Study of the oscillating ion wind induced by DBD for various O2/N2 concentration ratios

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Abstract

Flow control methods using dielectric barrier discharge (DBD) have significant advantages compared with traditional control techniques. The main disadvantage of DBD is low velocity of the ion wind. Increasing of DBD efficiency is connected with studying of the role of nitrogen and oxygen ions in the process of ionic wind production. DBD actuator was studied at various oxygen/nitrogen concentrations. Unsteady characteristics of the actuator were studied by means PIV technique and measurements of the discharge electrodynamic parameters. Significant change of the ion wind asymmetry was obtained with variation of nitrogen/oxygen ratio.

1. Introduction

Plasma actuator based on the dielectric barrier discharge (DBD) is a simple electrical device which can be easily integrated in the aircraft structure. DBD allows to achieve significant improvement of the airflow especially for separated flows. These two factors contributed to a significant popularity of DBD flow control research. One of the main mechanisms of the flow influence by DBD is generation of ionic wind. Many studies were devoted to investigate the effect of DBD on a flow (for example, see review [1]). Moreover there are some attempts to use DBD in flight experiment [2, 3]. Unfortunately significant success was achieved only for low Reynolds numbers [4]. To increase the efficiency of the ionic wind production it is necessary to extend our understanding of the plasma actuator operation.

One of the important questions is the process of oxygen and nitrogen ions formation and their influence on the flow. This kind of information may be obtained basing on the force measurements for various concentration ratios of O2/N2 [5,6]. It is well known that DBD generates an oscillating ionic wind therefore the measurement technique has to provide time resolved data [7]. The main role of negative oxygen ions in generation of ion wind in the air was revealed in the studies [5,6,7]. The review [1] shows the reduction of stationary thrust of DBD by increasing of the concentration of nitrogen. The study [5] was performed to measure of the force generated by DBD in real-time at various concentrations of oxygen by means of torsion pendulum. It was shown that the acceleration of the flow occurs twice during the period. It was assumed that at negative voltage acceleration occurs under the influence of negative oxygen ions, and at positive voltage due to the positive ions of nitrogen. At high concentrations of oxygen the main acceleration takes place at a negative voltage. When the concentration of oxygen decreases value of accelerations decrease and become equal. When the oxygen concentration becomes close to zero a torsion pendulum significantly changes its behavior. At positive and negative phase of the discharge at the beginning pendulum slowed down and then accelerated. The authors of [5] do not give an explanation of such pendulum behavior. The measurement technique used in the paper intends high level of noise and is not suitable for qualitative analysis. All conclusions were based on the measurement of the angular velocity of the pendulum, therefore these data are difficult to analyze. Moreover the self flexibility of the torsion has to be taken into account which affects the measurement results. The qualitative data of [5] were a background of the current study where this effect was studied in detail. PIV technique applied in these experiments [7] allows to obtain the distribution of nonstationary volume force produced by DBD with better precision. The current study is devoted to measurements in unsteady flow field induced by single DBD for various concentration ratios of O2/N2.

2. Experimental set up

The experiments were done in quiescent environment under atmosphere pressure and room temperature. The DBD scheme can be found in Fig. 1. The experimental model was made from glass of thickness 4 mm. Two aluminum electrodes were placed on the opposite sides of the plate. The closed electrode was grounded and insulated from the air by silicon resin. Length of the electrodes was 100 mm, thickness 40 µm. The insulated and open electrodes were 15 mm and 7 mm wide respectively. The coordinate system attached to the right edge of open electrode.

