Abstract

Visualizations and measurements by Particle Imaging Velocimetry are conducted in a wind tunnel in order to determine the influence of a DC corona discharge established between a wire and a plate collecting electrode on the properties of an airflow around a flat plate. Results show that the kinetic energy induced by the ionic wind inside the boundary layer allows a drag reduction for low Reynolds number (ReL < 68600).

Keywords: Electroaerodynamic; Airflow; Flat plate; Corona discharge; Flow control; Drag reduction

1. Introduction

Application of a DC high voltage between a wire and a flat plate may induce an ionic wind or electric wind whose velocity attain several meters per second. Because its importance in several engineering applications relating to heat transfer such as electrostatic cooling or electrostatic precipitation [1-3], this electrical effect has been widely studied between a needle and plate electrode without obstacle and surrounded by a stagnant free gas. The case of a corona discharge along a semi-insulating surface submitted to an airflow [4-6] has received less attention. This electrical process may be used as an air-moving mechanism in order to modify the airflow around an obstacle (Electro-Aerodynamic) and very few works at subsonic velocities have been published on this subject [6-12]. The main advantage of this process is that it directly converts electrical energy into kinetic energy without mechanical pieces. The energy injection has to be located near the separation line of the airflow. Then, this process might be used by the aeronautic industry to control the laminar-turbulent transition inside the boundary layer around a plane wing, to reduce the drag and to stabilize the flow in order to avoid unsteadiness which generate unwanted vibrations, noise and losses.
The purpose of the present paper is to determine by visualization in a wind tunnel the influence of a DC corona discharge between a wire anode and a plane cathode on the airflow around an inclined flat plate, in order to observe the influence on the flow properties. Two sets of experiments are conducted. The first one consists in visualizing the 2D airflow around a flat plate at low velocities (from 0.35 to 1.1 m/s i.e. Reynolds numbers \(Re_L\) between 3750 and 11800). Furthermore, measurements by Particle Imaging Velocimetry (PIV) are conducted in a loop wind tunnel (0-30 m/s) in order to determine the flow velocity field upstream the flat plate at higher velocities (20400 < \(Re_L\) < 68600).

2. Experimental Set-up

Concerning the first set of experiments, the size of the Plexiglas flat plate is 300 × 150 mm. Its thickness is 4 mm. The corona discharge is established between a 300 \(\mu\)m-radius cooper wire (270 mm length) at about +20 kV and an aluminium plate electrode (25 × 270 mm) at about −10 kV (Fig. 1a). The flat plate, for an angle of incidence between 0 and 40 degrees, is placed in a wind tunnel (0-3 m/s) presented in Fig. 1b. The airstream velocity is measured with a micromanometer. The airflow around the obstacle is visualized with an oil smoke filament lightened by a two-dimensional laser sheet. As the size of the mineral oil particles is very small (the mean diameter is 0.3 \(\mu\)m), the smoke presents a very little tendency to charge electrically. The corona discharge is a generalized glow discharge defined by Artana et al. [6]. The purpose of this electric discharge is to convert electrical energy into kinetic energy inside the boundary layer in order to accelerate the flow close to the wall (Fig. 2a). The wire diameter is a very important parameter [6]. A high positive potential is used to obtain a homogeneous discharge. A negative potential is used to avoid the influence of any surrounding grounded objects such as the wind tunnel. Although the ion deposition/removal due to interaction with the solid surface, which induces a non-homogeneous potential distribution [5] and the fact that the surface electrical conductivity may vary with time, this discharge is quite homogeneous. More, it is luminescent and noisy. Its current is quite stable with time. Current versus electric field is given in Fig. 2b. From about 7.75 kV/cm, some electrical arcs appear which induces unwanted high current peaks. In our experiments, the current is about 100 \(\mu\)A and a low increase of the discharge current with the airstream velocity was observed.

Fig. 1. (a) Above view of the flat plate; (b) schematic side view of the wind tunnel used for the first set of flow visualizations.
Concerning PIV experiments, they are conducted in a loop wind tunnel (0-30 m/s) in order to obtain a homogeneous smoke inside the wind tunnel. Its test cross section is $0.5 \times 0.5$ m$^2$ with a length of 1 meter. The loop length is 11 meters. The plate width is now 480 mm instead of 270 mm. In these conditions, the discharge current is close to 200 µm. PIV is a measurement technique which allows to obtain the 2D velocity fields from the Fourier analysis of digital images of smoke particles which follow the flow and which are illuminated by a laser sheet.

