Modeling Dielectric Barrier Discharge plasma actuators to be used for active flow control

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Abstract


Utöver simuleringen har praktiska experiment gjorts för att förstå effekten från en plasma aktuator bättre. Dessa experiment består av hur en plasma aktuator förändrar luftströmmen över en vinge som redan tappat sin lyftkraft och av att mäta vilken hastighet luften kan nå på grund av en plasma aktuator.

Sammanfattnignen är att mer arbete behöver göras för att effektivisera en plasma aktuator om den ska användas för flödeskontrol. Detta arbeta är ett steg i att förstå hur plasma aktuatorer fungerar vilket i förlängningen kommer leda till hur man ska använda en plasma aktuator på bästa sätt.

This Master Thesis work cover the simulation of the movement of charged species exposed to a high gradient electric field, the same environment a plasma actuator produces. The final goal is to use the plasma actuator as an active flow control device to decrease the drag of a body moving in air. This report describes how the problem was set up in COMSOL Multiphysics and the resulting volume force achieved. The volume force is the force generated by the plasma actuator that is acting on the air.

To understand the effect of a plasma actuator better experimental work was also performed. The experimental work include what effect a plasma actuator has on a wing that has stalled out and measuring the air velocity obtained from a single plasma actuator.

The conclusion is that more work has to be performed to make the plasma actuator a more effective flow control device. This type of work is a way to understand how plasma actuators work and in extension will lead to how a plasma actuator will be used effectively.
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Chapter 1

Introduction

1.1 Scope

In a world were energy efficiency is more and more important for every passing day the need to reduce fossil fuels is of great importance. There are many areas were improvements can be made, one of these areas is the transport area. One way to increase energy efficiency in transport is to reduce drag on vehicles. A reduction of drag on vehicles can be obtained by optimizing the flow around it. To optimize for every situation there is a need for an active flow control, that can change depending the situation. An example of such a situation is cross wind on a vehicle, this creates an asymmetric flow which is unwanted and inefficient. Vernet has done some research on how to use plasma actuators on semi-trucks [1], where Vernet looks at a way to reduce the extra drag created by cross wind. The plasma actuators are used to re-energize the flow around the truck a-pillar. This report is going to focus applying plasma actuators on airplane wings. Airplane wings are widely different than semi-trucks, so the application of active flow control is different. The goal is the same as for semi-trucks: optimizing the flow.

Today most airplanes use some kind of passive flow control, for example vortex generators. Vortex generators are effective but intrusive and ”always on”, this means that they are always creating drag even though they are not needed throughout the whole flight. Thus using active flow control drag can be reduced during flight where said flow control is no longer needed. One of the advantages of using a plasma actuator as the active flow control is that in contains no moving parts and is non-intrusive even when activated. A disadvantage today is the lack of knowledge on how to best apply plasma actuators and how to improve the the effective range of operation. The work in this report will focus on a simulation of the movement of electrons and protons when influenced by an electric field that typically would be found in a plasma actuator. Some practical experiments using particle image velocimetry (PIV) for a stationary case and a small wind tunnel for the flow around a wing profile were performed. The practical experiments were mostly made to aid in the understanding of how to create a plasma actuator and the physics behind it.
1.2 Theory

1.2.1 The Plasma Actuator

The plasma actuator to be modeled consist of an exposed electrode, a covered electrode and a dielectric layer separating the electrodes and can be seen illustrated in figure 1.1 below. This is a plasma actuator called a dielectric barrier discharge actuator, DBD-actuator for short. A high frequency and high voltage AC is supplied to the electrodes, the function of the sinus wave is to generate the plasma and to apply a body force onto the gas [2]. When the electric field between the two electrodes surpasses the breakdown value for the gas the ionization of the gas is started. The plasma is not constant at anytime, it changes with the concentration of electrons and ions which depend on ionization, detachment, attachment and recombination processes that occurs [3].

