Diffuse Coplanar Surface Barrier Discharge: Influence of Gas Humidity on Plasma Parameters

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It was found that the working gas humidity influences substantially the parameters of diffuse coplanar surface barrier discharge. The absolute humidity of air or N_2 has a strong influence on the discharge pattern and its macroscopic homogeneity. The amount of H_2O in working gas influences also generated radicals and the plasma chemistry. We suggest that the humidity of working gas should be a controlled parameter of in-line atmospheric pressure plasma treatment under real industrial conditions.

Keywords: DCSBD, barrier discharge, atmospheric pressure, humidity, pattern, OES

1 INTRODUCTION

The surface energy of commonly used materials, such as polymers (foils, nonwovens), exhibits low values of surface energy not sufficient for industrial processing (printing, adhesion, etc.) [1]. The atmospheric pressure plasma technologies gained an irreplaceable position in industrial surface modifications of such low-added value materials increasing their surface energy using environmentally friendly plasma treatment in safe gasses (air, N_2, O_2, Ar, …) [2–5]. The dielectric barrier discharges and jets [6–8] are the most significant plasma sources developed and tested for atmospheric pressure plasma modifications.

The presented study investigates the parameters of diffuse coplanar surface barrier discharge (DCSBD) [9]. This type of dielectric barrier discharge offers several industrially important attributes needed for high-speed in-line plasma processing: generation of highly non-equilibrium macroscopically homogeneous plasma with high power density (100 W/cm^3), easy scalability, long lifetime and capability of plasma processing in a wide range of working gases.

In present study the influence of working gas humidity on the plasma properties of DCSBD was investigated for two most common processing gases in industry – air and nitrogen. The influence of the absolute humidity on the discharge pattern and also on the plasma characteristics was studied using digital photography and optical emission spectroscopy.

2 EXPERIMENTAL

The experimental setup with DCSBD source is given in Fig. 1. The power input into plasma layer of 8×20 cm^2 (thickness of 0.3 mm) was 350 W at 15 kHz. Synthetic air/N_2 (0.1 MPa) was used with total mass flow of 5 slpm. The humidity of working gas was controlled from 2 to 80 $g_{H2O}/\ m^3{}_{GAS}$ by mixing of dry gas with gas flowing through thermostatic heated bubbler filled with distilled water. The relative humidity and temperature of gas were recorded using Extech Instruments RH520 and absolute humidity of the gas was then calculated. For N_2 the absolute humidity was recalibrated using the data for synthetic air.

Discharge spectra were recorded using Jobin-Yvon Triax 550 spectrometer equipped by liquid nitrogen cooled CCD detector. Discharge patterns were taken by digital camera.

