EFFECTS OF CORONA DISCHARGES ON A TURBULENT AIR FLOW: SIMULATION ON A HIGH-LIFT SYSTEM

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ABSTRACT

In this work, we simulate the effects of corona discharges on the air flow over a high-lift system. The numerical model reproduces the overall phenomenon of the boundary layer acceleration, and is not a model for the plasma itself, it integrates an electrostatic force to the Navier- Stocks equations, which depends on the electric charge density of the created plasma, the model is validated on turbulent air flow over a flat plate system. The CFD code FLUENT associated with a UDF module allows these simulations , the computational results of the high lift system show a significant increase of the lift coefficients between the angles of attack of 1.8 ° and 6 ° and a delay of the boundary layer separation.

1. INTRODUCTION

Air flow modification through electrical discharges give encouraging results in drag reduction [1], lift enhancement and separated flows attachment [2][3]. Numerical studies of fluid/plasmas interactions have increased in recent years, however, the modelling of the mechanisms of multi-species gas plasmas remains a complex task, the majority of authors model the equations of fluid mechanics separately from those of the electrostatics and solve the coupled system of the hydrodynamic equations and Poisson's equation [4]. In this work, the turbulent flow of air over a high-lift system will be simulated before and after the application of corona discharges by an electro hydrodynamic actuator.

2. MODELLING

The system consists of a main wing (NACA 4412) of 1.55m span fitted with a single slotted flap (NACA 4415), the fig. 1 shows the high-lift configuration. The system is placed in an air flow with $Re_{chord} = 0.55\ 10^6$, the K-ε RNG turbulence model is used to simulate the flows for the different angles of attack AOA, and reproduce the experimental values [5] before the mems actuation. Thereafter, the electrodes are subjected to high voltages (22kV to the anode and - 10KV to the cathode) to study the effects of the corona discharges produced on the flap.

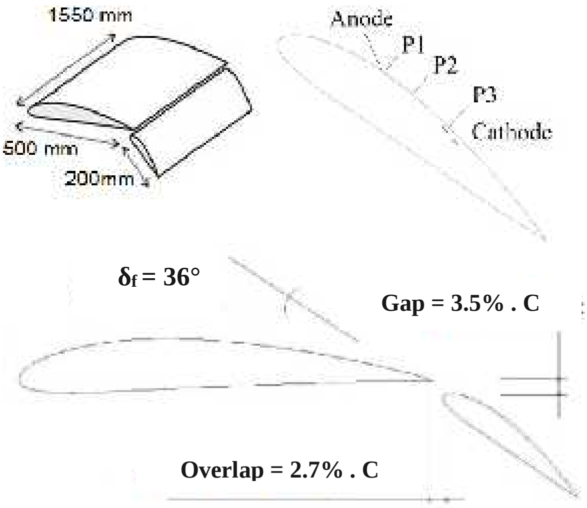

Fig . 1 Geometrical characteristics of the high-lift system

The numerical model is based on the turbulent boundary layer Navier-Stocks equations and the Poisson's equation for the electric field, the integrated electrostatic force depends on the electric charge density, assumed constant, of the plasma created between the electrodes and the applied high electric potential. The described phenomena are governed by the following equations systems:
For the area where the discharge does not affect the flow:

$$\nabla(\rho v) = 0 \qquad (11)$$

$$\frac{\partial}{\partial t}\rho\bar{v}_x = -\frac{\partial\bar{p}}{\partial x} - \left(\frac{\partial}{\partial x}\rho\bar{v}_x\bar{v}_x + \frac{\partial}{\partial y}\rho\bar{v}_y\bar{v}_x + \frac{\partial}{\partial z}\rho\bar{v}_z\bar{v}_x\right)$$
$$-\left(\frac{\partial}{\partial x}\rho\overline{v'_x v'_x} + \frac{\partial}{\partial y}\rho\overline{v'_y v'_x} + \frac{\partial}{\partial z}\rho\overline{v'_z v'_x}\right)$$
$$+\mu\nabla^2\bar{v}_x + (°g + \alpha E) \qquad (12)$$

$$E = \Delta\psi = 0 \qquad (13)$$

For the discharge area, the equation system becomes:

$$\nabla(\rho v) = 0 \qquad (14)$$

$$\frac{\partial}{\partial t}\rho\bar{v}_x = -\frac{\partial\bar{p}}{\partial x} - \left(\frac{\partial}{\partial x}\rho\bar{v}_x\bar{v}_x + \frac{\partial}{\partial y}\rho\bar{v}_y\bar{v}_x + \frac{\partial}{\partial z}\rho\bar{v}_z\bar{v}_x\right)$$
$$-\left(\frac{\partial}{\partial x}\rho\overline{v'_x v'_x} + \frac{\partial}{\partial y}\rho\overline{v'_y v'_x} + \frac{\partial}{\partial z}\rho\overline{v'_z v'_x}\right)$$
$$+\mu\nabla^2\bar{v}_x + (°g + \alpha E) \qquad (15)$$

$$E = -\nabla\Psi \qquad (16)$$

This model was validated on a turbulent air flow over a flat plate system fitted on its upper face with the same two electrodes actuator, the dimensionless electro hydrodynamic numbers N_{EHD} were used to compare the computational results to the experimental data of Moreau & al [1], the computational N_{EHD} shows very good agreement with the experiments in laminar and turbulent flows simulations up to $Re = 3.0\ 10^5$, the value of the charge density α was also determined for theses configurations, $\alpha = 0.5\ 10^{-3}$.

3. SIMULATION

We consider a turbulent, steady, incompressible air flow in the system, the 2D unstructured grid generated with Gambit 2.4.6 software, contains two subdivisions corresponding to the area where the discharge does not affect the air flow, and another for the discharge zone fig.2 shows a general view of the gird and the boundary conditions:

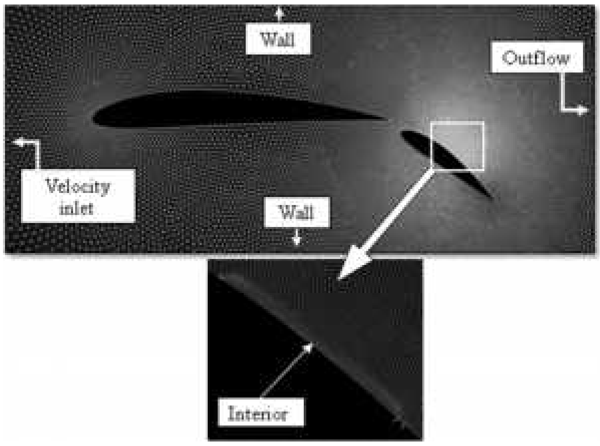

Fig . 2 General view of the grid and the boundary conditions

The CFD code Fluent 6.3 does not offer the possibility to make simulations with the electricity equations, for this reason, we hang a UDF Module written in C (UDF : User Defined Functions) [7] , which solves the equation of the electric field , taking into account the values of the potentials to the electrodes and the value of the charge density α of the plasma, hence the discharge is not explicitly taken into account, but represented by a force which depends on the electric potential difference and a coefficient which reflects the evolution of plasma parameters (μ_E and σ) .

4. RESULTS

A. FLOWS WITHOUT ACTUATION

Simulations of the flows without the corona discharges shows fairly good agreement with the experimental data, fig. 3 show a representative result of the case of AOA = 0 ° , the lift coefficients C_L curve is displayed in fig. 4:

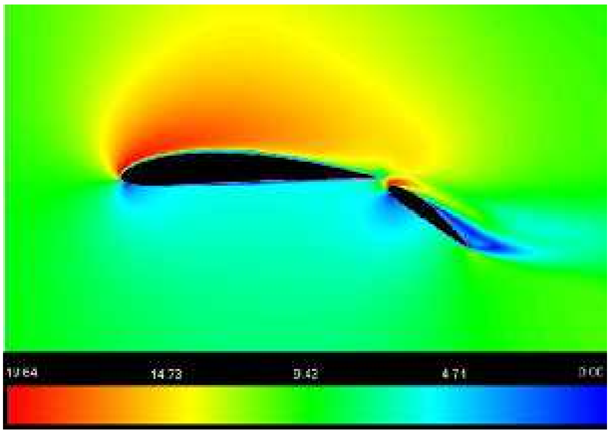

Fig. 3 AOA = 0 °, velocity contours (m / s) without discharge

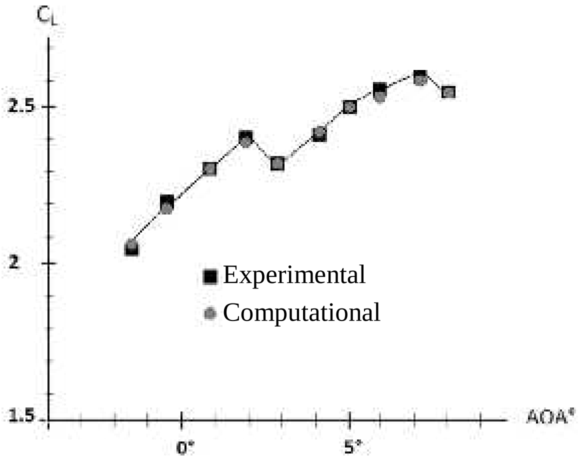

Fig . 4 Experimental and computational lift coefficients C_L

B. FLOWS WITH CORONA DISCHARGES

The simulated distribution of the electric potential obtained by equation (16) is shown in fig. 5 , the areas adjacent the electrodes show a strong variation of the electric potential , while the potential of the inter electrode region is substantially uniform , these observations confirm the characteristics of corona discharges, and our hypothesis concerning the constancy of the charge density α of the inter-electrode area ionized medium.

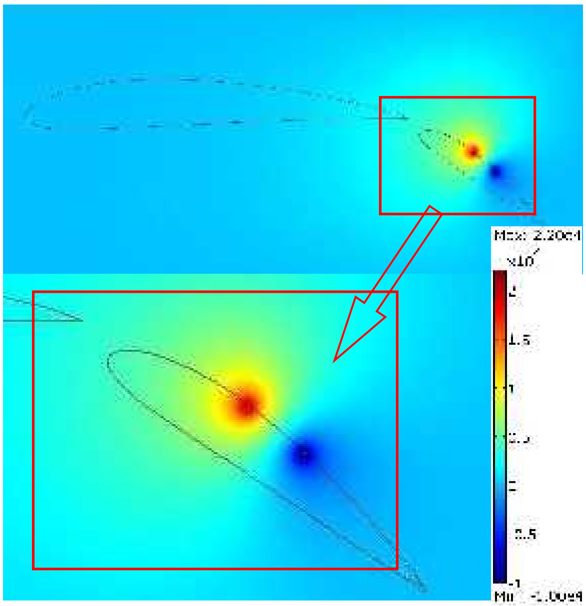

Fig. 5 Simulated contours of the electric potential (V) in the System

Fig. 6 displays the acceleration of the boundary layer profiles on three positions (P1: after the anode, P2: 5 cm after the anode, P3: 1 cm after the cathode see fig. 1) consequence of the discharges:

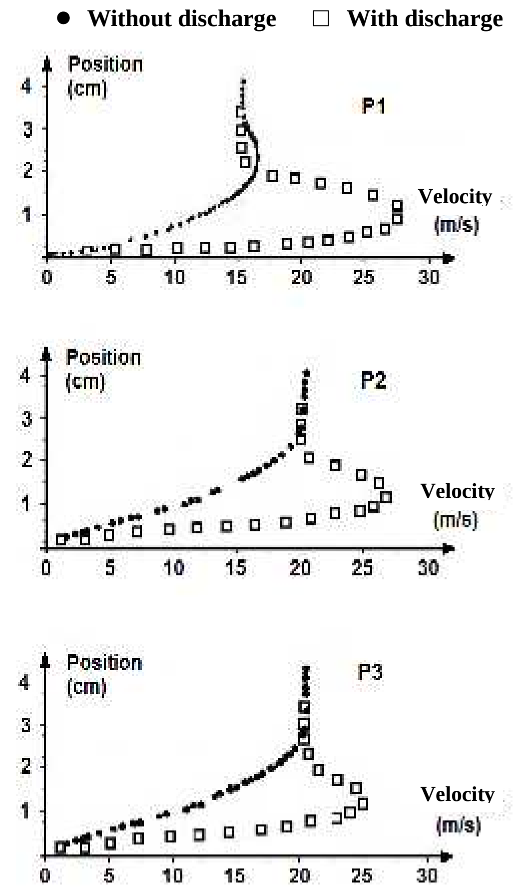

Fig . 6 Acceleration of the hydrodynamic boundary layers in P1, P2 and P3, after the application of corona discharges