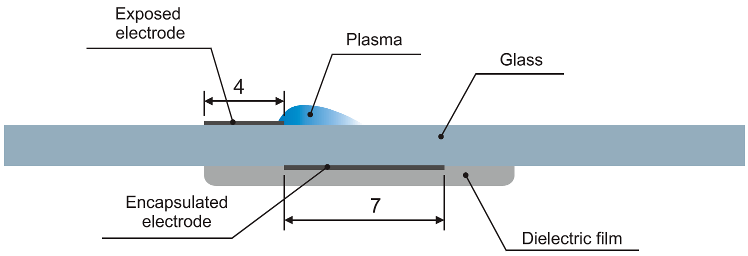


Figure 1: Scheme of DBD

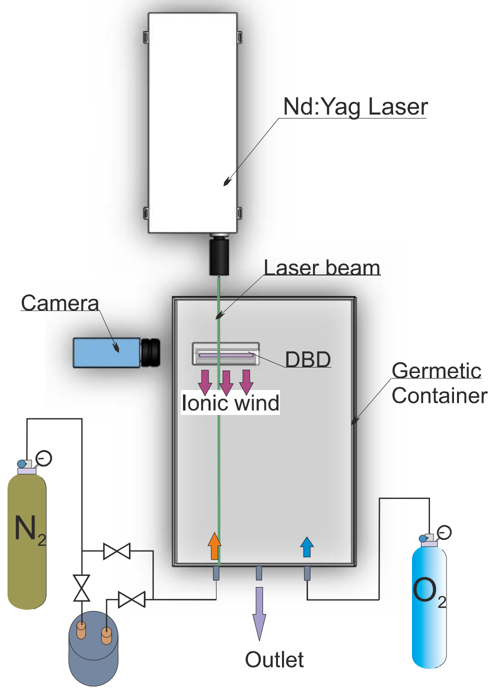


Figure 2: Scheme of experiment

Electric current and voltage were measured by digital oscilloscope RIGOL DS1102E using the current probe Tektronix P6021 and high-voltage probe Tektronix P6015A. Flow velocity measurements were done using PIV system Dantec Dynamics. The flow was seeded with oil particles of average diameter about 1 µm by the fog generator 10F03. Flow velocity vectors were obtained using adapting cross-correlation algorithms with sub-pixel interpolation and grid refinement of interrogation area. The total error of the technique was estimated as 1-2%. Frequency of the measurements by PIV (6 Hz) was limited by the camera used in the experiment. This value was significantly lower than discharge frequency (≈13.5 kHz). Therefore PIV system was synchronized with DBD and each frame was triggered with particular time delay during the period of AC voltage. Time delay for measurements was calculated as $\tau = nT + T/16$, where T - period of DBD voltage. This technique allowed to obtain the velocity distributions corresponded to 16 moments during a period of DBD.

It is necessary to note that the time interval between laser pulses of PIV system was 5 µs for discharge frequency 13.5 kHz. These time delays were chosen to provide sufficient displacement of the particles for the flow rate generated by the discharge. Thus, the time duration for measuring of flow velocity is comparable with the interval of measurements, therefore velocity fields are averaged over this time.

In order to generate high voltage AC step-up transformer was used, whose input was fed with an alternating square wave inverter. The output of step-up transformer was connected by the high-voltage cables with DBD. Since the DBD is actually a flat capacitor, the presence of inductance in the secondary circuit resulted in formation of an oscillatory circuit with a resonant frequency of 13.5 kHz. All experiments were performed at resonant frequencies.

Figure 2 shows the experimental setup. The discharge was placed in the camera (800x650x500 mm) made from Plexiglas. The oxygen concentration sensor Figaro KE-25 and mixture humanity sensor Honeywell HIH 4021-003 were placed inside the camera. The camera was connected with O_2 and N_2 cylinders and the desired mixture was created by displacement of the initial mixture by desired gas. A fan was installed inside the camera to provide fast mixing. Compressed N_2 was used as transport gas for tracer particles.

The distributions of the local acceleration were calculated based on the instantaneous velocity fields obtained by PIV. This technique allowed to estimate the time evolution of the force induced by DBD [7]. The oxygen concentration in the experiments was varied from ≈0% to ≈90%. All measurements were performed for the case of excitation by sinusoidal voltage with frequency of 13.5 kHz and amplitude ≈7-8 kV.

3. Results and discussion

The experiments were done in two stages. At the first stage the measurements were done in full range of O_2 concentrations. At the second stage the experiments were repeated in the range of O_2 concentration 0÷20% to provide the better accuracy. The voltage (and power) was decreased in the second experiment to provide better stability of the high voltage generator.

Fig. 3 shows the time variation of the power and longitudinal components of the force generated by the discharge, versus the current and voltage. This figure present only unsteady component of the streamwise force and corresponding power expended to generation of the flow pulsations. Generation of the pulsations is associated with acceleration and deceleration of the flow so the expended power is negative during the deceleration phase. Calculation of the power to excite the periodic pulsations was done as the magnitude of the mean value of power. The mean velocity profile downstream of the plasma region was used for calculation of the mean power. The detailed description of the data processing technique is presented in [7].