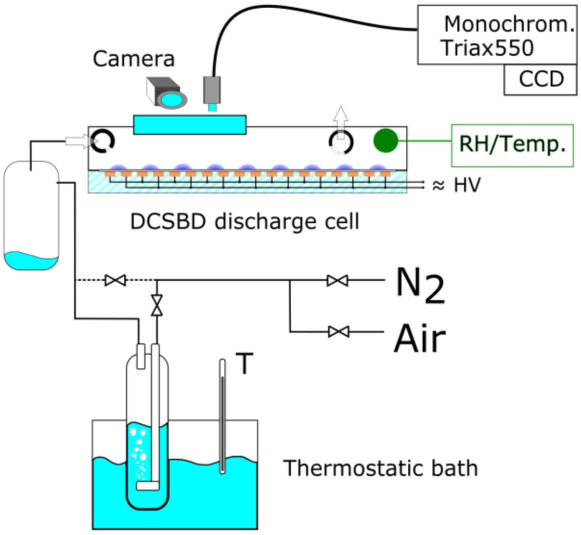

Fig.1: Setup of experiment and diagnostics

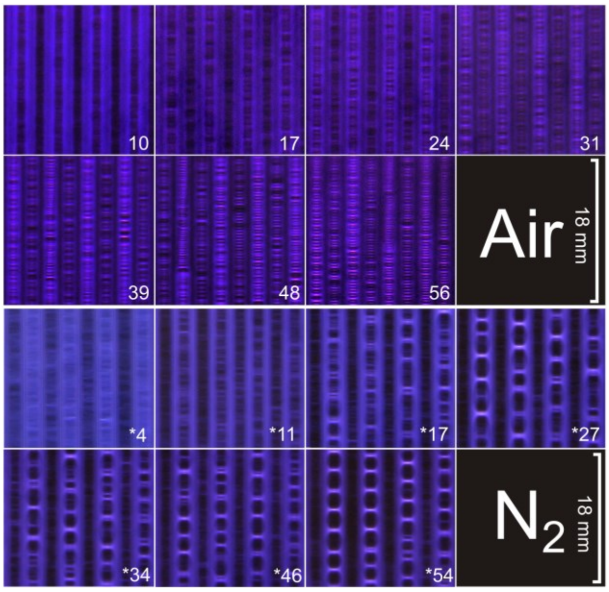

Fig.2: The discharge pattern evolution with increase of absolute humidity of gas (g_{H2O}/m^3_{GAS})

3 RESULTS AND DISCUSSION

In Fig. 2 the DCSBD discharge pattern evolution is given with respect to the absolute humidity of working gas with exposure time 1/40 s. For DCSBD generated in artificial air the discharge remains diffuse even for relatively high absolute humidity of 20-30 g_{H2O}/m^3_{GAS}. For comparison, under standard pressure of 101 kPa, temperature of 25ºC and 80% rel. humidity the absolute humidity is approx. 18 g_{H2O}/m^3_{GAS}. With further increase of air humidity the diffuseness is lost at the expense of densification and spatial stabilization of filamentary part of the discharge. For DCSBD generated in N_2 the loss of discharge diffuseness occurs at absolute humidity numbers lower comparing to synthetic air (Fig. 2). The discharge collapses then in a sparse, honeycomb-like filamentary structure.

The difference in the behavior of DCSBD in humid gas (synthetic air/N_2) is observable also in optical emission spectra (OES). The OES of DCSBD consists of N_2 molecular bands (2nd positive, 1st negative and 1st positive systems). Emission bands of NO-γ system and atomic oxygen lines were also present in synthetic air. In N_2 the emission bands of NO-γ system were also present (oxygen impurities and/or H_2O as possible sources of oxygen). The emission of OH radical was present under the presence of water vapors in processing gas, i.e., air or N_2.

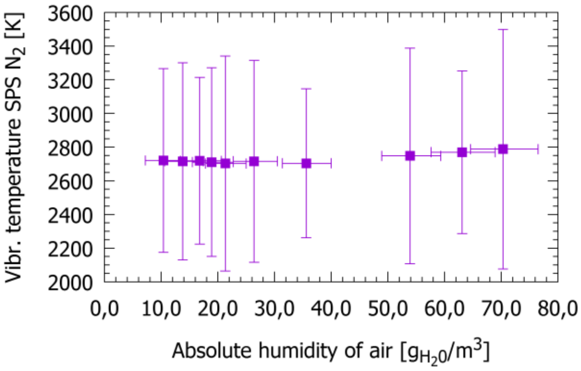

Fig.3: Vibration temperature of SPS with respect to the absolute humidity of air (g_{H2O}/m^3_{AIR})

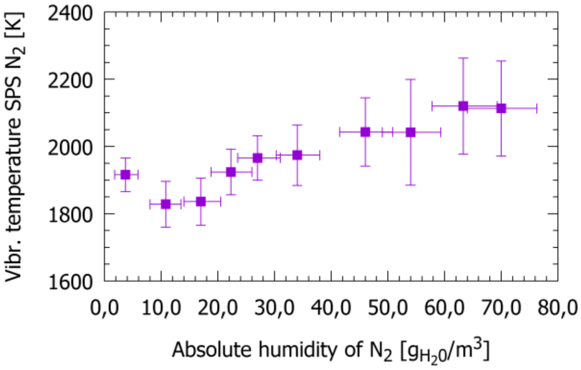

Fig.4: Vibration temperature of SPS with respect to the absolute humidity of N_2 (g_{H2O}/m^3_{AIR})

