Analysis of the flow field induced by a surface dielectric barrier discharge designed for air pollution remediation

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Abstract: A surface dielectric barrier discharge system has shown a comparatively high performance for volatile organic compound conversion at high gas flow rates [1]. The underlying gas chemistry is strongly influenced by the plasma-induced aerodynamics. To investigate this, schlieren measurements are compared to particle image velocimetry measurements to visualize the qualitative and quantitative behaviour and to obtain spatially resolved flow fields. Additional energy flux measurements complement these results.

Keywords: dielectric barrier discharge, schlieren, particle image velocimetry, energy flux

1. Introduction

Air pollution by microbiological organisms or toxic chemicals can be hazardous to the environment and human health. While conventional technologies are typically energy-intensive, dependent on fossil sources, and expensive, plasma technology represents a promising sustainable alternative. Non-thermal atmospheric pressure discharges, such as dielectric barrier discharges, represent a suitable candidate for the pollution remediation due to their scalability, simple implementation, as well as economic usage and production.

Our used surface dielectric barrier discharge (SDBD) was previously characterized regarding the fundamental plasma parameters [2, 3], conversion of volatile organic compounds [4], reactive species densities [5], voltage waveform tailoring [6], and the influence of additional catalysts towards conversion and selectivity [7]. In a recent study, Böddecker et al. [1], could show that a scaled up SDBD setup yields a higher VOC conversion performance than expected at high gas flow rates. To investigate these results in more detail, this study is focussing on the fluid dynamics produced by the SDBD analogous to plasma actuators. Plasma actuators is a term that is relevant in plasma aerodynamics for more than two decades [8]. A standard plasma actuator consists of a single SDBD with an electrode geometry that is asymmetric due to a spatial displacement between the electrodes in the flow direction. During the ignition of the discharge, which ignites exclusively at one position of the electrode, a body force is applied to the ambient gas. This force, also often referred to as ionic wind, is able to induce a flow or to modify an external circumfluent gas flow [9]. Other mechanisms, such as gas temperature effects, could also cause volume flows of the gas. The induced fluid flow by the SDBD should be investigated in more detail to enhance the understanding of the overall gas chemistry, to identify the dominant mechanisms and to find new ways to optimize the SDBD for industrial processes. In this study schlieren, particle image velocimetry (PIV) and passive thermal probe measurements will be shown to enhance the insight into these processes.

2. Setup

The measurements were performed with an electrode configuration as shown in Fig. 1. The ceramic plate has a size of 190 mm x 88 mm x 0.635 mm. While the visible metal grid represents one contact, the corresponding counter grid is located on the back side of the ceramic plate. One grid is constantly grounded and the driven one is excited with a damped sinusoidal high voltage pulse. It is possible to vary the pulse repetition frequency between 250 Hz to 4000 Hz and use initial peak to peak voltages between 9 kV to 13 kV. The resonance frequency of the damped sinusoidal waveform is about 86 kHz. The electrode is inserted in a reactor chamber with quartz windows to allow optical access.

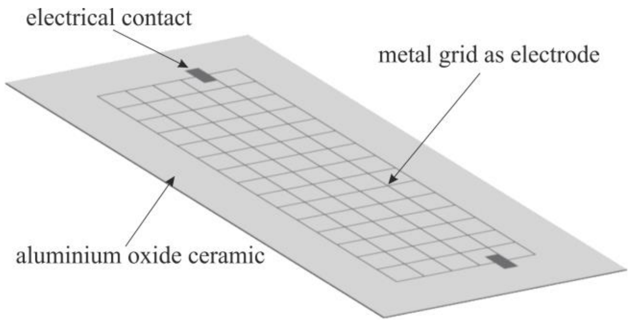

Fig. 1 Drawing of the used SDBD electrode.

3. Diagnostics

This study compares schlieren photography and PIV measurements to visualize and analyse the induced flow by the SDBD. All optical measurements were recorded with a high speed camera by Phantom (VEO-410L). The frame rate was set to 5200 fps for all measurements. Schlieren photography is utilized to record the density gradients in the fluid temporally resolved. The used configuration is usually referred to as a single-mirror coincident system [10]. This setup was chosen for two reasons: The system is not affected by astigmatism as well as coma and the high sensitivity is advantageous for the measurements. The sensitivity of a schlieren system of this type is directly proportional to the focal length of the mirror. Because in a single-mirror coincident system the light source is placed at the radius of the curvature, i.e. 2 times of the focal length *f*, the sensitivity of such a system is twice that of a z-type system [10]. In the schlieren setup, a light emitting diode (LED) in combination with a pinhole acts as the light source. The analysis of the recorded videos allows a determination of vortex core velocities and the visualization of the general qualitative behaviour.

For the PIV setup, a line laser (Z-Laser Model ZQ1, λ = 520 nm) in combination with a light sheet optic generates a 2D light section to illuminate the artificially added seeding particles which can follow the fluid flow [11]. Di-Ethyl-Hexyl-Sebacat (DEHS) is used as seeding fluid and the resulting particle diameters are in the order of 1 µm. By the use of a cross-correlation, the fluid flow in-plane velocity components are obtained from the particle displacement between two consecutive images [12]. The total record time is limited to 3 s because we found the flow field to reach steady state conditions within that time. The evaluated data show a spatially resolved velocity field that can be compared to the vortex core velocities, calculated from the schlieren measurements.

