Control of the gas flow by a surface barrier discharge

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Abstract: In this study, a surface dielectric barrier discharge (SDBD) at atmospheric pressure has been applied to investigate the plasma flow interaction and its contribution to the chemistry of transported species by taking advantage of the Schlieren imaging technique and fluid dynamic simulation.

Keywords: surface dielectric barrier discharge, flow pattern, vortices formation.

1. Introduction

Surface Dielectric Barrier Discharges (SDBD) are well-known plasma sources for gas stream purification and gas conversion due to their easy scalability in various applications [1]. In addition, SDBDs with versatile electrode configuration are used as plasma actuators to generate thrust and to manipulate, thereby, the flow pattern, to reduce the drag and to control the transition from laminar to turbulent flow [2]. The aim of this work is to visualize the fluid flow in an optimized SDBD electrode configuration using the Schlieren technique, which monitors the gradient in the refractive index of a medium in a particular direction. This method is sensitive to the density gradients and, therefore, also to the concentration of the species in the plasma as these determine the refractive index of the medium. The Gladstone–Dale equation for a plasma to express the refractive index of medium is [3]:

$$n=\frac{1}{4\pi\varepsilon_0}2\alpha'_{+}(\lambda)\rho_{+}+\frac{1}{4\pi\varepsilon_0}2\alpha'_{n}(\lambda)\rho_{n}-\frac{1}{4\pi\varepsilon_0}\frac{e^2\lambda^2}{2\pi m_e c_0^2}\rho_e+1 \quad (1)$$

where, $\alpha'_{+}(\lambda)$, and $\alpha'_{n}(\lambda)$ are polarizability of ions and neutrals, ρ_{+} , and ρ_{-}, the density of ions and neutrals, λ, c_0, light wavelength, light velocity, ε_0, m and e, free space permittivity, mass, and charge of an electron, respectively. This equation can be expanded to more species to describe a plasma more completely.

2. Experimental setup

In the experimental setup, a twin SDBD is employed, which consists of an aluminum oxide plate (190x88x0.63 mm) that is covered by nickel grids (comb design with 10mm electrode width and 10mm gap distance between coated electrodes) printed on both sides asymmetrically (figure 1). The SDBD is generated at atmospheric pressure using a burts of high voltages with a damped sinusoidal voltage waveform generated by an external transformer (G2000 Redline Technologies, Germany). The frequency of these bursts is a few kHz. The sketch of the experimental setup is depicted in figure 2. A single mirror Schlieren optical setup was set up out to visualize the gradient of the refractive index of the medium. The optical system to analyse the flow pattern is designed as follows: a halogen lamp is focused with a lens (f=50mm) on a pinhole, creating a point light source. This light then propagates towards the beam splitter and is divided into two parts. One half of the light passes through the SDBD then reaches the spherical mirror (with a focal length of 1150mm). The light ray is reflected by the spherical mirror and again passes through the plasma, is split by the beam splitter again. The pinhole is then focused on a knife edge (which is placed in normal direction with respect to the SDBD electrode), and afterwards reaches the camera. Images have been taken with a diginal camera (Canon EOS 60D). The recorded images of the plasma at different operation parameters have been subtracted from the background image. The background image is recorded when there is no plasma and gas flow in the chamber. In this study, measurements are performed at 4 kHz burst repetition frequency, 9 kV peak-to-peak voltage waveform in ambient air.

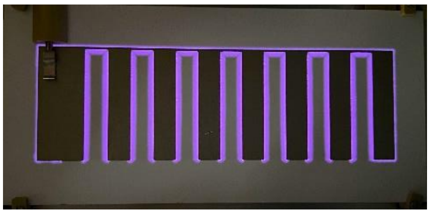

Fig. 1. Top view of SDBD, surface discharges can be seen with purple color on the Al_2O_3 plate on the powered nickel electrode.

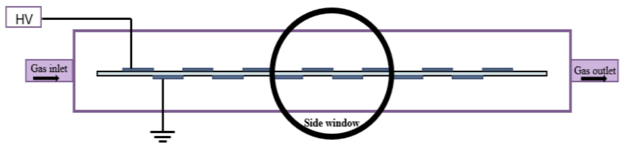

Fig. 2. Schematic of the experimental setup from the side view, where the measurements have been performed.

3. Simulation part

To predict the behavior of the plasma aerodynamic and how it could influence the surrounding fluidic flow, 2d fluid simulations have been performed in COMSOL. The model solves Navier Stokes equations for compressible Laminar flow assuming a low Reynolds number on a grid. The force exerted onto the flow by the plasma is modelled as a volume force in a defined region atop the SDBD electrode.