3. Visualization Results

Visualizations are undertaken for different angles of attack (0, 15, 30 and 40 degrees) with airstream velocities from 0.35 m/s to 1.1 m/s i.e. $3750 < \text{Re}_L < 11800$ where $\text{Re}_L$ is the Reynolds number given by:

\[
\text{Re}_L = \frac{\rho U_e L}{\mu}
\]

with $\rho$ the air density, $U_e$ the airstream velocity, $L$ the plate chord and $\mu$ the air viscosity. The flow visualizations shown in Fig. 3 indicate that the DC corona discharge leads to a high acceleration of the airflow along the trailing edge. In fact, when the airstream flows along the flat plate without electric field, it separates from the wall forming an important wake and when the electric field is applied for low angles attack, the airflow remains attached to the wall. For higher angles, the airflow is reattached and the wake highly decreases. Nevertheless, one can assume that the influence of the DC corona discharge when it takes place out of the boundary layer decreases with the airstream velocity. This may be explained by the fact that the discharge energy is constant and the energy of the airflow in these regions increases with its velocity.

Concerning the electrostatic charge tendency of the smoke particles, it seems that this phenomenon is negligible. Indeed, the same airflow behavior is verified when the smoke wire is placed several centimeters above the anode, that is to say when the oil particles can not be attained by the discharge. Furthermore, these visualizations allow determining approximately
the velocity field of the ionic wind. The ionic wind flows round the leading edge of the plate, from the anode to the cathode and it seems that the effect of the discharge might be more intense in the proximity of the wall. The efficiency of the electroaerodynamic process is higher when the electrical discharge and consequently the ionic wind acts strongly very close to the wall. This is a requirement for practical applications but also it seems necessary that the electrodes should be placed in such a way to perturb the flow as less as possible when the discharge is not acting on the fluid. As a result with an optimization of the anode-cathode placement we think that still stronger effects could be attained.

![Diagram of anode-cathode placement](image)

4. P.I.V. Results

PIV experiments are conducted using the DANTEC system controlled by FlowMap® PIV Processor. Each image is 768 × 484 pixels. Measurement area is 32 × 32 pixels with an overlap of 50 %. A large number of experiments have been realized, from 1.9 to 30 m/s, with different angles of attack. In each case, three different fields of view have been observed: a large field of view which includes the whole plate and its wake and two smaller fields of view.
with a higher resolution, one at the anode (leading edge) and one at the cathode (trailing edge). In this paper, one PIV result at the trailing edge is presented. Its parameters are followings: incidence angle of 7 degrees, mean airstream velocity of 1.9 m/s \( i.e. \, Re_L = 20400 \). The airflow is stored during 100 seconds. Consequently, 2000 digital images are taken in order to obtain the velocity field of the airflow every 0.1 second. Each velocity field is filtered. About 50 to 100 vectors are then removed on 1363 initial vectors. This low number of rejected vectors shows the quality of experiments. An average is performed in order to obtain a mean velocity field of the airflow. The streamlines of the air flow at the cathode with and without corona discharge is presented in Fig. 4. Fig. 4b shows a net reduction of the wake when the electric field is applied. More, Fig. 5 shows a high acceleration of the airflow (until 0.9 m/s) downstream the cathode, at about 5-10 mm from the wall. This confirms the results obtained by visualization at higher velocity.

![Fig. 4. (a) Streamlines of airflow around a flat plate for an angle of attack of 7 degrees with a mean airstream velocity of 1.9 m/s \( (Re_L = 20400) \); (b) idem with the corona discharge.](image)

![Fig. 5. Velocity difference (m/s) between airflow with and without corona discharge.](image)
5. Conclusion

This experimental work has shown that a DC corona discharge established inside the boundary layer might have a high influence on the properties of an airflow around a flat plate for low Reynolds numbers (Re_L < 68600).

Visualizations of the 2D air flow around a flat plate for different angles of attack at low velocity (from 0.35 to 1.1 m/s i.e. Reynolds numbers Re_L between 3750 and 11800) has shown that the electrostatic process allowed to reduce highly the wake size and that it leaded to a net drag reduction. More, measurements by Particle Imaging Velocimetry (PIV) have confirmed this result for higher Reynolds numbers (20400 < Re_L < 68600) and shown that the discharge produces an important acceleration of the fluid layers close to the plate.

However, it seems that the electrostatic effect decreases with the airstream velocity. In our experimental setup, the effect of the corona discharge did not take place so close to the wall as desired, certainly because the electric field configuration was not optimized. More, the low curvature radius of the plate collecting electrode may induce electrical instabilities. These problems will have to be ameliorated because for aeronautic applications, the process needs reliability and an energy supply as close to the wall as possible in order to accelerate the airflow inside the boundary layer. Consequently, others electric field configurations and others types of discharge produced by a polyphase electric field are under the scope of future work.

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References