Study of the unsteady flow field induced by dielectric barrier discharge

A. A. Sidorenko, P. A. Polivanov, O. I. Vishnyakov and A. A. Maslov
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS
630090, Institutskaya, 4/1 , Novosibirsk, Russia

Abstract
Research of new techniques of the flow control is of great importance because the capability of traditional control devices is one of the limits of the aircraft efficiency. The promising technique involves application of electrogasdynamic devices based on the direct transformation of the electric energy to the force acting on the flow. The paper deals with the flow actuator based on a principle of dielectric barrier discharge. By means of measurements of electrodynamic parameters of the plasma discharge coupled with PIV measurements of the induced velocity the unsteady behavior of the actuator was investigated. The instantaneous and time averaged parameters of the flow acceleration were obtained and efficiency of the actuator was estimated.

1. Introduction

The active methods of flow control based on introduction of additional energy to the flow are intensively developed [1]. Prospects of these techniques are associated with the possibility of a global restructuring of the flow with minimal affect on the controlled flow, as well as the ability to implement flow control systems with feedback. We consider the use of such systems to prevent flow separation, reduce noise by modifying the boundary layer, control of shock-wave interactions, etc. [1]. Among the other actuators used for a direct influence on the flow the special attention is paid to ones using low-temperature surface plasma. Effect of surface plasma actuator is complex and depends on the type of discharge. First of all there is the effect due to the generation of ionic wind and secondary influence of plasma on such parameters as gas temperature, density, viscosity, etc. EHD principle of influence on the flow has several advantages: simple design of plasma actuators and their possible integration into the surface of the aircraft, possibility to introduce to the flow the perturbations with high frequency and etc. Moreover, it is possible to directly convert electrical energy into kinetic energy of the flow by using of the ion wind effect. Two types of plasma discharges are usually considered for production of the ionic wind the corona and dielectric barrier discharge (DBD).
Initially, the flow modification by ion wind was tried to implement by corona discharge [2], but some progress has been achieved only at low Reynolds numbers [3] due to low values of flow velocity induced by the discharge. Further increase of the momentum introduced by the discharge ion wind can not be achieved by increasing the voltage between the electrodes due to the transition of the discharge to arc phase. Dielectric barrier discharge avoids this limitation because the presence of a dielectric barrier increases the field strength compared to corona discharge. The idea of using DBD for control of separated flows was first expressed in [4]. At present, there is a considerable number of experimental results (see, for example, [5] and [6]) which has been shown the feasibility of this method of flow control. At the Institute of Theoretical and Applied Mechanics for several years such studies are carried out successfully in wind tunnels and flight experiment [7, 8]. The effectiveness of the DBD for control of the flows on the straight and swept wings was proved in the wind tunnel experiments [9], as well as its ability to manage the burst of the vortexes on the lee side of a delta wing [10].
Currently the effective flow control using DBD is possible only at moderate flow speeds. To improve the effectiveness of DBD for the flow control and expand its applicability it is required to have a thorough understanding of all processes associated with the initiation and maintenance of the discharge. The most interesting effect of the flow acceleration in the discharge has no unequivocal explanation. There is a large number of numerical studies on the problem of the flow acceleration in the DBD (see [11], [12]). Analysis of these studies shows that there is quite a large spread of results. Each group of authors uses their approach and assumptions about the choice of working gas, the modelling of surface and volume charge, etc. Choosing the correct physical model of the processes in the discharge can be made only on the basis of comparison with detailed experimental data. Despite the abundance of experiments of the measurements of the average velocity induced by the discharge, there is a lack of data on variation of the velocity field during a period of voltage fluctuations. Present experimental study focuses on the measurement of unsteady velocity field generated by a dielectric barrier discharge, electrodynamic and electrostatic characteristics of barrier discharge, as well as the forces acting on the flow of the DBD.