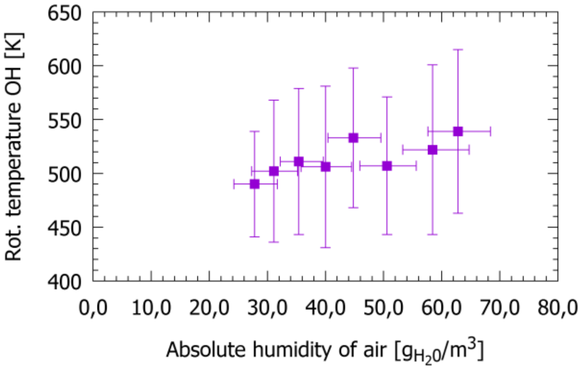

Fig.5: Rotational temperature of OH with respect to the absolute humidity of air (g_{H2O}/m^3_{AIR})

The spatially unresolved vibration (T_{vibr}) and rotation (T_{rot}) temperatures of DCSBD represents mainly the behavior of filaments between electrodes [10, 11]. In air the T_{vibr} is higher than in N_2 (compare Figs. 3 and 4). In air the T_{vibr} does not depend on the gas humidity, while in N_2 the increase of humidity leads to increase of T_{vibr}. This correlates with the behavior of micro-discharges in Fig. 2. Whereas the filaments in N_2 become pronounced and enlarged with increase of gas humidity, in air the filaments remains practically the same - just closer to each other. This discharge densification in humid air is accompanied by the slight increase in rotational temperature of OH, see Fig. 5. The T_{vibr} was estimated from the intensities of 2nd positive system of N_2 (SPS), band 0-2 at 380 nm. The T_{rot} of OH was estimated from the OH band Q1 at 308 nm.

When the Figs. 3, resp. 4 and 5 are compared the non-equilibrium character of DCSBD in dry or humid gas is clearly visible. The vibration temperature is considerably higher than rotational temperature, i.e. T_{vibr} being 2700 K, resp. 2000 K (air, resp. nitrogen), while T_{rot} remaining between 500 K and 550 K.

The influence of humidity of working gas on the plasma properties of DCSBD can be seen also in the OES characteristics. The values of intensity of SPS (N_2) remained practically uninfluenced, so the relative intensities with respect to SPS were introduced for OH, O and NO-γ. Namely following lines/bands intensities were compared: SPS – band 2-0 at 298 nm, OH radical – integrated bands R1 and R2 at 306 nm, NO-γ system – band 0-3 at 259 nm and O atomic lines intensity – integrated triplet lines at 777 nm.

