Organization of dielectric barrier discharges in the presence of structurally-inhomogeneous wood substrates

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Abstract: The spatial organization of atmospheric-pressure plasmas controlled by dielectric barriers in the presence of complex wood substrates was analysed using optical imaging and current-voltage (I-V) characteristics. The structural inhomogeneities of wood species produced non-uniform light emission patterns while maintaining homogeneous-like I-V characteristics. Based on a simple electrical model of the discharge, this feature was ascribed to a spatial modulation of the relative dielectric permittivity on “early” versus “late” wood affecting the local voltage applied to the gas, and thus the local discharge current.

1.Introduction

There has been a growing increasing interest in the use of dielectric barrier discharges (DBDs) for the treatment of polymers. We have recently extended the range of applications of DBDs to the functionalization of wood with the objective of improving its durability following natural weathering [1]. Applications of DBDs to wood is however much more challenging than for conventional substrates such as Si or SiO_2. This can be attributed not only to the highly porous nature of wood which can produce significant outgassing effects but also to the presence of "early" vs. "late wood" sections which can introduce local modification of the properties of the dielectric exposed to plasma. In this work, we examine the organization of DBD in the presence of complex wood substrates.

2.Experimental details

The atmospheric-pressure, He plasma controlled by dielectric-barriers used in this work was described in details in ref. [1]. Briefly, the discharge is sustained between two thin alumina sheets and a 3.2 mm-thick douglas pine or sugar maple sample with the discharge gap fixed to 4 mm. The frequency and peak-to-peak voltage were maintained at 12 kHz and 3.5 kV, while the He gas flow rate was set at 4.35 SLM. Optical imaging of the spatial distribution of the discharge in the presence of wood samples was done with a digital single-lens reflex camera. Analysis of the electrical characteristics of the discharge was performed through I-V measurements. The substrate capacitance and resistivity were measured with the plasma off. As described below, this set of data was used as input parameters into an electrical model aiming at simulating the spatial emission profile of the discharge.

3.Results and discussion

Figure 1A shows the spatially uniform distribution of the He plasma emission in presence of sugar maple substrates (1A) as opposed to the organized light emission patterns in presence of Douglas pine samples (1B and 1C). For Douglas pine, the emission was less intense on “early wood” (the section of the tree that grows in the spring, producing pale and porous wood fibres) than on “late wood” (section that grows later in the year, producing dense and dark wood fibres). Typical I-V characteristics of the He plasma in presence of a Douglas pine sample are shown in Fig. 2A. Even if the plasma emission pattern is organized, the electrical properties show homogeneous-like behavior comparable to those obtained with conventional substrates.

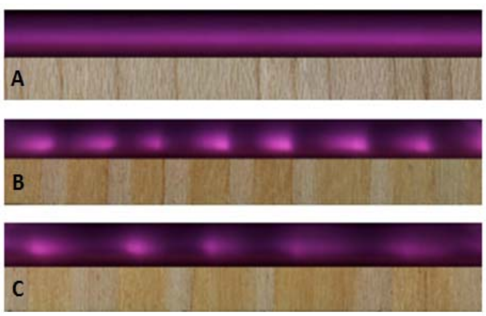

Figure 1: Spatial distribution of the He plasma in presence of a sugar maple substrate (A) and Douglas pine samples with tight (B) and wide (C) late and early wood sections.

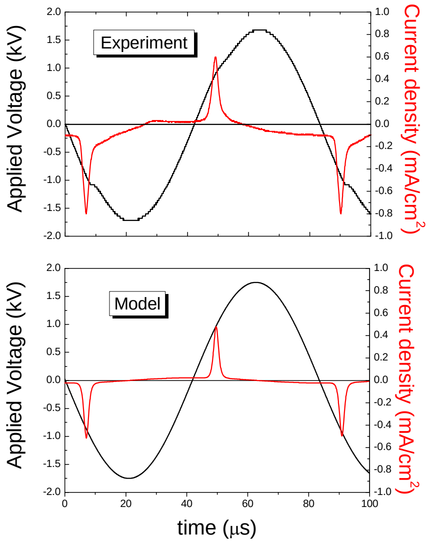

Figure 2: Measured and simulated I-V characteristics for a pure He plasma in presence of a douglas pine sample. Applied voltage : 3.5 $kV_{pk\text{-}pk}$ at 12 kHz.