2. Experimental setup

The experiments were done in still air environment under atmosphere pressure and room temperature 295 K. The experimental model was made from glass-fiber laminate of thickness 1.5 mm. Two copper electrodes were placed on the opposite sides of the plate. The closed electrode was grounded and insulated from the air by epoxy resin. Length of the electrodes was 150 mm, thickness 50μm. The insulated and open electrodes were 8 mm and 4 mm wide respectively (see Figure 1). 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 POLIS. The flow was seeded with the oil particles of the average diameter about 1 μm by the fog generator SAFEX-2010. Flow velocity vectors were obtained using adapting cross-correlation algorithms with sub-pixel interpolation, grid refinement and deformation of interrogation area. The total error of the technique was estimated as 1-2%. Frequency of the measurements by PIV (2.5 Hz) were limited by the camera used in the experiment. This value was significantly lower then discharge frequency (up to 8 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 corresponding to 16 moments during the period of DBD.
Is necessary to note that the time interval between laser pulses of PIV system was 10 ms in the case of a discharge frequency 8 kHz and 35 ms for the frequency of 1.6 kHz. These time delays were chosen to obtain a sufficient displacement of the particles at a flow rate generated by the discharge. Thus, the time duration for measuring of flow velocity is comparable with the interval of measurements, and velocity fields are averaged over this duration.
Electrical scheme of the experiment is shown in Figure 1. 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 leads to the formation of an oscillatory circuit with a resonant frequency of about 8 kHz. Two experiments were performed at different frequencies of discharge 1.6 kHz and 8 kHz.

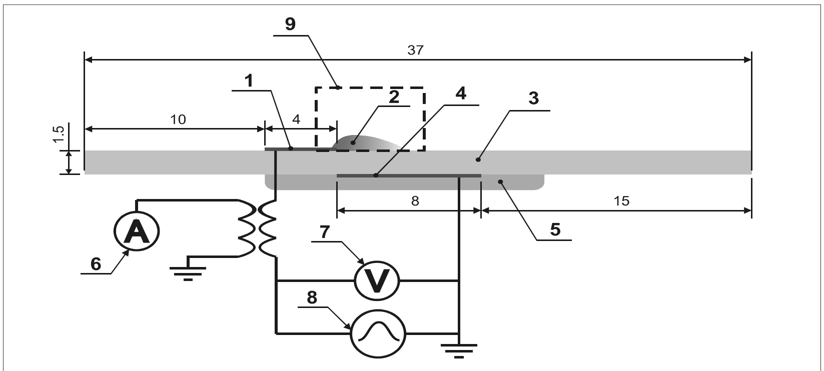
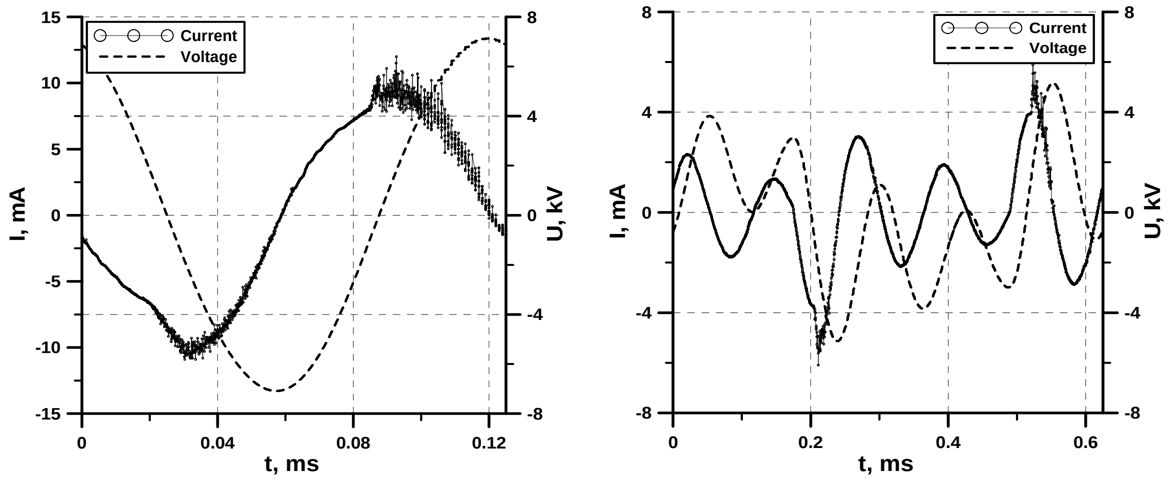


Figure 1 Scheme of DBD (1 – open electrode, 2 – plasma region, 3 – glass-fiber laminate, 4 – closed electrode, 5 – epoxy resin, 6 – current probe, 7 – voltage probe, 8 – high-voltage source, 9- region of PIV measurements)