![Figure 1.1: An illustration of the plasma actuator, showing the position och components. Not to scale.](image)

1.2.2 Governing equations

The plasma discharge model used in this report is described by a combination of Poisson’s equation to describe the electric field and a drift-diffusion equation to describe the density of the ions and electrons [4]. Poisson’s equation is

\[ \nabla^2 \phi = \frac{\rho}{\varepsilon_0 \varepsilon_r} \]  

(1.1)
where $\phi$ is the electric potential, $\rho$ the total volume charge density, $\varepsilon_0$ is the permittivity of free space and $\varepsilon_r$ is the relative permittivity of the medium. The corresponding electric field is defined as

$$\nabla \phi = -\vec{E}. \quad (1.2)$$

The drift-diffusion equations describing the densities of ions and electrons are defined by

$$\frac{\partial n_e}{\partial t} - \nabla \cdot (n_e \mu_e \vec{E} - D_e \nabla n_e) = R_e \quad (1.3)$$

$$\frac{\partial n_i}{\partial t} - \nabla \cdot (n_i \mu_i \vec{E} + D_i \nabla n_e) = R_i \quad (1.4)$$

for electrons and ions respectively. In the two equations above $n_e$ and $n_i$ are the number densities for electrons and ions, $\mu_e$ and $\mu_i$ are the mobility coefficients for electrons and ions, $D_e$ and $D_i$ are the diffusion coefficients for electrons and ions. $R_e$ and $R_i$ are reaction terms defining production and depletion of the charged species.

The reaction terms, $R_e$ and $R_i$, are defined by Che and co-authors [4] to be

$$R_e = \alpha(\vec{E})|\Gamma_e| - \beta n_i n_e \quad (1.5)$$

$$R_i = \alpha(\vec{E})|\Gamma_e| - \beta n_i n_e \quad (1.6)$$

where $\beta$ is the recombination coefficient, $\alpha(\vec{E})$ is the ionization coefficient and $\Gamma_e$ is the electron flux. $\alpha(\vec{E})$ and $\Gamma_e$ are defined by the equations below.

$$\alpha(\vec{E}) = Ap \exp \left( \frac{B}{E/p} \right) \quad (1.7)$$

where $p$ is the pressure and $A$ and $B$ are given coefficients.

$$\Gamma_e = -D_e \nabla n_e - \mu_e n_e \vec{E} \quad (1.8)$$

where $D_e$ is the electron diffusion coefficient and $\mu_e$ is the electron mobility coefficient. The definitions for the different coefficients used in this report are specified later in the simulation section.

According to [4] the body force acting on a neutral fluid can be described as

$$\vec{f} = \sigma e n_i \vec{E} \quad (1.9)$$

where $\sigma$ is an efficiency factor, for fluid calculations the body force $\vec{f}$ is included in the Navier-Stokes equations. The Navier-Stokes equations will not be used in the simulation preformed in this report. It is included to get a understanding of the connection between the charged particles created through ionization and fluid flow.

The above mentioned equations are simplified to only consider electrons and protons with a charge of $\pm 1$. In reality there are plenty more possibilities to consider. When you excite normal air to begin the ionization process more
than one electron can leave excited molecule giving a different charge than ±1. To calculate the exact excitation and to achieve a more accurate estimation of the charge all the different excitation possibilities needs to be considered for all molecules and particles involved. Therefore \( n_e \) and \( n_i \) should be \( n_m \) where \( m \) is all the different reactions and combinations that can occur, to solve the whole problem describing all the different stiff differential equations.

### 1.2.3 Boundary Conditions

The most important boundary is the one between the dielectric material and the plasma itself. The dielectric layer acts as an insulator limiting the charge current transported by the micro-discharges [3], this is described by applying a local surface charge on the dielectric boundary. Here the surface charge, \( \rho_s \) is defined as

\[
\vec{n} \cdot (D_d - D_p) = \rho_s \tag{1.10}
\]

where \( D_d - D_p \) is the difference in electric displacement between the plasma and the dielectric material. Equation 1.10 is derived from Gauss’s law for the dielectric displacement and equation 1.2. For the simulations, described in the next section, the surface charge is described as

\[
\frac{\partial \rho_s}{\partial t} = (\Gamma_e - \Gamma_i) \tag{1.11}
\]

where \( \Gamma_e \) and \( \Gamma_i \) are the fluxes of electrons and ions through the surface and \( \vec{n} \) is the normal direction. \( \Gamma_e \) is described by equation 1.8 and \( \Gamma_i \) is defined as

\[
\Gamma_i = -D_i \nabla n_i + \mu_i n_i \vec{E} \tag{1.12}
\]

here \( D_i \) is the ion diffusion coefficient, \( \mu_i \) is the ion mobility coefficient and \( n_i \) is the ion number density.

