Proceedings of ASME FEDSM'02:
FLOW INSTABILITIES AND CONTROL FORUM
2002 Fluids Engineering Division Summer Meeting
Montreal, Quebec, Canada
July 14-18, 2002

FEDSM2002-31041

CONTROL OF THE AIRFLOW CLOSE TO A FLAT PLATE WITH ELECTROHYDRODYNAMIC ACTUATORS

Juan D'Adamo
Dept. Mechanical Engineering-University of Buenos Aires-Argentine

Guillermo Artana
Dept. Mechanical Engineering-University of Buenos Aires-Argentine

Eric Moreau
Laboratoire d'Etudes Aerodynamiques-UMR CNRS 6609-Futuroscope Cedex-France

Gerard Touchard
Laboratoire d'Etudes Aerodynamiques- UMR CNRS 6609-Futuroscope Cedex-France

ABSTRACT

This work analyses the ability of an electrohydrodynamic actuator to modify the characteristics of a flow over a flat plate. The device considered uses flush mounted electrodes and a d.c. power supply to create a plasma sheet on the surface of the plate. We analyze the effect of this plasma sheet on the flow in the region close to the leading edge of the plate. From Particle Image Velocimetry and at incident flow velocities in the range 11.6-18.6 m/s, we estimate the force per unit surface exerted by the discharge. We conclude that it can induce an important acceleration of the flow close to the surface with a relative good efficiency when compared with other actuators.

Keywords: electroaerodynamics - flow control - flat plate

INTRODUCTION

Recently, the use of actuators based on electromagnetic forces has been receiving special attention. These actuators have important advantages like simplicity, reliability (they have no moving parts) and a very short electrical response time (lower than 1 ns). When currents involved are so low that the magnetic effects may be disregarded these devices usually are named electrohydrodynamic (EHD) actuators.

The use of EHD actuators in a gaseous media requires in most cases the creation of ions to materialize an electric force on the electrically neutral fluid. The ions can be created and injected in a dielectric fluid flow by means of an electrical discharge. These charged particles under the action of coulombian forces will drift and exchange momentum with the neutral fluid particles. If their trajectories take place close to the wall, they can introduce changes in the fluid layers close to the surface where inertia forces are not so important and the kinetic energy of the flow is relatively low. So, uniform discharges of low intensity concentrated in this region could largely modify the boundary conditions and hence in some cases a large part of the fluid flow field.

Prior research concerning EHD actuators has focused in different possible applications like shock wave control in hypersonic vehicles, heat transfer augmentation, or drag reduction

Concerning this last application Malik and Bushnell [1-2] proposed a device consisting on needle points placed at the wall surface of a flat plate. This made possible to increase the air momentum mainly in the direction of the normal to the surface. As no mass is added to the flow the continuity equation indicates that this leads to a reduction of the longitudinal momentum. In consequence the velocity gradient at the wall can be diminished enabling a drag reduction. However as with this device the discharge was concentrated only in some discrete points, it seems that it is needed a large amount of power to produce a measurable drag reduction.

Other kind of devices with electrodes placed flush-mounted on the surface and momentum added to the fluid tangentially to the wall have recently been developed. With these devices the ions drift under the action of a more controlled electric field configuration and in consequence a major control of the trajectories of the ions can be achieved. Two different kind of devices based on this concept has recently been studied .

Roth [3] has proposed a device based on a surface-generated atmospheric radio frequency plasma. The device named One Atmosphere Uniform Glow Discharge (OAUGDP) uses two electrodes separated by an insulating surface that avoids the knocking of the ions on the cathode preventing the heating of it and the formation of new avalanches or breakdown from electron secondary emission. The authors explains that paraelectric forces associated to the square of the electric field gradients enable ion acceleration, and via particle collision, acceleration of the neutral particles. Other devices that use electrodes separated by a dielectric barrier like the OAUGDP but consider a polyphase RF power or a pulsed excitation have been presented recently [4-5].

The devices of the second kind use a different approach as no dielectric barrier is used. They consist on two electrodes flush mounted on the same side of an insulating surface which enable to create a bipolar corona with a d.c. voltage excitation.