3. Results and discussion

In the first experiment the transformer was fed by a square wave with a frequency of 8 kHz. This frequency is near-resonance one in the oscillatory circuit formed by the output transformer of the generator and the system of cable-discharge. As a result the voltage and current traces on DBD were close to sine wave (Figure 2a). In this case the plasma arises twice per period. The surface discharge operating at atmospheric pressure is characterized by streamer breakdown, so during the discharge there are transient plasma formation - streamers, which are visible on the current waveform in the form of noisy areas. The most characteristic feature of plasma is the appearance of the active components of the current associated with the current flowing in the plasma against the background of the prevailing bias current. This feature allows one to clearly distinguish the area of the discharge in the waveforms.
The second experiment was carried out by applying to the transformer the rectangular signal with frequency of 1.6 kHz. This non-resonant frequency resulted in a complicated behavior of voltage and current in DBD (Figure 2b). Discharge occurs at the moment of the most rapid change of voltage and appearance of additional oscillation process causes the existence of the discharge 4 times over the period. The total duration of the discharge in relation to a period less than for resonant frequency.

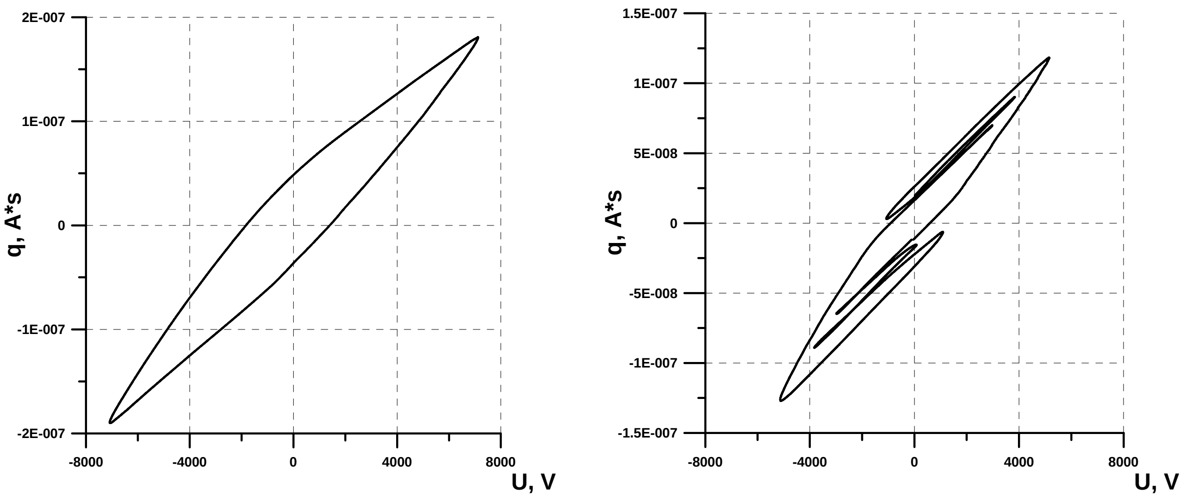


a) f = 8 kHz, b) f = 1.6 kHz

Figure 2. Oscillograms of voltage and current measured on DBD

Time integration of the current allows to calculate the value of the charge on the DBD and to to plot the dependences of charge vs. voltage, as it shown in Figure 3. In the case of conventional capacitor, such dependence would appear as a straight line. In the case of the DBD there is a deviation from a straight line due to the fact that under the influence of the electric field there is the electron emission and neutralization of positive ions on the electrode surface, as well as the formation of surface charge on the dielectric. Changes of the slope during the plasma existence are associated with various intensity of these processes. In the absence of plasma the dependence becomes linear again.

When a sinusoidal voltage of the resonance frequency applied, there are two active phases of the discharge (Figure 3a). Plasma can exist only when there is an excess of a certain potential difference between the open electrode and dielectric surface. Due to the current flowing in the plasma and depending on the phase of discharge there is a transmission of positive or negative charge on the dielectric surface, which leads to equalization of potential between it and an exposed electrode. Accordingly to maintain the potential difference, necessary for the discharge existence, a permanent change of the potential of the open-electrode has to be provided.