It can be seen from the figures that distributions of the streamwise force and pulsation power are not strongly affected by oxygen concentration. At the same time there is gradual smoothing of the corves with decreasing of oxygen content. It means that the ion charge remains the same and does not depend on the O_2 concentration.

Completion of the positive phase of the discharge is happened due to equalization of the potentials between the open electrode and dielectric surface that is caused by a decrease of the growth rate of the voltage between the electrodes. In this moment the voltage reaches its maximum. At this point the streamwise components of the force is close to zero. Further, the voltage begins to decrease, which causes the appearance of a negative potential difference between the open electrode and dielectric surface. Upon reaching the breakdown voltage the surface discharge starts its negative phase. Until the negative phase of the discharge the value of the streamwise component of force at changes slightly.

During the negative phase of the discharge, the value of streamwise components of the force is positive. Value of the force increases rapidly at the beginning and after that the force begins to decrease and reaches zero approximately at the end of the negative phase of the discharge. This change of strength can be explained by existence of the uncompensated space charge of negatively charged ions and its intensification during the negative phase of the discharge. Negatively charged ions are accelerated from the left to the right and due to collisions with neutral atoms produces the general acceleration of the flow.

After the end of the negative phase the modulus of the streamwise components of the force starts to grow, but its direction is reversed. Now the force is directed from the right to the left and slows down the flow. This is going on due to increase of the voltage between the electrodes, which leads to a positive potential difference between the open electrode and dielectric surface. Due to the electric field the negative ions begin to move against the flow, causing some deceleration.

