Axial integrated emission spectrum of the plasma jet in pure argon

The most intensive argon lines can be found in the spectral region between 680 and 900 nm, which can be assigned to different excited states of the argon atom. The discharge also produces a significant amount of UV radiation, which belongs to transitions of the OH band at 309 and 287 nm. Apart from the previously mentioned lines, spectral lines from atomic oxygen (777.4 and 844 nm) and nitrogen (310-440 nm) can be identified. In pure argon, these lines result from dissociation and ionization of the surrounding atmosphere which contains nitrogen, oxygen and water. The electron temperature (T_e) can be estimated from the ratio of argon lines considering the correction of the line intensity for self-absorption and it was found that for the pure argon plasma T_e is 1.1 eV.

4. Influence of water vapor addition on plasma characteristics

Water vapour can be introduced to the argon plasma jet via a bubbling system containing distilled water, carried by a secondary argon flow. By changing the argon gas flow through the bubbling system, the water content in the argon/water vapour plasma jet can be varied between 0.0% and 0.76%. This water vapor addition results in an increase of the amplitude of the current peaks with a simultaneous decrease in pulse duration time. Time resolved ICCD images are presented in Figure 3 for an Ar/H_2O plasma jet (0.31 %H_2O), showing that also in this case a discharge in filamentary mode is generated. Comparison of the ICCD images in pure Ar and Ar/H_2O reveals that the lifetime and dynamic of filaments does not change. Using current density measurements, it was also found that the DBD plasma jet in an Ar/H_2O mixture has a lower electron density due to the higher rate of electron collisions with molecular species.

From optical emission spectroscopy, it has been found that addition of water vapor to the feed gas results in a drastic decrease of the intensity of all atomic lines, which is most likely due to a decrease of the electron temperature. It was indeed observed that T_e decreases with increasing water vapor content in the plasma to the value of 0.6-0.8 eV at a water vapour content of 0.76 %. Moreover, it has been observed that addition of a small amount of water vapor results to an increasing UV band (306-312 nm) intensity and the highest intensity has been found for 0.05% H_2O in Ar. This effect cannot be explained by a change in gas temperature which is estimated from the rotational distribution of OH radicals. The OH rotational temperature has been determined by fitting the experimental spectra and using the Boltzmann plot method and was found to be 620 K for pure argon and an argon/0.05% H_2O mixture. In addition, both techniques show that the OH rotational temperature increases up to 800 K with increasing water vapor content to 0.76%. Therefore, we suggest that the main mechanism of OH band intensity change is the variation of the hydroxyl radical concentration, especially at low water vapor contents, when quenching of excited OH by H_2O has a negligible role.

5. Surface modification of PET non-wovens

The application of non-equilibrium plasmas to modify the surface properties of textile materials is experiencing rapid growth [5]. In a first part of this section, the atmospheric pressure plasma jet in pure argon will be used to modify the surface properties of a PET non-woven (single layer). The textiles are modified by scanning 24 cm^2 of the polymer surface with the plasma jet at a scanning velocity of 0.1 m/min. The hydrophilicity induced by the plasma treatment is evaluated using a horizontal wicking experiment [8], since contact angle measurements are not possible on porous substrates. A needle which provides a continuous supply of distilled water at a rate of 1.9 ml/min makes contact with the test specimen. As a result, water is absorbed by the fabric forming a wetted spot. The area of the spot after 15 s of water supply (A_{15s}) is taken as a measure for the hydrophilisation effect. A picture of the wetted area A_{15s} is taken with a digital camera and subsequently quantified using image-processing software. Figure 5 shows A_{15s} for varying distances between the end of the capillary and the PET non-woven (plasma treatment time=0.78 s). It should be noted that for the untreated PET non-woven A_{15s} is zero, while at small capillary edge-sample distances A_{15s} is approximately 15 cm^2. These results thus clearly show that the APPJ in pure argon can greatly enhance the hydrophilic character of the PET non-woven, which can be attributed to the incorporation of oxygen-containing groups on the textile surface [9]. Figure 5 also shows that the hydrophilicity increase is less pronounced when the distance between the capillary edge and the sample is increased above 6 mm. Due to the limited lifetime of the reactive plasma species responsible for oxygen incorporation, only a very small amount of active species will reach the textile surface at these large capillary-sample distances resulting into less hydrophilic surfaces. As a result, one can conclude that the position of the PET non-woven should be as close as possible (1-4 mm) to the plasma jet to obtain the most efficient increase in surface hydrophilicity.

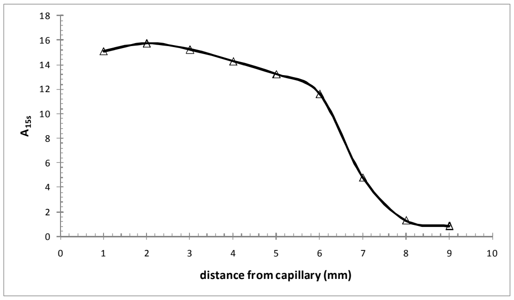

Figure 5. Evolution of the wetted area as a function of distance between capillary edge and PET non-woven (single layer).

Besides the treatment of a single textile layer, also the surface modification of five layers of non-woven fabric has been carried out to study the plasma penetration effect. The plasma jet is placed perpendicularly onto the textile layers while the distance between the top layer and the edge of the capillary is set to 2 mm. As a result, the upper textile layer 1 is in contact with the plasma plume and should be efficiently treated. Figure 6 shows A_{15s} for each individual layer after a plasma treatment time of 0.78 s. This figure clearly shows that the APPJ in argon can effectively enhance the hydrophilicity of several textile layers and can thus modify the inner surface of porous materials.

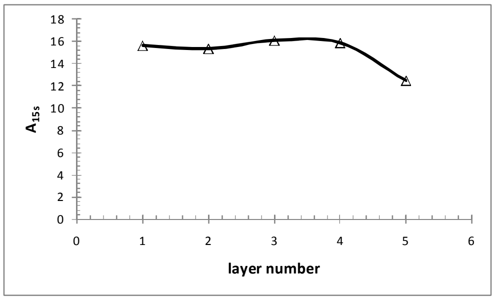

Figure 6. Wetted area of different non-woven layers after APPJ treatment in pure argon (treatment time:0.78 s)

6. Conclusion

This paper studies the electrical characterization and optical emission spectroscopy of a DBD plasma jet in argon and an argon/water vapor mixture. From current measurements, the electron density is estimated to be of the order of 1.5×10^{13} cm^{-3}. For the APPJ in pure argon, the electron temperature has been estimated to be 1.1 eV, while for the argon/water vapor mixture it decreases to 0.6-0.8 eV. OES showed an emission spectrum containing lines of OH (308 nm and 287 nm), atomic oxygen (777.4 and 844 nm), N_2 (310-440 nm) along with intensive lines of Ar. Different layers of PET textiles are treated with the studied APPJ sustained in argon and an effective and uniform treatment up to 5 layers of textile is achieved.

Acknowledgments

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