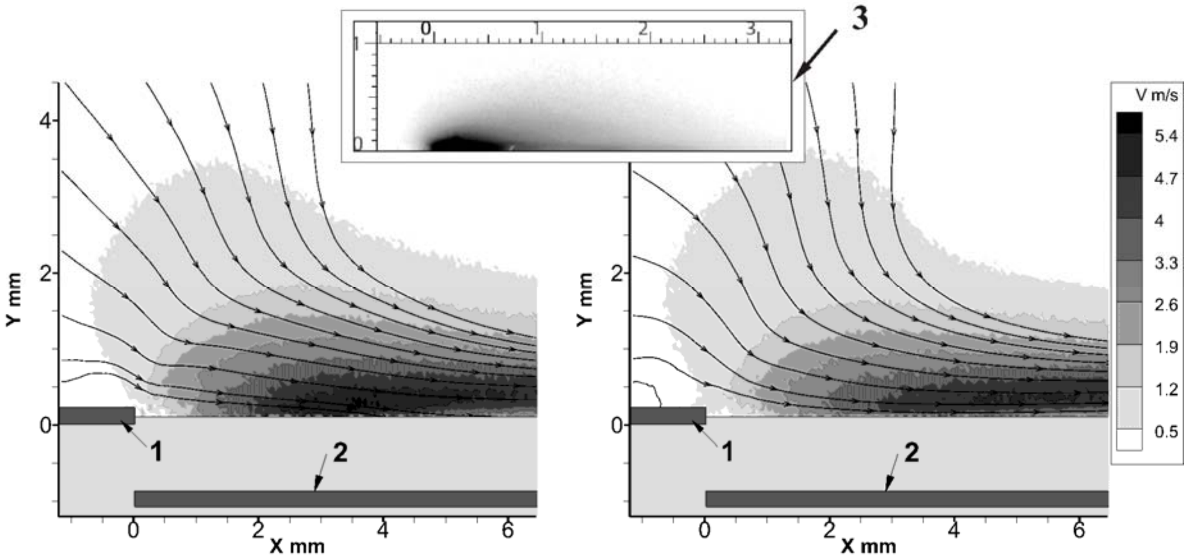


a) f = 8 kHz, b) f = 1.6 kHz

Figure 3. Cyclograms of the voltage and charge variation on DBD a) 8 кГц, b) 1.6 кГц

Figure 3b shows more interesting dependence caused by complex variation of voltage and current. As noted above, at the frequency of 1.6 kHz the breakdown appeared in the air 4 times per period. Respectively on the plot there are substantial changes in the slope of the curve 4-times over the period. In this case, the coincidence of the slopes can

be clearly seen at the moment of absence of plasma. The slight discrepancy of short sections at the bottom of the chart (Q<0) can be explained by insufficient accuracy of measurements.
Figure 4 presents two velocity fields obtained for the discharge frequency 8 kHz and an inverted photo of barrier discharge. Plasma region is formed near the right edge of the open electrode and spreads over the surface of the insulator. Recombination and secondary ionization in this region leads to the formation of photons. The main emission occurs in the near ultraviolet and violet range of visible light. The radiation intensity is proportional to the concentration of ions. Thus, the darker areas in the photo correspond to a higher concentration of ions in the plasma.



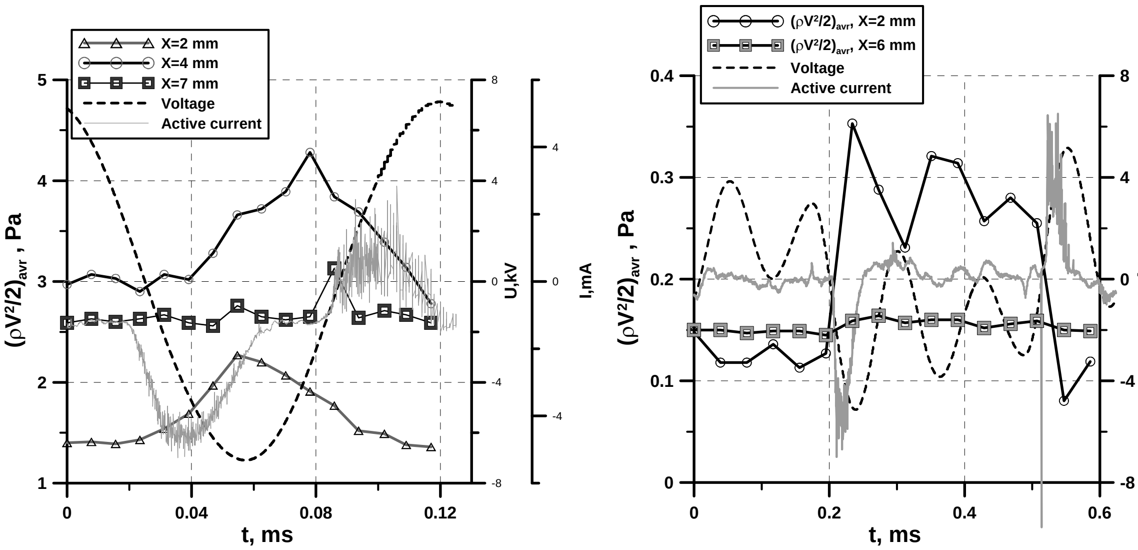
a) negative polarity, t=70.2 μs b)positive polarity, t=7.8 μs