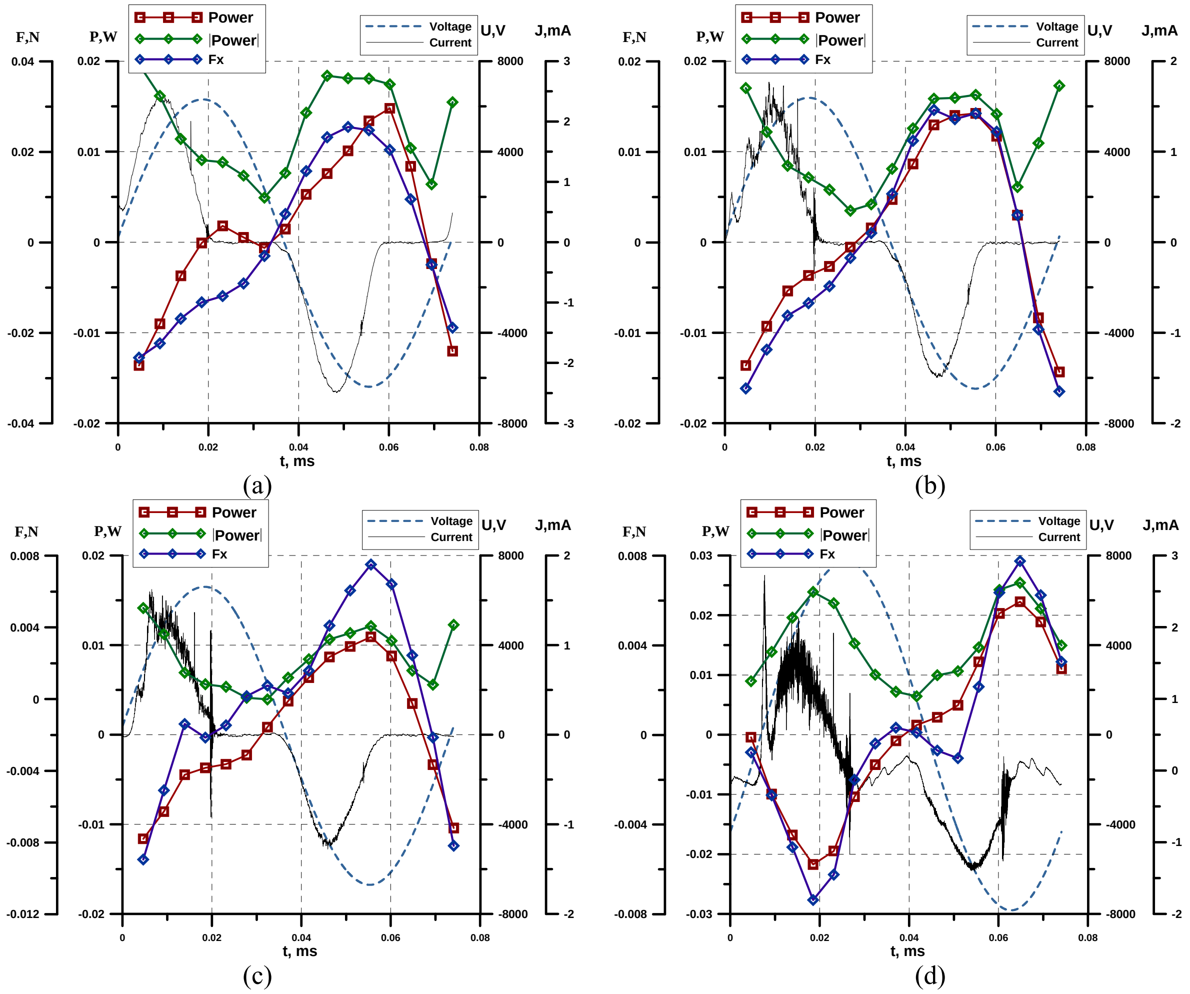
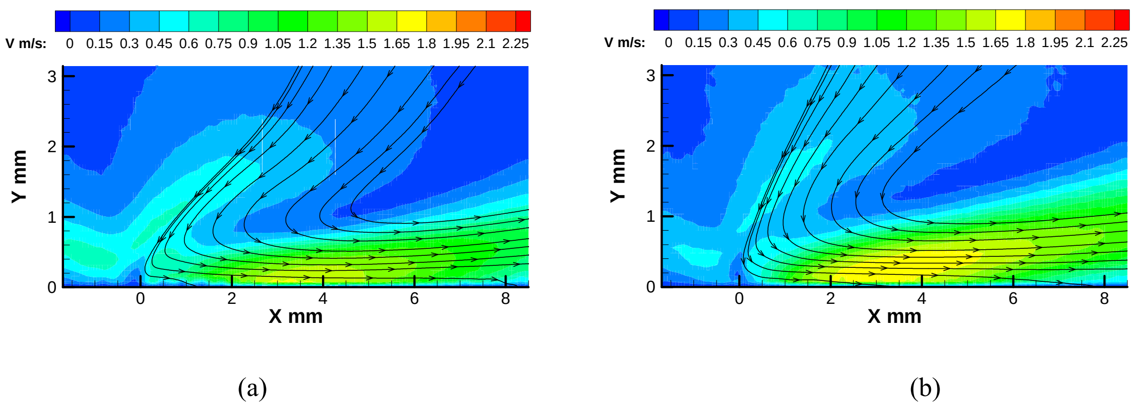
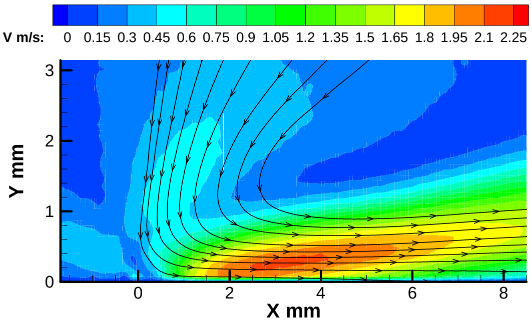


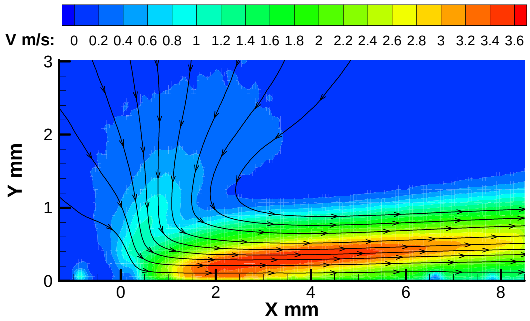
Figure 3: Variation of power and force during one period on the background of active current and voltage (a – 0.1% O_2, b – 4.8% O_2, c – 20.3% O_2, d – 69% O_2)

The averaged velocity distributions obtained for various O_2 concentrations are presented in Figure 4. The data presented in Figure 4a,b c were obtained in the second stage of the experiments (voltage amplitude 7 kV) and the data of Figure 4d and e were obtained in the first stage (voltage amplitude 8 kV). It can be seen that there is large decrease of the velocity generated with decreasing of oxygen concentration from 21 % to 2 % (Figure 4 a, b, c). At the same time there is an expansion of the plasma region and corresponding increase of the conduction current (see Figure 3). Increasing of the concentration from 21 % to 69 % (Figure 4 e, d) does not change the velocity distributions but size of the plasma region and conduction current decrease.