Colver and members of his group [6-8] have undertaken numerical studies with a flat plate and a wire-wire electrode configuration of very small diameter (2µm). Their model predicts a corona thinning for the boundary layer and a reduction in the drag of a flat plate. The predictions where compared with experimental results obtained with a very small flat plate (25x75x1 mm^3) with razor blades electrodes flush mounted. The experimental drag reduction was found to be almost one order less than the one predicted by their model. This discrepancy seems to be associated to the characteristics of their device that produced a non uniform discharge along the electrodes.

Other similar devices with very well finished wire-wire or wire-plate electrodes are now being used. When they are suitable operated the problems of spot formation seems not to be so important and uniform discharges can be achieved. More, recent results [9-15] indicate that with a wire-plate electrode configuration it is possible to obtain a discharge regime characterized by a uniform plasma sheet contouring the body surface in the inetrelectrode space (generalized glow regime).

A refined model that could indicate the different mechanisms governing the establishment of this last discharge regime is still missing. However an heuristic explanations can be proposed considering previous works of laser research with devices of this kind but excited with a pulsed voltage. The regime with the uniform luminosity like a plasma sheet covering the space between both electrodes has received in these works different names like “sliding” discharge, “grazing” discharge or “skimming” discharge. Rutkevich[16,17] proposed a model of a stationary wave of ionization to describe the propagation of this discharge. This model predicts typical results of the plasma sheet thickness between 0.1-1mm, apparently quite close to the one we could observe with a d.c. excitation.

The similarities that exists between both processes, the pulsed voltage case and the d.c. voltage case, in consequence seems to indicate that both phenomena have the same origin. Then, presumably the regime that leads to a uniform plasma sheet though produced with a d.c. excitation should be a pulsating discharge with a repetition of some kHz. The scenario should then be a repetition of ionization waves, each front of ionization screening the electric field and impeding the formation of a new discharge until the neutralization of the effect of the front. Actual research is now trying to elucidate this question.

The effect on the flow of the EHD actuator operating in the regime that gives rise to a plasma sheet is very distinctive because of two main factors :

-its intensity (luminescence in all the arc distance indicates the phenomena involves high momentum particles)

-its uniformity (the uniformity of the discharge occurs all along the electrode length and not in some isolated points).

As a result of this description, it is clear that to achieve a technological flow control device is necessary to obtain a better definition of the capabilities of the actuator to modify the different flow configurations.

In prior articles[11,12] we have analyzed the effect of the actuator when operating in this regime on the fluid mechanics occurring around the plate when traversed by an air flow. The measurements of the drag force at different mean flow velocities (1-5.25m/s) has been performed with a balance and indicate that even though the discharge occupies only about 20% percent of the plate surface it can be obtained important drag reductions for this surface in the range of 7 to 34% decreasing with flow velocity .

The goal of this article is to analyze for this flow configuration and at a mean flow range of 10-20m/s the magnitude of the momentum transfer from ions to the flow and the efficiency of this process.

EXPERIMENTAL SETUP

In our study the injection of ions is obtained with a d.c. corona discharge between a wire type electrode (0.90 mm diameter) and a plate electrode of aluminum foil (of the same length than the wire). The electrodes are located flush mounted on the surface of a flat plate of PMMA (4mm thick) as shown in Figure 1. Two different H.V. sources of opposite polarity (+20kV, -20kV, 1.5 mA) impose a voltage difference between both electrodes. The wire type electrode is connected to the positive polarity source and the plate electrode to the negative one. By increasing the voltage difference between both electrodes different discharge regimes can be established. The current measurement was undertaken with an electrometric circuit which can detect currents of 1 nA. The characteristic voltage current curves are similar to the ones previously published[11-12].