Figure 4. Induced velocity fields at the moment of plasma collapse (1 – exposed electrode, 2 – closed electrode (grounded), 3 – inverted photo of plasma region).

Velocity fields are shown for the moment of the discharge collapse at the negative and positive voltage between the electrodes. Under the positive potential difference there is a situation where an open electrode is the anode. The figure shows that the streamlines came down and go in the direction of the closed electrode. The maximum value of the velocity induced by discharge is approximately 5.4 m/s, and achieved at a negative voltage. Viscous forces in this case have little influence compared with action created by the ionic wind. This suggests that the flow is accelerated at negative voltages, and decelerated with a positive voltage.
Figure 5a shows the variations of the averaged dynamic pressure $(\rho V^2)/2$ for two vertical sections on the background of voltage and the active current component measured during a single period. This graph confirms that acceleration occurs during the discharge with negative potential difference. It is seen that the velocity changes only in the discharge region and further from the outer electrode sections the dynamic pressure is almost constant for the entire period of oscillations.
When rectangular signal with a frequency of 1.6 kHz was applied, the discharge appeared 4 times over the period. In this regard, on the chart it is possible to see 2 regions of acceleration and 2 regions of deceleration of the flow. It may be noted that the flow pattern in this experiment does not have any fundamental differences from the above data. The difference is that the maximum induced speed (1.2 m/s) in this experiment much lower then for the resonant frequency, since the potential difference and the size of the plasma region (where there is growth of speed) in this case is much smaller. When considering changes of dynamic pressure during one period in the different sections (Figure 5b) it may also be noted that the change in dynamic pressure continues in the absence of plasma current and is correlated with the voltage variation. This means that the processes of acceleration and deceleration of the flow occur not only at the moments of the plasma. Comparing the results of two experiments, one can notice that for increasing of DBD effectiveness it is necessary to increase the duration of the discharge and the current in the plasma.
Basing on the velocity fields it is possible to study the dynamic behavior of the force generated by DBD. Calculation of the force components was carried out by integrating the corresponding components of the acceleration across the field of measurements. Calculation of acceleration was based on the measured velocity distributions and performed using the left difference of the first order

$$a_i = \frac{V_i - V_{i-1}}{\Delta t}. \tag{1}$$

Differentiation was performed for the longitudinal and vertical velocity components for each point in space. The absolute values of acceleration presented below were calculated as the root of the sum of squares of the components of acceleration.



a) f = 8 kHz, b) f = 1.6 kHz

Figure 5 Variation of the dynamic pressure, voltage and plasma curent

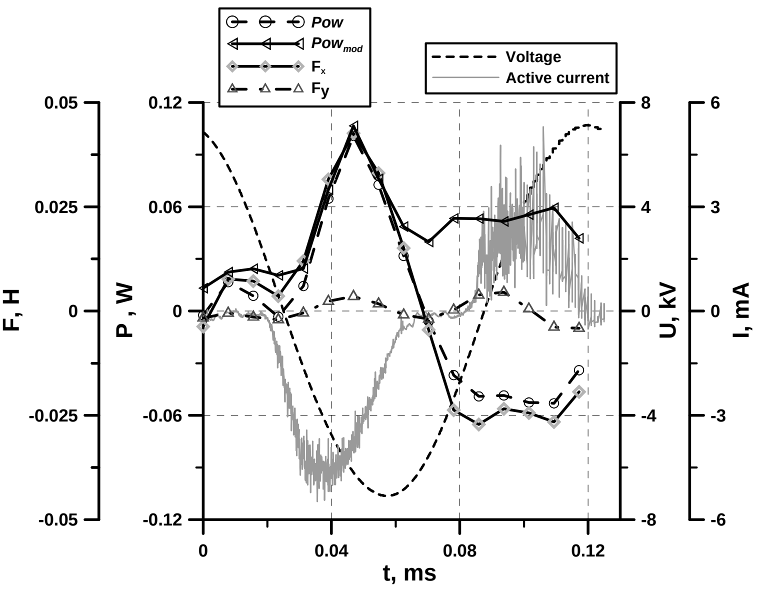


Figure6 Variation of power during one period on the background of active current and voltage.