4. Results and Discussion

To analyse the plasms induced flow pattern, Schlieren measurements have been performed, as illustrated figure 3, by applying a damped sinusoidal high voltage with microsecond rise time on the nickel electrodes (marked as dashed black oversized rectangles in the images). The discharges ignite along the dielectric surface and by increasing the voltage, the area where the surface streamer propagate along the SDBD surface is extending. On the other side, from the opposite electrode(indicated by number 2 in the figure3), the same phenomena occur then both surface discharges from the electrodes indicated by 1 and 2 meet each other and collide together which leads to the creation of upstream and downstream vortices with dark and bright patterns in the image. In another word, the force from the electric wind in the plasma acts on the fluid. In the simulation shown in figure 4 and artificial Schlieren image is created from the modelled flow pattern based on equation 1. One can clearly see that the same flow pattern that is observed in the experiment can be reproduced in the simuation. The velocity field from the simulation in figure 5, shows vortices that are created in the vicinity of electrodes (streamlines are emphasized by arrows). The combination of vortices creates the different velocity regions; the dark blue shows an area with high velocity and the light blue is distinguished as a low-speed area.

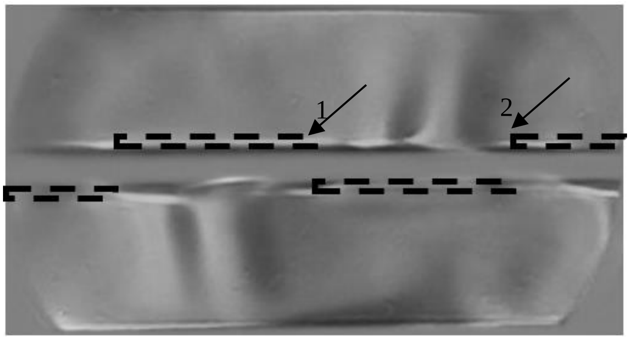

Fig. 3. Schlieren image of SDBD recorded from side window (black dash rectangles show the place of nickel electrodes in all images)

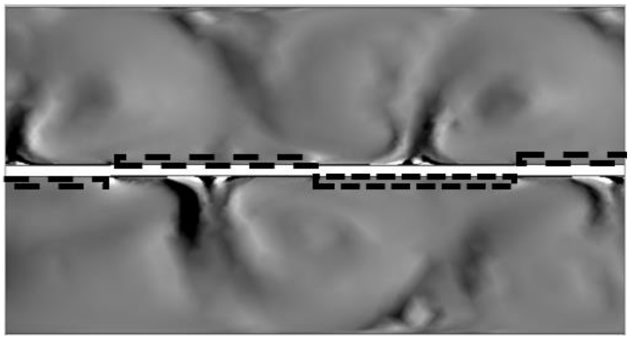

Fig. 4. 2D simulation of Schlieren effect of SDBD (black dash rectangles show the place of nickel electrodes)

These vortices are a result of electrohydrodynamic force; transferring ion momentum to the neutral molecules via collisions which leads to the electric wind modifying the flow field. One might argue, however, that such pattern might also be induced by simply heating effects of the plasma [4-6]. This is investigated by using an excess temperatures of typically $+\Delta T = +50$ K as boundary condition in the simulation yielding no distinct impact on the flow pattern.

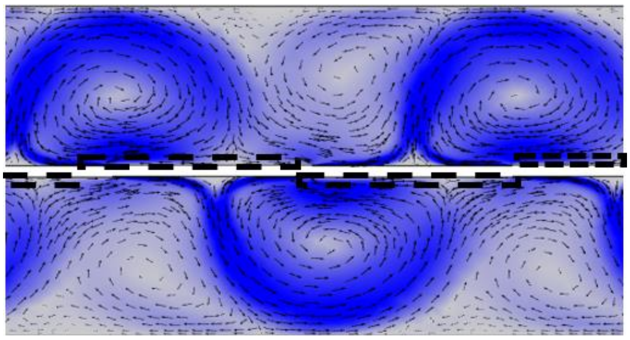

Fig. 5. 2D simulation of the velocity field of SDBD (black dash rectangles show the place of nickel electrodes)

5.Conclusion

The purpose of this project is to combine plasma chemistry and plasma-based flow control concepts for a surface dielectric barrier discharge used for gas conversion. In the flow pattern that had been recorded by the Schlieren imaging technique, the perturbations in the vicinity of the electrodes are observed. The 2D simulation of the Schlieren images agrees well with the experiment leading to the identification of pronounced vortices. In the future, this electrode configuration as the SDBD is further optimized to maximize the plasma-induced thrust on the species conversion for future works.

Acknowledgment

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6.References

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