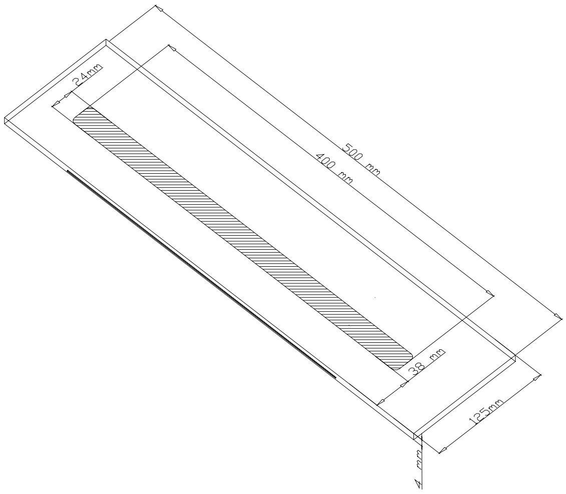

Figure 1 Plate and Electrode arrangement

The plate was placed horizontally in a closed wind tunnel (probe section of 0.50x0.50m^2 –velocity ranges 2-30m/s) with the wire electrode facing the flow in the leading edge. The flow field was determined with a Particle image velocimetry system (PIV-DANTEC system controlled by FlowMap®). The plate was illuminated with a laser sheet produced by a Yag laser of 200mJ. In our experiments each pulse had a duration of 0.01 microseconds and the time between a pair of pulses was 50 microseconds. We have used a progressive scan interline camera that can produce images of 768 × 484 pixels. The interrogation area was 32 × 32 pixels with an overlap of 50 % and the images were obtained with a scale factor of 5.33.

We considered 600 pairs of digital images to obtain the mean velocity field of the airflow of one experiment. Each velocity field was filtered with a peak-validation and a range validation filter. Peak validation filter is based on the detectability criterion[14] which validates vectors with a ratio of the highest peak to the second highest peak in the correlation plane larger than a fixed value (1.2 in our case). The range validation filter enables to establish the range admitted for the modulus of the velocity vectors. In our case we have considered a value of 2.0 times the incident flow velocity Uo as the upper limit. Undertaking these filtering processes, about 50 to 100 vectors are removed from 1363 initial vectors.

Seeding was produced with a smoke generator EI 514 Deltalab that uses a pure cosmetic grade oil and operated to obtain a cloud with a mean particle diameter of 0.3µm. As analyzed in a previous article[12], the influence of coulombian forces on tracers trajectory, when operating the smoke generator under these circumstances can be disregarded without introducing a large error.

EXPERIMENTAL RESULTS

Mean Flow field modifications

As a consequence of the sharp wedge of the plate the flow presents a bubble of recirculation and downstream of it a reattachment region. It is in these regions where the discharge takes place and where we concentrate our analysis.

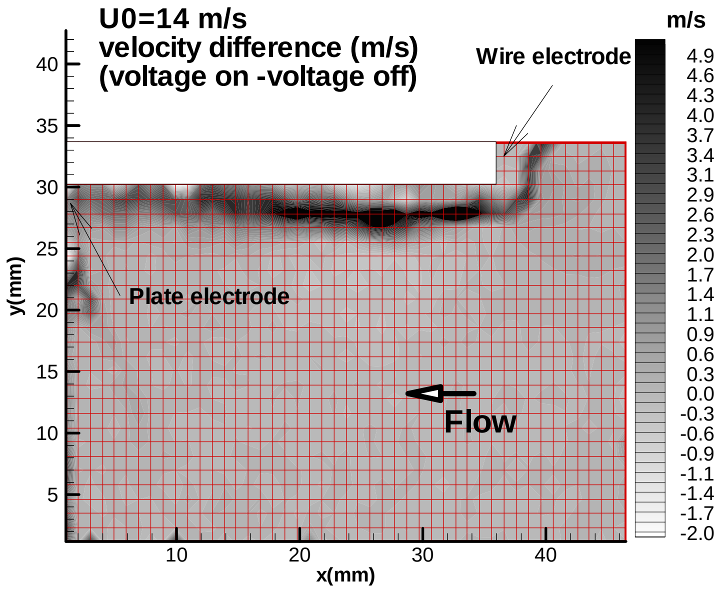

Figure 2: Mean velocity field difference U_0=14.6m/s. Discharge on with ∆V=31.0 kV.

We show typical results concerning to the effect of the actuator on the mean velocity field in Figure 2. The figure show at a flow velocity of 14.6 m/s the difference of the averaged vectors for the cases with discharge on and discharge off. It can be seen that the electric force exerts an important acceleration of the fluid close to the wall. The maximum values detected of the velocities differences in our experiments are 4.6, 4.9 and 10.7 m/s corresponding respectively to incident flow velocities of 11.6, 14.6 and 18.5 m/s.

Figure 3 shows typical velocity profiles at a streamwise of the reattachment region for the cases voltage on and off. Figure 4 enables to emphasize the effect of the voltage on velocity distribution as it represents the difference of the velocities profiles at different streamwise station. Similar effects are observed at other incident flow velocities.