The acceleration distributions obtained allow us to make a direct estimation of the discharge power consumed for acceleration and deceleration. This instantaneous power was calculated by integrating the products of the components of accelerations to the corresponding components of velocity across the measurement field.

$$Pow = \rho l \left(\int V_x(x,y) \cdot a_x(x,y) dxdy + \int V_y(x,y) \cdot a_y(x,y) dxdy \right), \tag{2}$$

where ρ = 1.225 kg/m^3- air density, l - length of the electrode, V_x and V_y-longitudinal and vertical components of flow velocity, a_x and a_y - longitudinal and vertical components of the flow acceleration.

The analysis of acceleration fields also shows that EHD force at certain moments can slow down the flow and accelerate it as well. In order to estimate the total power consumed for the creation of such disturbances in the flow we used the integration of modules of the corresponding products:

$$Pow_{\mathrm{mod}} = \rho l\left(\int \left|V_x(x,y)\cdot a_x(x,y)\right| dxdy + \int \left|V_y(x,y)\cdot a_y(x,y)\right| dxdy\right). \tag{3}$$

Figure 6 shows the time variation of the power and two components of the force generated by the discharge, against the current and voltage for the first experiment. Let's consider the variation of force and dynamic pressure for this case (Figure 6 and Figure 5a).

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 dynamic pressure reaches a minimum and the value of the longitudinal 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 dynamic pressure remains virtually unchanged, while the value of the longitudinal component of force at first slightly increases and then decreases slightly, but remains positive. This effect may be caused by the prevalence of negatively charged oxygen ions in the periphery and the presence of positively charged ions of nitrogen near the electrode (appeared after the positive phase of the discharge). The combination of negative and positive components of the force generated respectively by positive and negative ions in the complex electric field created by two electrodes and the dielectric surface, gives such a behavior of the total force.

During the negative phase of the discharge, the value of dynamic pressure is continuously growing. Value of the longitudinal component of the force also increases rapidly at the beginning but reaches its maximum at the moment of maximum current in the plasma. After that, the force begins to decrease and reaches zero at the end of the negative phase of the discharge. This change in strength can be explained by the 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. The variation of the current in plasma there is due to changes of voltage between the open electrode and dielectric surface. Therefore the maximum current coincides with the maximum field strength, which leads to the maximum value of the longitudinal component of the force.

After the end of the negative phase the value of dynamic pressure begins to fall. Modulus of the longitudinal 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.

The efficiency of gas acceleration in DBD is often estimated as the ratio of the average kinetic power of the gas flow (P_{ut}) to the electrical power (P_s). For calculation of the electrical power only the active component of the current (I_A), associated with the formation of the ionization region is used. For this experiment, this estimate yields:

$$\eta_t = \frac{P_{ut}}{P_s} = \frac{\frac{\rho\cdot l}{2}\int V^3(y)dy}{\frac{1}{T}\int_0^T I_A(t)\cdot U(t)dt} = \frac{0.00641[W]}{6.663[W]}\cdot 100\% = 0.096\% \tag{4}$$

where V - the average flow velocity, U - voltage across the electrodes, T-period of oscillations.

In this case, the estimation of net power takes into account only the steady flow field generated by the discharge. As shown above, during its cycle the DBD has an oscillatory character and not only speeds up the flow, but also decelerated it. Therefore, for a correct estimation of the DBD effectiveness one should also take into account the average power spent on the generation of periodical disturbance (P_{up}):

$$\eta_p = \frac{P_{up}}{P_s} = \frac{\dfrac{\rho \cdot l}{T}\int_0^T \left[\int \left|V_x(x,y,t)\cdot a_x(x,y,t)\right| dxdy + \int \left|V_y(x,y,t)\cdot a_y(x,y,t)\right| dxdy\right] dt}{\dfrac{1}{T}\int_0^T I_A(t)\cdot U(t)dt} = 0.71\% \quad (5)$$

This formula takes into account the nature of the pulsating flow generated by the discharge. As a result, the overall efficiency of energy conversion to the flow kinetic energy consists of the generation of steady flow and the periodic perturbations. It should be noted that the resulting efficiency is still low, but the current study did not pursue the goal of improving the efficiency of the discharge and its optimization.