The application of the discharges improve the lift coefficients according to the variation of the angles of attack , a relatively small effect is computed for the angles less than 1.8° and greater than 6°. The effect of the discharges between these two extremes is important, the maximum computed for the AOA = 2.8° where the lift coefficient is increased by 17.4 % these results are shown in fig. 7:

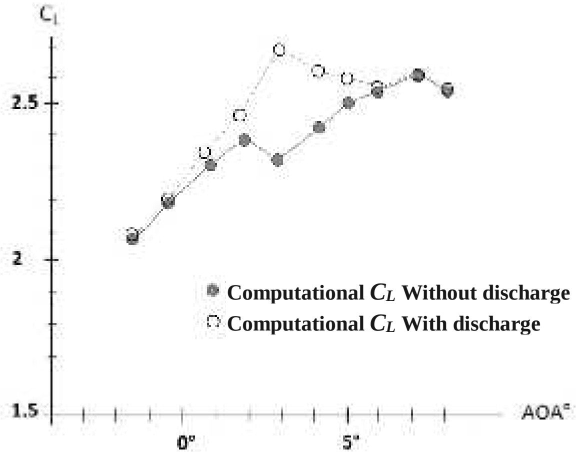

Fig . 7 Lift coefficients C_L with and without discharges

The simulation of a 32 KV corona discharge delay the separation of the boundary layer to AOA = 2.8 ° therefore an increase of 1 °, fig. 8 shows this case of flow before the discharge where the flow separates from the surface of the flap , fig. 9 shows the flow attached after the plasma actuation:

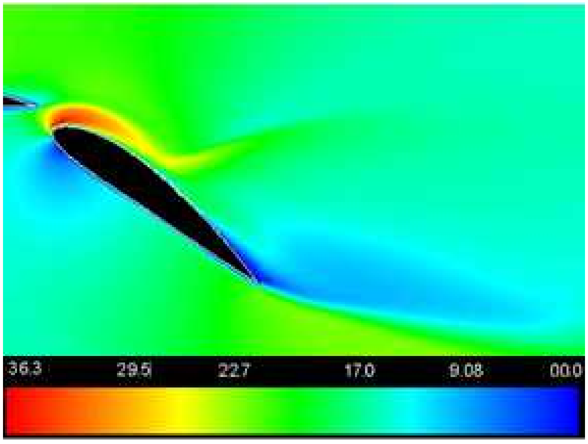

Fig. 8 AOA=2.8°, Velocity contours (m/s) without discharge

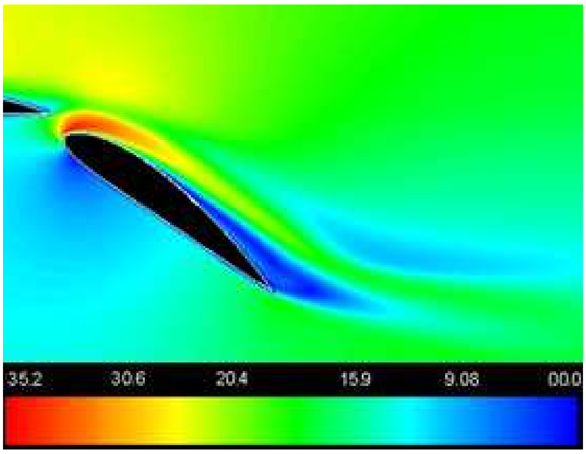

Fig. 9 AOA=2.8°, Velocity contours (m/s) with discharge.

4. CONCLUSION

A validated computational model of electro hydrodynamic effects of corona discharges on turbulent air flows, which depends on the charge density α (assumed constant) of the plasma, and the electric potential of the discharges, was used to numerically study the effects of corona discharges on the lift coefficients of a high-lift configuration. We showed that the simulation of corona discharges produced on the flap significantly increase the lift coefficients C_L on a range of angles of attack, up to 17.4%, the point of separation of the boundary layer is also delayed by 1°.

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