We can observe in these figures that the changes in the velocity field produced by the EHD actuator are more pronounced in fluid layers close to the wall. At larger distances from the leading edge, the changes tend to be more uniform and velocities differences can be detected in layers at larger wall distances. This can be explained considering that the momentum changes on the boundary layers produce changes on the flow that are subjected simultaneously to diffusion (mainly in the direction of the normal to the surface) and convection processes (mainly in the flow direction).

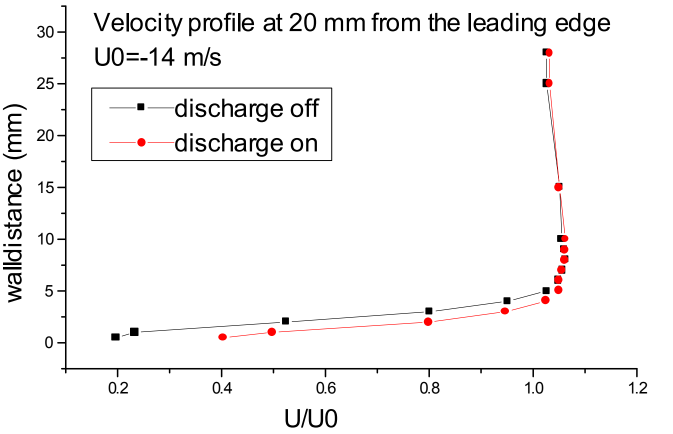

Figure 3 Velocity profile ratio. Streamwise station 20 mm from the leading edge. U0=14.6 m/s. ΔV=31.0 kV

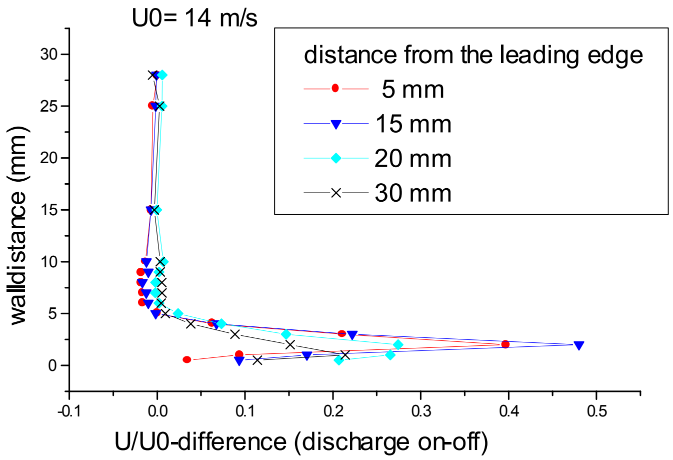

Figure 4: Velocity difference profiles for different streamwise stations, U0=14.6 m/s., ΔV=31.0 kV

Ion-neutral particle interaction: Momentum transfer

The plasma sheet produced by the actuator involves modifications of the boundary conditions of the flow. The modifications are linked to changes on the fluid properties itself and also to the apparition of a volumetric force acting on the fluid. Neglecting the effect of the fluid properties changes, a first approach to the forces that induce the electric discharge in the fluid can be obtained if we assume that these forces act concentrated only in the thin layer of the plasma sheet.

Then the velocity field data from P.I.V. allow us to calculate the local skin friction coefficients along the plate. In order to achieve the calculus, the field was divided in narrow control volumes as indicated in Figure 5.

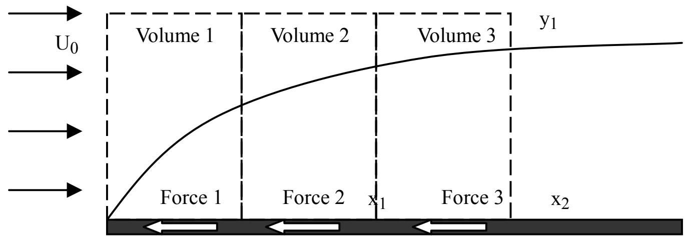

Figure 5: Scheme for estimate the electric forces per unit area acting on the flow.

We considered in our analysis the region of the reattachment of the flow and so the region of analysis comprises only a part of the interlectrode space. Assuming a bidimensional flow and a negligible pressure gradient the skin friction stress τ is calculated with the integral momentum equation applied in each volume :

$$\tau = \frac{\rho}{L}\left(\int_0^{y1} u_{x1}{}^2 dy - \int_0^{y1} u_{x2}{}^2 dy - \int_{x1}^{x2} u_{y1} v_{y1} dx \right)$$

$$L = x_2 - x_1$$

The value of y1 is large enough so that the shear stress force on the top of the side of the volume can be disregarded.