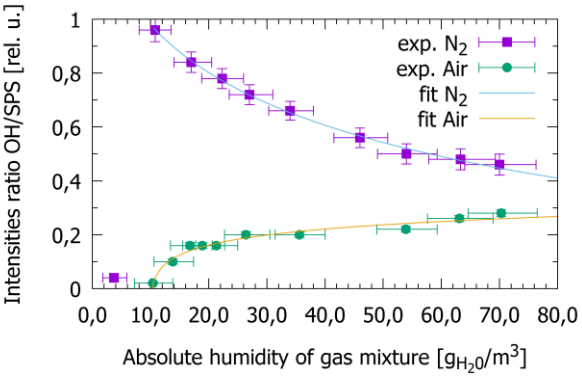

Fig.6: OH intensity dependence on g_{H2O}/m^3_{GAS}

In Figs. 6, 7 and 8 the courses of relative intensities of OH, NO-γ, resp. O are given with respect to absolute humidity of working gas. In air the relative emission intensity of OH radical increases with increase of water content (saturation above 40 g_{H2O}/m^3_{GAS}). In N_2 the relative emission intensity of OH decreases with water content increase (barring nearly no OH emission in dry N_2). The relative intensities of O, resp. NO-γ in air DCSBD also decreases with increase of water content. In Figs. 6 to 8 the rel. intensities were rescaled to the common maximum value of approx. 1 for better readability of graphs. The actual maxima of rel. intensities (instrumental function un-corrected) were as follows: 0.02 for NO-γ/SPS ratio, 0.04 for O/SPS ratio and 0.5, resp. 0.14 for OH/SPS ratio in N_2, resp. in air.

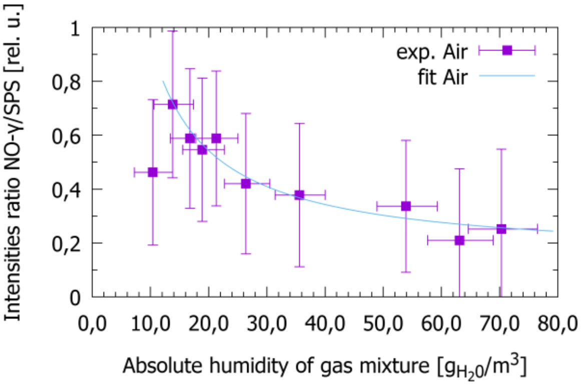

Fig.7: NO-γ intensity dependence on g_{H2O}/m^3_{AIR}

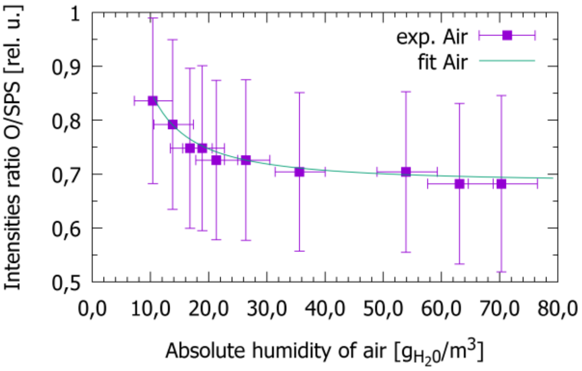

Fig.8: O intensity dependence on g_{H2O}/m^3_{AIR}

The results obtained using discharge imaging and optical emission spectroscopy show substantial influence of water vapors presence in the working gas on the plasma chemistry and the overall behavior of DCSBD discharge. For further clarification of this influence the plasma-chemistry model and the data on the absolute density of generated plasma species are necessary, e.g., adoption of techniques like laser induced fluorescence [12, 13] and laser diode optical absorption spectroscopy [14] could be of a great interest for further research on this topic.

4 CONCLUSION

The absolute humidity of working gas has significant influence on the behavior of DCSBD.

The micro-discharges patterns in humid air densify in thin channels, while in N_2 the sparse honeycomb-like structures appear. The micro-discharges' patterns correlate with vibrational temperatures that were higher in air, while lower in N_2. The vibrational temperatures increases with increasing concentration of water vapors in N_2, while remains constant in air. These differences are also clearly observable in the trends of relative intensities of OH radical.

The influence of water vapors concentration on the parameters of DCSBD was measured through extended range of water vapor concentration – from 2 to 80 g_{H2O}/ m^3_{GAS}. Even though the detailed mechanisms of plasma-chemical processes in DCSBD in humid air or nitrogen are not known at the moment, the results can be of great interest for plasma applications of DCSBD plasma source in industry, see e.g. [15].

The results presented in this work make demands on the extension of monitored parameters of DCSBD in plasma applications, i.e., to follow and/or influence the working gas humidity. Presented results could be also of importance for applications using other types of dielectric barrier discharges, however for better understanding of plasma processes in humid gasses further research using e.g. laser induced fluorescence spectroscopy and/or laser diode absorption spectroscopy is necessary.

Acknowledgements

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