(c)



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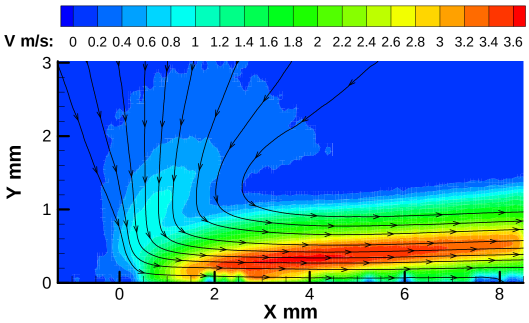


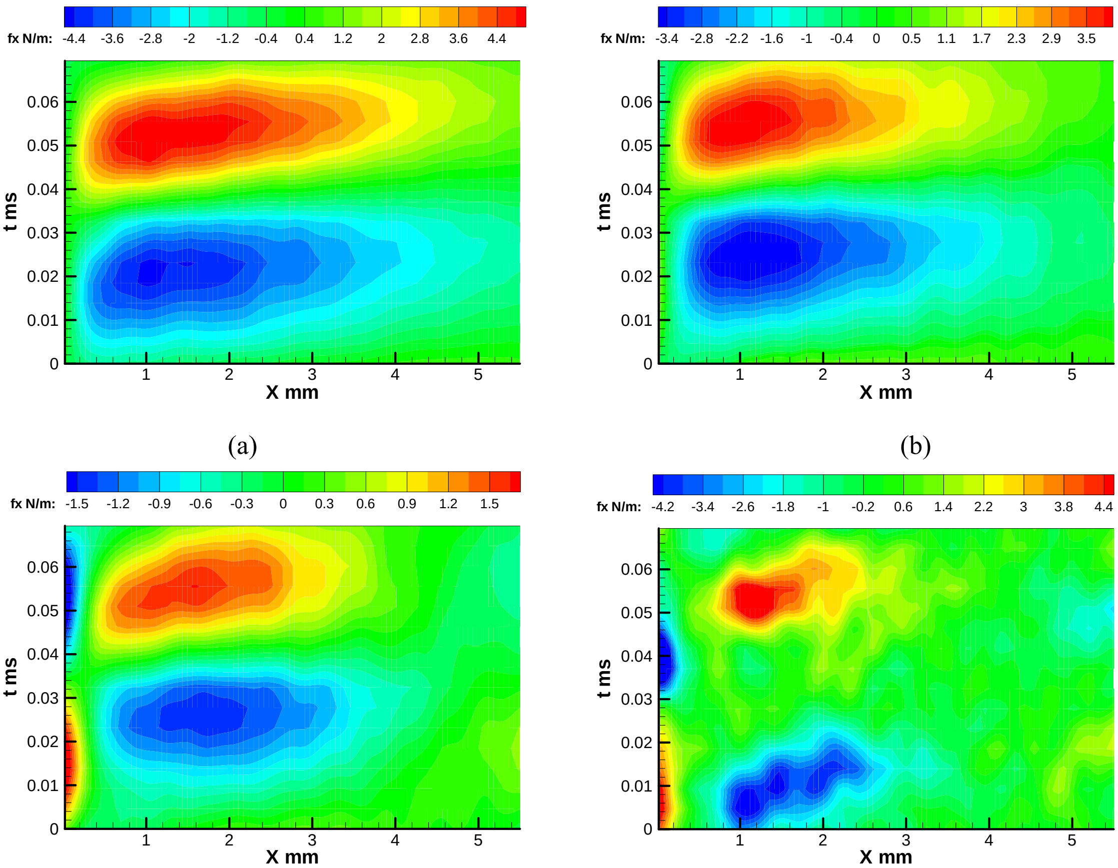
(e)

Figure 4: Average velocity fields (a – 0.1% O_2, b – 4.8% O_2, c – 20.3% O_2, d – 69% O_2, e – 20.8% O_2)

Figure 5 presents variation of the streamwise component of unsteady force during one period of oscillations for several values of oxygen concentration. There is evident displacement of the force maximum with time connected to charge accumulation by dielectric. This effect results in extension of the streamers and corresponding extension of the area of high electric field strength. It can be seen from the figures that the area of force generation is extended for low oxygen concentration. This effect is connected with expansion of the plasma region and as a consequence the region of the flow acceleration.