We can estimate then the friction coefficient with $C_f = \frac{\tau}{0.5\,\rho U_0{}^2}$. This coefficient is associated to the position lying on the surface at equal x distance from the coordinates x1 and x2. In order to minimize errors all volume controls leading to an error higher than 1.5% of the integral continuity equation were not considered in our analysis.

With this procedure for the flow velocities 11.6, 14.6 and 18.6 m/s, for the cases with and without discharge, the skin friction coefficients were obtained for the different positions. Figures 6 show these coefficients. These figures show as expected that skin friction coefficients in the reattachment region are larger than the ones observed in a well established laminar boundary layer along a flat plate Also in the figures we can see that the curves with voltage on have similar shape with voltage off and always they show lower values.

The difference between both curves at each streamwise position gives the force per unit surface produced on the flow by the discharge (electric stress) at this point. Figure 7 resumes the results for each one of the flow velocities of the electric stress τ_e at the different positions along the plate.

As we can see in this figure the electric stress depends on the value of the incident flow velocity. So, the interaction of ions with neutral fluid particles is velocity dependent, being larger when the fluid is animated with more important velocities. However, it seems that more experiments should be undertaken to confirm this tendency for a range of larger flow velocities.

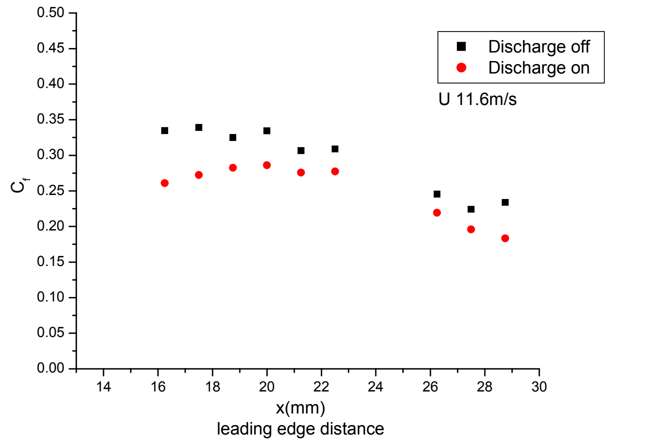

Figure 6a: Local skin friction coefficient U0=11.6 m/s. Discharge voltage. ΔV=31.0kV