The charge flow pattern on early versus late wood was analyzed for Douglas pine samples using surface potential measurements [2]. Both sections exhibited decaying behaviors, with time constants, τ, of 40 s for late wood and 10 s for early wood. Considering that τ=RC=$\rho\varepsilon$, where R is the resistance, C is the capacitance, ρ is the resistivity and ε is the dielectric permittivity, the difference in time constants can *a priori* be attributed to differences of either R or C. The equivalent capacitance of the whole transmission line and plasma was measured for various Douglas pine samples with different fractions of late and early wood fibres. After subtraction of the capacitances from parasite, gas, and alumina, we extracted a relative dielectric permittivity of 5.3 for late wood and 2.4 for early wood; a result consistent with the higher density of late versus early wood. Based on these results and the time constants measured above, we estimated a resitivity $\rho=8.5\text{x}10^{11}$ Ωm for late wood and $\rho=4.7\text{x}10^{11}$ Ωm for early wood.

To examine the respective roles of the variation in ε and ρ of late and early wood on the evolution of the light emission pattern, a simple electrical model based on the 0D macroscopic approach presented in [3] was developped. In this work, however, the model was extended to 2D for the dielectric and 1D for the discharge. In addition, either the resistivity or the relative permittivity of the wood substrate can be modulated following a sine function with the maxima (late wood) and minima (early wood) values obtained above. As shown in Fig. 2, the I-V characteristics deduced from this simple simulation are in very good agreement with the measurements. The spatial distribution of the discharge current is presented in Fig. 3 for a modulation of the substrate relative dielectric permittivity. It can be seen that the plasma emission pattern exhibits a modulation comparable to those displayed in Fig. 1. No modulation was observed by varying the resistivity instead of the permittivity (not shown). This indicates that capacitance modulation plays a crucial role in the discharge organization by lowering the local voltage applied to the gas and thus the local discharge current.

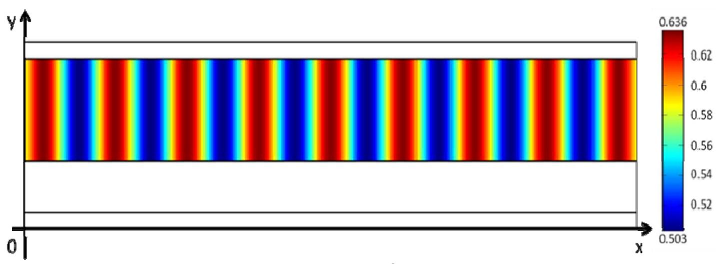

Figure 3:Simulated distribution of the discharge current (in $mA.cm^{-2}$) over a substrate with modulated relative permittivity (max 5.3 for late wood and min 2.4 for early wood).

4.Conclusions

We have analysed the spatial structure of an atmospheric-pressure He discharge controlled by dielectric barriers in the presence of complex wood substrates. It was found that the chemical and structural inhomogeneities of selected wood samples can produce spatially non-uniform light emission patterns even with homogenous-like I-V characteristics. Based on a simple electrical model of the discharge, this result was ascribed to a modulation of the relative dielectric permittivity which affects the localized voltage applied to the gas, and thus the local discharge current. It is worth mentionning that wood inhomogenities can also modify the coefficient for secondary electrons emission from the cathode which play a very critical role in the physics of DBDs. This aspect was also investigated through scanning electron microscopy measurements.

References

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