By the use of a passive thermal probe developed at the university of Kiel the emitted energy flux of the discharge can be evaluated [13]. The probe measures the temperature of a calibrated substrate that is located close to the discharge. When the discharge is operated, the heating of the substrate by the emitted energy flux is recorded. This measurement is compared to the case when the discharge is turned off to separate the energy loss terms that are only existent in the heating case. Both processed signals should be separated by an offset that can be directly used for the energy flux calculation. A more detailed derivation and description of the analysis can be found in the paper of Rosenfeldt et al. [13].

4. Results and Discussion

The presented measurements are performed in quiescent air to get insight into the fundamental process which is not influenced by an external flow. Fig. 2 shows one recorded image of a schlieren measurement for the shown electrode in Fig. 1. The used schlieren setup configuration only visualizes the density gradient in the vertical direction. The electrode is placed in the middle of the image at around pixel ~ 410 and a flow is induced towards the top and the bottom. While flows which are directed upwards can be identified by an increase in intensity, flows that move downwards show the opposite behaviour as visible below the electrode. From each grid line, where the discharge is ignited on both sides, a flow is induced and collides with its respective counterpart of the next grid line. This results in a flow that is directed normal to the surface.

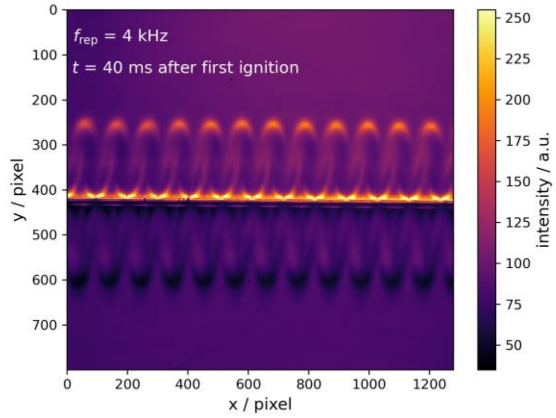

Fig. 2 Schlieren image of the SDBD in still air with the electrode in horizontal position at around pixel 410 [14].

Fig. 3 shows a velocity field for a single grid line electrode. Therefore, no interaction between colliding flows as in Fig. 2 is observable. The velocity field is averaged over the time period in which the flow was already at a quasi-steady state and shows that the fluid is pulled from the top above to the centre of the grid line and pushed out to the left and the right side of the grid line (see yellow arrows). An initial counter-rotating vortex pair is formed after ignition that starts close to the electrode and travels out of the image.

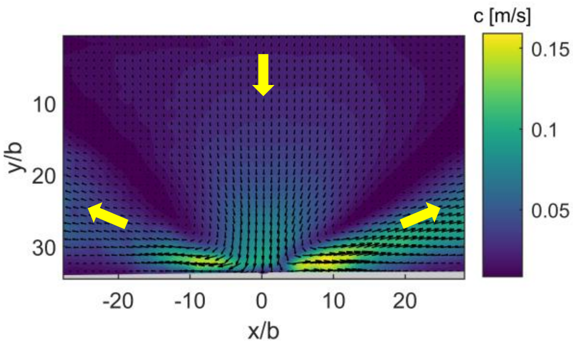

Fig. 3 Averaged velocity field of the fluid flow induced by a single grid line electrode at a repetition frequency of 2 kHz. c is the velocity magnitude and b is the width of the grid line (0.45 mm). The yellow arrows highlight the qualitative behaviour.

Fig. 4 shows the energy flux from the discharge to the passive thermal probe as a function of the repetition frequency. This measurement was also performed for the shown electrode in Fig. 1. The measurement was done with an external flow of 1 m/s to ensure no overheating of the electrode. The distance of the probe to the electrode was set to 5 mm. Each measurement point is repeated four times to get information about the statistical error and it is displayed as error bars. The energy flux is rising linearly with an increase of the repetition frequency.

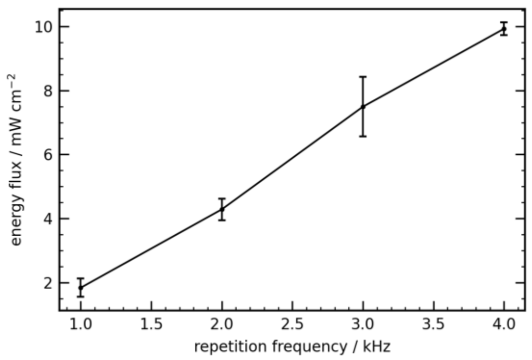

Fig. 4 Measured energy flux as a function of the repetition frequency of the discharge at a constant peak to peak voltage of 11 kV.

5. Conclusion

The results present a wide set of experimental data which describe the aerodynamic behaviour of the SDBD. Schlieren, PIV and energy flux measurements are compared. The data can be used for future work simulations of the ionic wind or advanced chemistry models of the SDBD to analyse the high performance of the discharge source in conversion experiments. In combination with additional catalysts for the application the energy flux measurements can be used to help to decide whether a special catalyst would be suitable or not and optimise the electrode, the grid, as well as the distance to neighbouring electrodes.

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