At the same time the acceleration process does not substantially change. The acceleration corresponds to negative stage of the discharge and deceleration corresponds to positive one. Taking into account the data obtained in [7] it may be concluded that the negative ions are mostly responsible for the force generation and the oxygen ions are the most probable candidates for this role. However the flow behavior does not change for the case of very low oxygen concentration (about 0.1%). It means either that the rest of oxygen is enough for ion wind generation or other negative ions (for example, negative ions of atomic nitrogen) begin to play the main role. It is interesting to see that positive ions of molecular nitrogen does not create the ionic wind even for low concentration of oxygen. This result forced us to double check an effect of tracer particles on the force generation. Several kings of particles were tested with the same results.

The force variations during a period of voltage in study [5] are more pronounced with decrease of oxygen concentration than in the current study. Apart from the measurement accuracy the reason may be connected with big difference of DBD frequency (current study - 13.5kHz, [5] - 200 Hz). In this experiments the ions do not have enough time to leave the region of DBD due to high frequency of voltage oscillations. In the case of low frequency each cycle of discharge is associated with generation of new set of the ions. Unfortunately the design of the high voltage generator did not allowed to get frequency lower than 8 kHz to verify this hypothesis. It has to be mentioned that the results obtained for very low oxygen concentration in [5] and present study can not be clearly explained and this effect have to be studied experimentally.



(a) (b)

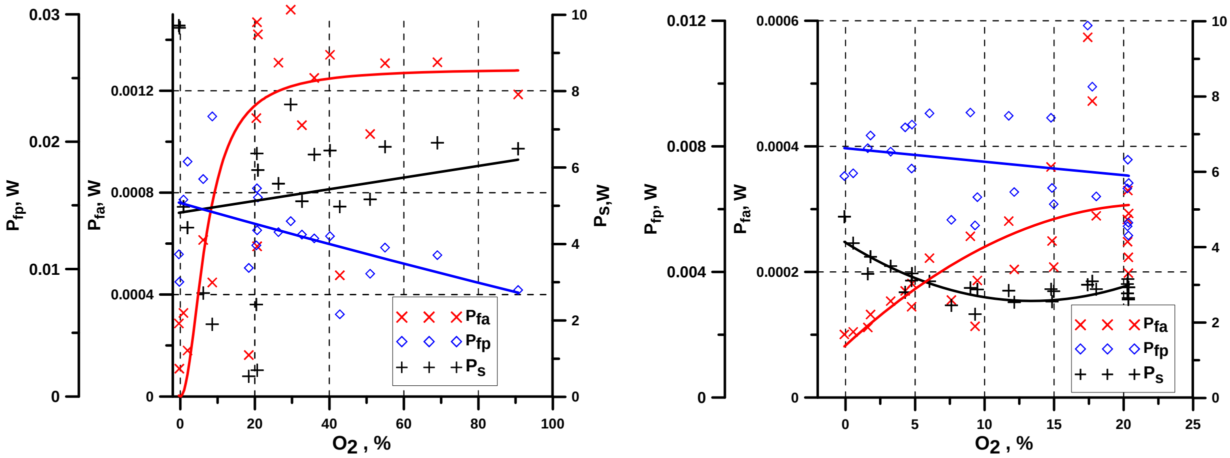
(c) (d)

Figure 5: Time evolution of streamwise force distribution (a – 0.1% O_2, b – 4.8% O_2, c – 20.3% O_2, d – 69% O_2)

The Fig. 6 shows dependences of the mean flow power (P_{fa}) and power of the flow pulsations (P_{fp}) (both induced by DBD) as well as the supplied electrical power (P_s) on the oxygen concentration. It is clearly seen that for all oxygen concentrations $P_{fp} > P_{fa}$. The electric power is approximately constant for all oxygen contents. Molecules of oxygen are electronegative and easily capture the electrons. Reducing of the oxygen concentration leads to creation of more favourable conditions for the plasma formation. This leads to an extension of the plasma region and rise of electrical current (for the constant voltage). The mean flow power (P_{fa}) increases till the oxygen concentration reaches about 20% and then remains approximately constant.