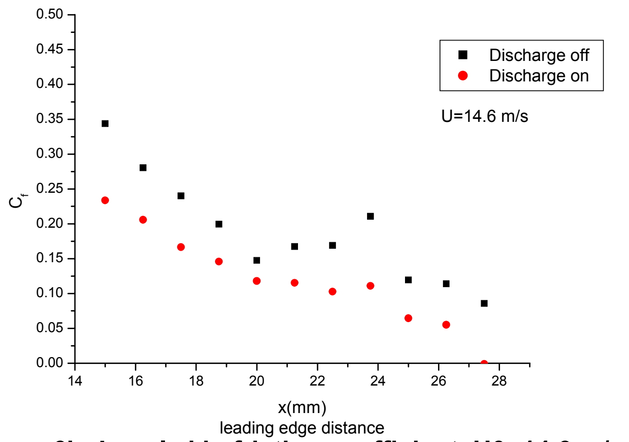

Figure 6b: Local skin friction coefficient. U0=14.6 m/s ΔV=31.0kV

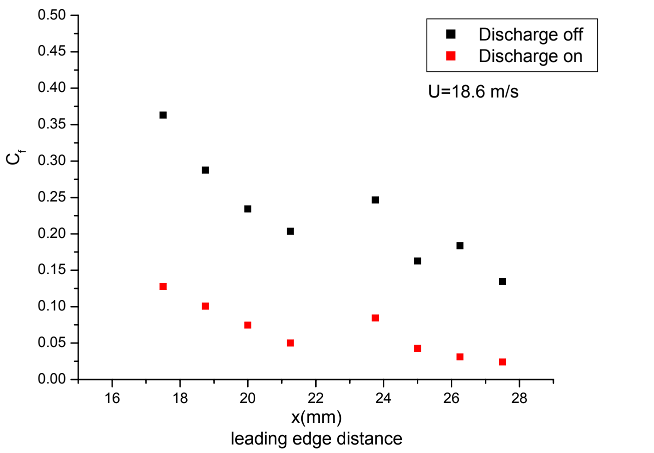

Figure 6c: Local skin friction coefficient U0=18.6 m/s. ΔV=31.0kV

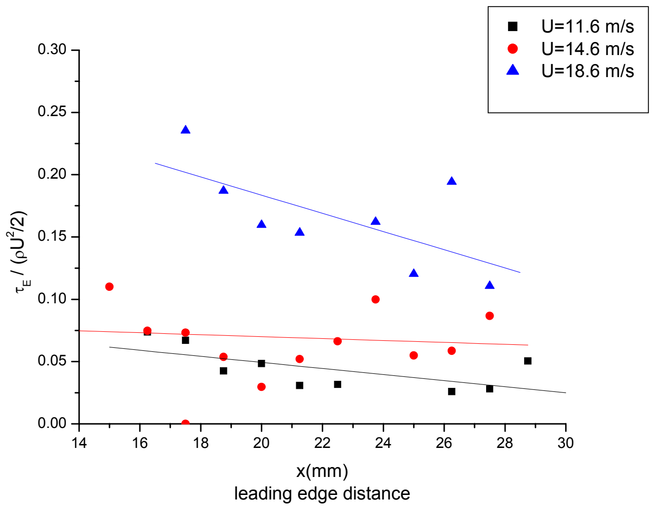

Figure 7: Non-dimensional electric force per unit surface.

Efficiency Estimation

From a technological point of view associated to the effect of the actuator appears the need of an estimation of the power required to obtain this effect and in consequence of the efficiency.

The electric power required for the effects on the flow shown in this article was about 7.5 W and the power per unit surface of interelectrode space about 495 W/m^2.

The efficiency of the actuator may be estimated comparing the power added to the fluid flow in the form of kinetic energy with the electric power dispensed.

The power added to the flow in kinetic form can be obtained with integral methods with a similar analysis to the previous paragraph. To obtain this we consider a steady state and then the integral equation of the kinetic energy flow is:

$$\Delta K = \frac{\rho}{L}\left(\int_0^{y1} U_{x1}{}^2 u_{x1} dy - \int_0^{y1} U_{x2}{}^2 u_{x2} dy - \int_{x1}^{x2} U_{y1}{}^2\ v_{y1} dx \right)$$

With this definition it is necessary to consider volume controls that involve the whole interelectrode space. This means in terms of the flow the whole recirculation region and the reattachment region.

The efficiency of the actuator η is evaluated then as the difference of ΔK in the case with electric field on and off compared to the electric power used by the actuator P.

$$\eta = \frac{\Delta K_{on} - \Delta K_{off}}{P}$$

By fixing the criteria of an error lesser than 1.5% in the integral continuity equation we obtained efficiencies of 8.1% corresponding to flow velocities of 11.6 m/s. At larger flow velocities it seems that the evaluation of this efficiency with PIV results gives only a rough estimation probably as a consequence of the large volume controls and the influence of error propagation.

CONCLUSIONS

The effect of the dc corona discharge on the flow operating in the generalized glow regime is very distinctive because of two main factors :

- its intensity (luminescence in all the arc distance could be associated to ionization produced by high velocity charged particles)
- the homogeneity of the discharge occurring all along the electrode length.

The flow field measurements enabled us to conclude that for this kind of actuators, in the region of the ineterelectrode space a strong acceleration of the flow is produced. The acceleration occurs in fluid layers quite close to the wall surface and this effect diffuses perpendicularly to the wall.

By integral methods an estimation of the shear stresses at the wall was made and revealed the momentum addition generated by the actuator. By doing this calculation it is observed that the force per unit surface produced by the discharge is dependent on the incident flow velocity.

The results obtained concerning the electrical energy that is transformed into kinetic energy in the flow indicates that the actuator shows a relative good efficiency when compared with other EHD actuators.

The PIV technique seems adequate to estimate values of the electric stress by integral methods in the reattachment region of the flow downstream the recirculation region produced by the sharp wedge. However, the analysis of energy efficiency with integral methods and PIV results seems to be limited to low incident velocities.

