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Plasma Actuator Influence on Air Flow

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Abstract: There is growing interest in the use of plasma discharges for control of aerodynamic flows in a variety of speed regimes. A particular class of such discharges called "surface plasma actuators" is used to modify the flow field in the immediate vicinity of a wall boundary. The principal advantage offered by these actuators is the ability to switch them on and off at very high rates. A number of recent studies have demonstrated plasma actuation of flows at low speeds as well as at high speeds, using different surface plasma.
Plasma actuation is physically achieved through basic mechanisms: rapid gas heating of the flow due to the plasma, electrostatic forcing owing to charged species responding to the imposed electric fields in the discharge.
The frame of this paper is to present the interest of using numerical simulation to investigate the multi-physics approach of plasma actuator.

Keywords: Aerodynamics, plasma, discharge, 2D

1. Introduction

The lift performance of an airfoil, as the angle of attack increases, is limited by the ability to maintain the boundary layer attachment to the suction surface. When the chord wise pressure gradient becomes sufficiently large, the boundary layer looses its momentum and separates from the surface. A method consist to the used of a plasma to impart momentum to the boundary layer.1-6 It has been successfully employed for boundary layer separation control in airfoils and turbine blades.2-5 It is called a plasma actuator and is effective in increasing lift and lowering drag.4 The method consists of generating a plasma (ionized gas) in the boundary layer which is in danger of separation. The ions and electrons accelerate in the electric field used to generate the plasma and then impart their momentum to the air molecules through collisions. The plasma, therefore, acts as a momentum source to the boundary layer allowing it to remain attached throughout a larger portion of the airfoil.
The plasma actuator consists of two long conducting (metal) strips placed parallel to each other. (see figure 1) The two strips act as electrodes and are arranged with a horizontal offset from each other. The lower electrode is covered with a dielectric while the upper electrode is exposed to the flow. An alternating voltage is applied across the electrodes resulting in the generation of plasma in the vicinity of the electrodes. The voltage difference applied between the electrodes can vary from 1 kV to as high as 5 kV. The frequency of the driving voltage is typically from 1 to 10 kHz.

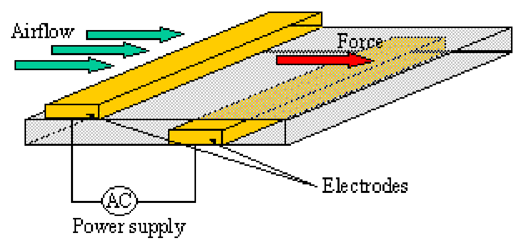

figure 1: plasma actuator configuration

Simulation of the plasma was accomplished using 2 different approaches. The first one is a macroscopic approach in which we are considering only one gas that thermodynamics properties are depending of temperature, pressure and electric field. This model is limiting the number of equations that has to be solved with Comsol and enables to see the influence of the actuator on air flow and thus on drag. The second approach is focused on the discharge area. For modeling a Dielectric Barrier at atmospheric pressure we use a 2 dimensional fluid model [2]. In this kind of model we assume that the plasma species form a continuum in equilibrium with the electric field. The different species present in the plasma, such as electrons, ions and neutrals are described by balance equations (based on conservation laws) and flux equations of diffusion and migration in the electric field. For the electrons an energy balance equation is also solved. The electric field is calculated using the Poisson equation.

2. Macroscopic model

2.1 Computational model

The first approach is to consider only one gas with thermodynamics properties depending of temperature, pressure and electric field [1]. Equations that have to be solved are:

$$\rho\frac{\partial\vec{u}}{\partial t}+\rho\vec{u}\circ\overrightarrow{\nabla u}=\vec{\nabla}\circ[-p\vec{I}+\eta(\overrightarrow{\nabla u}+(\overrightarrow{\nabla u})^{T})]+\vec{F}$$

$$-\vec{\nabla}\circ d(\sigma\overrightarrow{\nabla V}-\vec{J^{e}})=dQ_{j}$$

$$\delta_{ts}\rho C_{p}\frac{\partial T}{\partial t}+\vec{\nabla}\circ(-k\overrightarrow{\nabla T})=Q-\rho C_{p}\vec{u}\circ\overrightarrow{\nabla T}$$

Where:

ρ is the mass density, [kg/m^3]
u is the velocity, [m/s]
p is the pressure, (Pa)
η is the dynamic viscosity, [Pa.s]
F is the force created by the actuator, [N/ m^3]
σ is the electric conductivity, [S/m]
V is the electric potential, [V]
$\mathbf{J}^{\mathbf{e}}$ is the external curent density, [A/ m^2]
C_p is the heat capacity, [J/(kg.K)]
T is the température, [K]
k is the thermal conductivity, [W/(m.K)]
and Q is the heat source given by the ohm law, [W/m^3]

Because the local thermodynamic equilibrium is assumed, this modeling can be used only for low velocity flow.

2.1 Computational results

To see the influence of the plasma on the flow close to the surface, we have solved the problem in an easy geometry. We consider a flow parallel to a surface where a discharge is created.

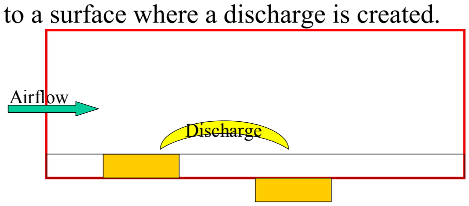

figure 2: macroscopic model configuration

The result (figure 3) of the discharge is an increase of velocity close to the discharge area. Results obtained are in agreement with experimental measurements.