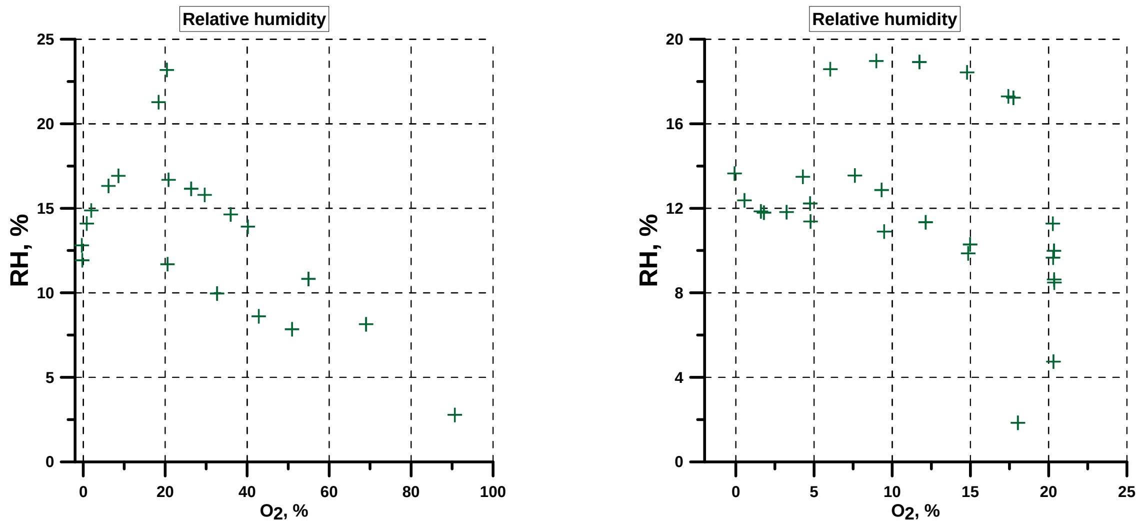
Power of the flow pulsations (P_{fp}) varies in another way. It slightly decreases with increasing of the oxygen content. This is an important and new result which allows to conclude that the oxygen concentration affects the balance of the acceleration and deceleration of the flow produced by EHD forces. The previous studies were focused mainly on the oxygen and nitrogen content on the mean flow, therefore this phenomenon wasn't revealed. These data extend the understanding of the ion wind generation processes occurring in DBD.

The general trends presented in Figure 6 are obvious but the data scattering is very high. This scattering of the data was associated with change of humidity in the experiments. It was shown in the study [8] that variation of humidity strongly affects the ionic wind generation. Comparison of the data presented in Figures 6 and 7 reveals evident correlation of the humidity and the measured values of power. To take into account this effect the following dimensionless parameters will be considered: mean and unsteady efficiency as a ratio of the mean flow power and power of the flow pulsations to the supplied electric power correspondingly; asymmetry equal to ratio of the mean flow power to power of the flow pulsations.



(a) (b)

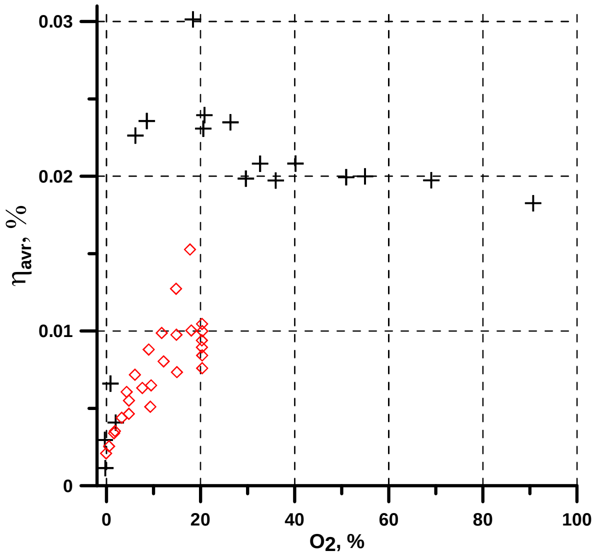
Figure 6: Variation of the mean flow and pulsations kinetic power vs. oxygen concentration (a – first stage, b – second stage)