The estimations we show in this article gives insight on the capability of this actuator and on the way it should be used for other flow types.

NOMENCLATURE

ρ: air density
L: length of a control volume
u_{x1}: horizontal velocity for the streamwise station $x=x_1$
u_{y1}: horizontal velocity for the station $y=y_1$
v_{y1}: vertical velocity for the station $y=y_1$
U_{x1}: Absolute velocity for the streamwise station $x=x_1$
U_0: Free flow velocity.
K: Kinetic energy.

ACKNOWLEDGMENTS

This research has been done with grants UBACYT AI-25 and PICT 12-02177 of the Argentine government

REFERENCES

1. Bushnell D., “Turbulent Drag Reduction for External Flows”, AIAA-83-0231, Jan. 1983.
2. Malik , Weinstein L., Hussaini M., “Ion Wind Drag Reduction”, AIAA-83-0231, Jan. 1983.
3. Roth J. R., Sherman D., “Boundary Layer Flow Control with a One Atmosphere Uniform Glow Discharge Surface Plasma”, AIAA paper #98-0328, Jan. 1998.
4. Corke T., Mattalis E., “Phased Plasma Arrays for Unsteady Flow Control”, AIAA paper #2000-2323, June 2000.
5. Lorber P., McCormick D., Pollack M., Breuer K., Corke T., Anderson I., “Rotorcraft Retreating Blade Stall Control”, AIAA paper #2000-2475, June 2000.
6. El-Khabiry S., Colver G., “Drag Reduction by D.C. Corona Discharge Along an Electrically Conductive Flat Plate for Small Reynolds Number Flows”, *Physics of fluids*, Vol 9, No 3, 1997, pp 587-599.
7. Colver G., El-Khabiry S., “Modeling of DC Corona Discharge Along an Electrically Conductive Flat Plate with Gas Flow*”, IEEE Trans on Industry Appl.,* Vol 35, No 2, 1999, pp 387-394
8. Soetomo F., “The influence of High Voltage Discharge on Flat Plate Drag at Low Reynolds Number Air Flow”, M. S. Thesis, Iowa State University, Ames, Iowa, 1992.
9. Artana G., Desimone G., Touchard G., “Study of the Changes in the Flow Around a Cylinder Caused by Electroconvection”, *Electrostatics’99*, IOP Publ. Ltd, Bristol-Philadelphia, 1999, pp 147-152.
10. Desimone G., DiPrimio G., Artana G., “Modification of the Flow Around a Cylinder by Means of Electrodes Placed on its Surface”, *Proc. Colloque de la Societé Francaise d’Electrostatique*, Poitiers, June 1999, pp 80-84.
11. Artana G., D’Adamo J., Desimone G., DiPrimio G., "Air flow control with electrohydrodynamic actuators", 2[Nd] Intnl Workshop on Conduction Convection and Breakdown in Fluids, Grenoble, 190-194 , 2000.
12. Artana G., D’Adamo J., Léger L., Moreau E., Touchard G., "Flow Control With Electrohydrodynamic Actuators", AIAA Paper# 2001-0351, 39[th] Aerospace Sciences Meeting and Exhibit, Reno, 2001.
13. Artana G., DiPrimio G., Moreau E., Touchard G., "lectrohydrodynamic Actuators On A Subsonic Air Flow Around A Circular Cylinder", AIAA Paper# 2001-3056, Anaheim, 2001.
14. Leger L., Moreau E., Artana G., Touchard G., "Influence of a DC corona discharge on the airflow along a inclined flat plate", *Journal of Electrostatics*, Vol. 50-51, 2001, pp 300-306.
15. Leger L., Moreau E., Artana G., Touchard G., "Modification de l’ecoulement d’air autour d’une plaque plane par une decharge couronne", Colloque de la Societe Francaise d’Eectrostatique, Montpellier, 2000, pp 97-101.
16. Rutkevich I., “Structure of a Grazing Discharge Front”, *Sov. Phys.-Tech.Phys,* Vol 31, No 7, 1986, pp. 841-842.
17. Lagarkov A., Rutkevich I., “*Ioniztion Waves in Electrical Breakdown of Gases*”, Springer, NY, 1993, pp 195-207.
18. R. Keane, Adrian R., “Theory of Cross Correlation Analysis of PIV Images”, *Applied Scientific Research*, Vol 49, pp 1992, pp 191-215.