For the exposed electrode the applied voltage is described by a sinusoidal function of a reference voltage, \( \phi_{ref} \), a frequency, \( \omega \) and the time, as can be seen in the equation below.

\[
\phi(t) = \phi_{ref} \cdot \sin(\omega t) \tag{1.13}
\]

The particle densities on the exposed electrode depend on \( \phi(t) \) and they are defined by the equations below.

\[
\begin{align*}
\frac{\partial n_e}{\partial t} &= 0 & \phi(t) > 0 \\
n_e &= 0 & \phi(t) < 0
\end{align*}
\tag{1.14}
\]

\[
\begin{align*}
n_i &= 0 & \phi(t) > 0 \\
\frac{\partial n_i}{\partial t} &= 0 & \phi(t) < 0
\end{align*}
\tag{1.15}
\]

Similarly for the dielectric surface, the particle densities are defined by

\[
\begin{align*}
n_e &= 0 & \phi(t) > 0 \\
\frac{\partial n_e}{\partial t} &= 0 & \phi(t) < 0
\end{align*}
\tag{1.16}
\]
on the dielectric surface the condition defined in equation 1.11 is also applied at all values of \(\phi(t)\). The covered electrode is defined as an electric ground point for all times.

### 1.2.4 Initial conditions

The number of electrons and ions in the reaction area is set to be equal in number to simulate a quasi-neutral gas. This quasi-neutrality is set to simplify the problem and remove the first ionization step of the true problem. The electric potential on the exposed electrode is set to zero.
Chapter 2

COMSOL simulation

2.1 Method

The simulations in COMSOL were made by using three built in modules, the transport of diluted species module, the electrostatic module and a boundary ODE. These are applied to a two dimensional geometry containing a asymmetrical DBD-actuator and a small area where the particle movement is calculated. The governing equations are as mentioned above in section 1.2.

However, due to the complexity of the numerical problem [5][6] and how computationally heavy these calculations are some modifications and simplifications have been made. First off only two particle species are included in the simulations, the electrons and the protons. Secondly the boundary condition between air and electrode, air and dielectric material, as well as how these boundaries change with the supplied voltage. On the dielectric area there is also a surface charge condition to simulate the accumulation of charged particles. Thirdly the initial condition is set to be quasi-neutral plasma with the same amount of electrons and protons available in the simulated area.

2.1.1 Geometry

The problem is simulated over a small area, the effective area of the plasma is very close to the electrodes. As seen in figure 1.1 the plasma is situated above the covered electrode. For the COMSOL simulations the rectangular area has a width of 3.5 cm and a total height of 1.2 cm, as can be seen in figure 2.1 below. The total area of simulation is 4.2 cm². The exposed electrode is 0.5 cm wide and is positioned above the dielectric material, the covered electrode is 1 cm wide and positioned at the bottom of the dielectric material. Both electrodes are 0.07 mm thick and the dielectric area between them is 0.2 cm thick resulting in that the electrodes are only separated by 0.193 cm in the y-direction. There is no overlap of the electrodes in the x-direction. To prevent extreme points (points of “singularity”), figure 2.2, in the simulation fillets with a radius of 0.035 mm were applied to the exposed electrode.
Figure 2.1: The simulation area in COMSOL, the total height is 1.2 cm and a total width of 3.5 cm.

Figure 2.2: A zoomed image of the fillets on the exposed electrode, a similar fillet is present on the other end of the electrode.
2.1.2 Mesh

When creating the mesh COMSOL’s built in triangular meshing was used. Even when using the finest predefined general physics meshing setting the mesh was too coarse for a good result. Instead the maximum and minimum element sizes were adjusted and extra refinements where introduced to critical areas. One of the refinements was to refine the whole length of the boundary between the air and the lower wall. This area is important for the accumulated charge along the wall and how the effect of the charge expands into the air. The other refinement was over and around the exposed electrode. The electrode is the source of the electric field and charged particles (mainly electrodes) and it is critical that the parameter growth between two element points is low enough to get proper distribution in this area.

The final mesh can be seen in figure 2.3, as well as a zoomed image of the mesh close to the exposed electrode in figure 2.4. Even in the zoomed image the finest mesh is hard to distinguish. When inspecting the statistics of the meshing it is found to have a very good quality, the average element quality is 0.9371 where 1 is the optimal element quality [7].