4. Conclusions

EHD and electrodynamic characteristics of dielectric barrier discharge were obtained and analyzed. It was established that between the open electrode and dielectric there is an exchange of charge. The waveforms of the current flowing in the plasma were extracted from the total current to determine uniquely the time of appearance and disappearance of plasma formations.

Analysis of velocity fields showed that the temporal variations of velocity occur only in the plasma region. At some distance from the plasma region the flow generated by the discharge becomes almost stationary. It was found that the acceleration of flow occurs when the open electrode is negatively charged, and some deceleration when it is charged positively.

The acceleration distributions significantly improved the understanding of the processes occurring in the DBD. It was shown that the main effect of DBD on the flow is the creation of periodical perturbations, rather than steady acceleration. This allowed us to introduce a more correct estimation of the discharge effectiveness. It is concluded that the main mechanism for acceleration of the flow is the appearance of uncompensated negative electric charge in the gas generated during the negative phase of the discharge. After completion of the positive phase of discharge the ions are almost complete disappear. The concentration of negative ions only near the plasma region is a result of low induced velocity (and consequently their low drift) at the chosen discharge frequency.

Acknowledgments

This study was supported in part by the RFBR (project no. 09-01-00524-a), the Siberian Branch of the Russian Academy of Sciences (Integration Project no. 80-2009), and the Federal Analytical Targeted Program “Development of the Scientific Potential of Universities in Russia” (project no. 2.12.1/3693).

References

[1] Joslin R.D. and Miller D. Fundamentals and Applications of Modern Flow Control / Vol. 231: Progress in Astronautics and Aeronautics Series. AIAA, Inc. 2009.
[2] Velkoff H. and Ketchman J. Effect of an electrostatic field on boundary layer transition // AIAA Journal. 1968. Vol. 6. No. 7. p. 1381-1383.
[3] Moreau E., Leger L. and Touchard G. Effect of a DC surface non-thermal plasma on a flat plate boundary layer for airflow velocity up to 25 m s-1 // J. Electrostat. 2006. Vol. 64. p. 215-225.
[4] Roth J.R., Sherman D.M., Wilkinson S.P. Boundary layer flow control with one atmospheric uniform glow discharge surface plasma // AIAA-Pap. 98–0328.
[5] Post, M.L., and Corke T.C. Separation Control on High Angle of Attack Airfoil Using Plasma Actuators // AIAA Journal. 2004. Vol. 42. No. 11. p. 2177-2184.
[6] Corke1 T.C., Enloe C.L. and Wilkinson S.P. Dielectric Barrier Discharge Plasma Actuators for Flow Control // Annual Rev. of Fluid Mech. 2010. Vol. 42. p. 505-529.
[7] Malmuth N., Maslov A., Sidorenko A., Fomichev V., Korotaeva T. ITAM Study of Aerodynamics in Weakly Ionized Plasma // AIAA-2008-4336.
[8] Sidorenko A., Budovsky A., Pushkarev A., Maslov A. Flight Testing of DBD Plasma Separation Control System // AIAA-2008-373.

[9] A. A. Sidorenko, A. D. Budovskii, B. V. Postnikov, I. D. Zverkov, B. Yu. Zanin, V. V. Kozlov, and A. A. Maslov Electric Discharge Control of Flow Separation on Oblique Airfoil // Technical Physics Letters, 2010, Vol. 36, No. 4, pp. 304–307.
[10] Andrei A. Sidorenko, Anatoly A. Maslov, Boris V. Postnikov, Boris Yu. Zanin, Ilya D. Zverkov and Victor V. Kozlov. Plasma control of vortex flow on delta-wing at high angles of attack // 3rd European Con-ference for Aero-Space Sciences (EUCASS). 6-9 July, Paris-Versailles 2009.
[11] Lagmich Y., Callegari Th, Pitchford L.C., Boeuf J.P. Model description of surface dielectric barrier discharges for flow control // J. of Physics D: Applied Physics. 2008. Vol. 41. No.9. pp. 095205.
[12] Cho Y-C., Jayaraman B., Viana F. A. C., Haftka R.T., Shyy W. Surrogate Modeling for Characterizing the Performance of Dielectric Barrier Discharge Plasma Actuator // AIAA Pap. 2008-1381.