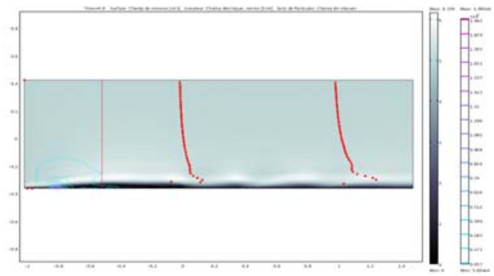

figure 3: results in a simple case

figure 4 is presenting results (pressure) that we have obtained by applying a plasma on a cylinder. Here also, results are in good agreement with experimental measurements [4] and show that plasma can be used to decrease drag.

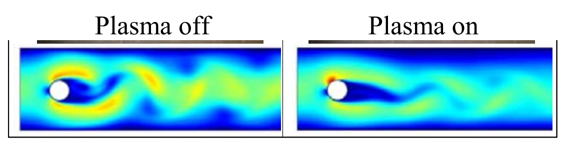

figure 4: plasma actuator action around a cylinder

3. DBD modeling

3.1 Computational model

Figure 1 shows schematic of an asymmetric single dielectric barrier plasma actuator. It consists of two electrodes separated by a dielectric. The upper electrode is exposed to the free stream flow while the lower electrode is placed underneath the dielectric. For most of the cases presented here, unless otherwise specified, these two electrodes overlap horizontally with each other.

The drift-diffusion form of continuity and Poisson's equations for the electrons and ions are solved as described together with the following fluid momentum and continuity equations:

$$\frac{\partial n_e}{\partial t}+\vec{\nabla}\circ[-n_e\mu_e\vec{E}-D_e\overrightarrow{\nabla n_e}]=n_e\nu_i-rn_en_i$$

$$\frac{\partial n_i}{\partial t}+\vec{\nabla}\circ[n_i\mu_i\vec{E}-D_i\overrightarrow{\nabla n_i}]=n_e\nu_i-rn_en_i$$

$$\vec{\nabla}\circ(\epsilon\,\vec{E})=\frac{e}{\epsilon_0}(n_i-n_e)$$

where :

n_e and n_i are electron and ions density [1/m^3]

μ_e et μ_i are electro and ion mobility, [m^2/(s.V)]

E is the electric field [V/ m]

D_e et D_i are diffusion coefficients

ν_i is the ionization frequency, [1/s]

r is the recombination rate, [m^3/s]

ε_0 is the vacuum permitivity [F/m]

ε is the relative permittivity

and e electron charge, [C]

The influence of the discharge on the airflow is calculated using the following equations:

$$\rho\frac{\partial \mathbf{u}}{\partial t}-\nabla(\eta\nabla\mathbf{u})+\rho(\mathbf{u}.\nabla)\mathbf{u}+\nabla p=e(n_e-n_i)\nabla\phi\ ,$$

$$\frac{\partial\rho}{\partial t}+\nabla(\rho\mathbf{u})=0\ .$$

3.1 Computational results

The region simulated is 10 cm long and 5 cm high (figure 5). The lower part of the domain consists of a 0.1 cm thick insulator. The thickness of the electrodes is assumed to be infinitesimally small. The rf electrode extends from x=0.3 cm to x=1.5 cm at y=0.1 cm, the grounded electrode is from 1.48 cm to 2.75 cm at y=0, with a 0.02 cm overlap between electrodes along the x-axis. The embedded electrode is grounded and an impulsion voltage is applied to the exposed electrode. The frequency of excitation is fixed at f =5 kHz.

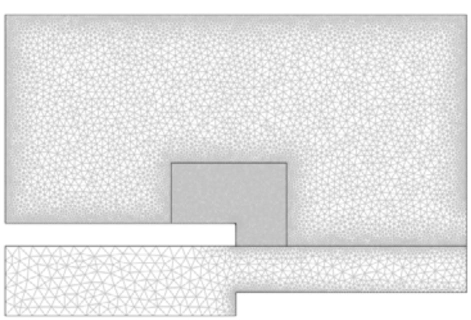

figure 5: mesh used for the microscopic model

Figure 6 is representing results that we have obtained at 60 ns after one impulsion. Color is representing the ions density and arrows are the force acting on the flow done by the expression:

$$e(n_e-n_i)\nabla\phi$$

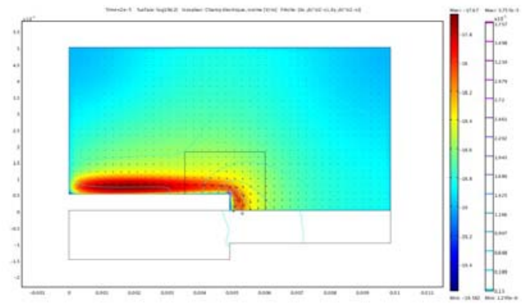

figure 6: Microscopic model results

The EHD (ElectroHydroDynamic) force exerted on the gas molecules in a dielectric barrier discharge has been studied with the help of a 2D fluid model of the discharge at atmospheric pressure. The goal was to identify the basic mechanisms and the order of magnitude of the EHD force. This force is significant only in the sheath of the surface discharge which propagates along the dielectric surface when
the cathode is below the dielectric layer. The principle of the EHD force in a DBD is due to the ion wind that exists in the non-neutral

7. Conclusions

The following paper is showing that plasma actuators can be modeled using Comsol. It is the first step to understand phenomena responsible to the airflow actuation.
Next step is to solve navier-stockes equations taken into account the microscopic model with a more complex geometry and used Sogeti HT knowledge in optimization to have a more efficient system.

8. References

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9. Acknowledgements

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