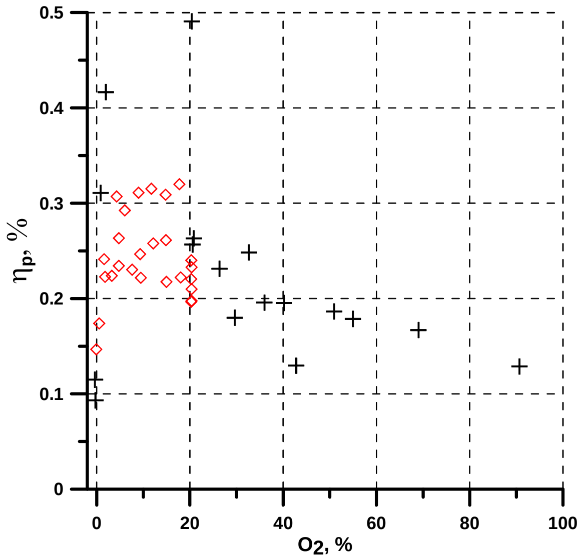
(a) (b)

Figure 7: Variation of relative humidity for various run (oxygen concentration) (a – first stage, b – second stage)

Figure 8 shows the efficiency of the average and pulsation kinetic powers generated by the DBD depending on the concentration of oxygen. It is clearly seen that the results of two stages of the experiment are in good agreement and data spread is reduced. It is arguable that for this experimental case the main part of the power was spent for periodic acceleration and deceleration of the flow (pulsation). The pulsation efficiency increases with concentration of nitrogen from ≈0.15% for ≈100% O_2 up to ≈0.3% for ≈1.5% O_2. Perhaps this is caused by more favorable conditions for the ignition of the plasma at low concentrations of oxygen. Further reduction of the concentration of O2 to ≈0% is followed by sharp decrease the efficiency of the pulsation. This can be explained by disappearance of negative oxygen ions which until then played a major role in the generation of the volume force. It should be noted that the experimental facility did not allow to achieve 100% nitrogen environment and small portion of the oxygen still remained.



(a)



(b)

Figure 8: Variation of the mean flow (a) and pulsations (b) efficiency vs. oxygen concentration (cross – first stage, diamond – second stage)

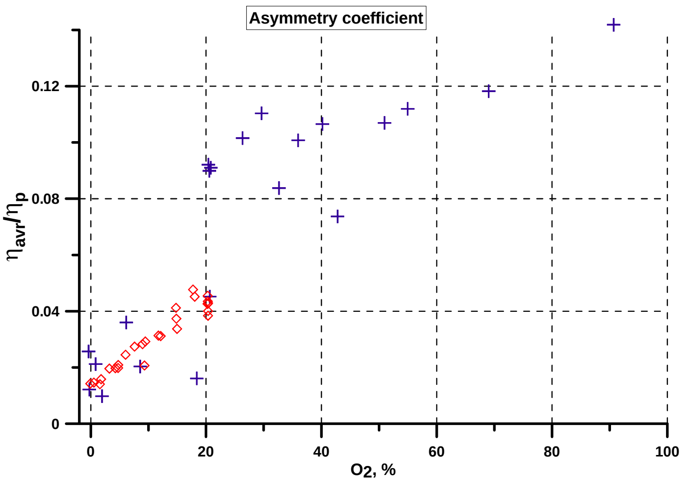


Figure 9: Variation of asymmetry of DBD force vs. oxygen concentration

The mean efficiency of DBD is much smaller and its dependence on O_2 concentration is different. The mean efficiency increases intensively up to about 20% O_2 and then value of the efficiency varies slightly. Taking into account that the pulsation efficiency is higher it can be assumed that induced mean flow occurs because of presence of an asymmetry between the accelerating and decelerating component of the volume force. The dependence of the asymmetry on the oxygen concentration is shown in Figure 9. The figure reveals approximately linear dependence of the asymmetry on the oxygen concentration. With high probability the value of the asymmetry may be affected by other parameters of DBD (type of dielectric, voltage, etc.). This gives a chance to increase the average speed of the ion wind by changing the asymmetry of force. Unfortunately, the obtained data do not allow to develop a well-defined model of the ion wind generation by DBD. Therefore further studies are needed.

Acknowledgements

This study was supported in part by the RFBR (project no. 12-01-31093-mol_a).

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