Figure 2.3: An overview of the applied mesh, the areas with the finest mesh are over the surface area and the two electrodes.
Using a fine mesh results in a longer computational time, but a more accurate calculation. Thus when applying the mesh a consideration has to be made, what is of most importance, the quality or the computation time. First some courser mesh was used to quickly confirm the simulations and thereafter the mesh quality was increased to achieve the best simulation result possible in a reasonable time frame. In table 2.1.2 below the mesh statistics from the final mesh is found.

Table 2.1: asdfasdf

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>132 215</td>
</tr>
<tr>
<td>Number of degrees of freedom</td>
<td>343 343</td>
</tr>
<tr>
<td>Maximum element size</td>
<td>0.001 [m]</td>
</tr>
<tr>
<td>Minimum element size</td>
<td>8e-6 [m]</td>
</tr>
<tr>
<td>Minimum element quality</td>
<td>0.3351</td>
</tr>
<tr>
<td>Average element quality</td>
<td>0.9371</td>
</tr>
</tbody>
</table>

2.2 Simulation setup

When using COMSOL’s built in modules the initial setup of variables and parameters is not as straight forward as it would seem. Some identification of variables
in the equations has to be done, the connection between the different modules has to be identified and the correct unit. In this section the different modules will be described and what equations that are used in each will be presented. The parameters and variables used will also be defined and what conditions were used where will also be presented.

2.2.1 COMSOL Equations

The transport of diluted species module contains the description of the two species, electrons and ions, and how they behave in the simulation. The governing equations for the species movement in the air are

\[
\frac{\partial c_i}{\partial t} + \nabla \cdot (\mathbf{D}_i \nabla c_i - z_i u_{m,i} F c_i \nabla V) + \mathbf{u} \cdot \nabla c_i = R_i \tag{2.1}
\]

\[
\mathbf{N}_i = -\mathbf{D}_i \nabla c_i - z_i u_{m,i} F c_i \nabla V + \mathbf{u} c_i \tag{2.2}
\]

where \(c_i\) is the concentration of the species, \(D_i\) is the diffusion of the species, \(z_i\) is the charge of the species, \(F\) is Faraday’s constant, \(V\) is the voltage, \(\mathbf{u}\) is the velocity field, \(R_i\) is the reactions of the species and \(\mathbf{N}_i\) is the species flux.

The electrostatics module contains the description of voltage and the volume charge is distributed in the simulation area, the governing equations for the electrostatics module are

\[
\nabla \cdot \mathbf{D} = \rho_v \tag{2.3}
\]

\[
\mathbf{E} = -\nabla V \tag{2.4}
\]

where \(\mathbf{D}\) is the electric displacement defined as \(\mathbf{D} = \varepsilon_r \varepsilon_0 \mathbf{E}\). Here \(\varepsilon_0\) is the permittivity of free space and \(\varepsilon_r\) is the relative permittivity of the medium, \(\mathbf{E}\) is the electric field, \(\rho_v\) is the volume charge density and \(V\) is the electric potential.

The boundary ODEs and DAEs module is used to express the surface charge density on the border between the air and the dielectric material. A distributed ordinary differential equation is used, and is is defined as

\[
\frac{\varepsilon_a}{\rho_a} \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} = f
\]

where the mass coefficient, \(\varepsilon_a\), is set to zero, the damping coefficient, \(d_a\), is set to one. Which gives

\[
\frac{\partial u}{\partial t} = f \tag{2.5}
\]

as the equation used for the surface charge. Where the source term, \(f\), is defined as the difference between the flux of electrons and ions and \(u\) is the surface charge.

2.2.2 Initial and boundary conditions

The boundary and initial conditions are as previously described in Section 1.2 and are applied to relevant boundaries in the simulation area.
For the transport of diluted species module only consist of the air part of the simulation area. In this module the exposed electrode is described by equation 1.14 and 1.15. The boundary to the right of exposed electrode, the dielectric surface is described by equations 1.16 and 1.17. The boundary to the left of the exposed electrode and the outer boundaries are set to have zero specie flux. The area bound by the previous mentioned boundaries of the transport module is the air area, in this area the reactions, $R_e$ and $R_i$, occur. Initially an equal amount of electrons and ions are set in this area.

The electrostatics module consist of the entire simulation area. The exposed electrode is described by equation 1.13, the covered electrode is defined as a ground, $\phi(t) = 0$ and the outer boundaries are set to have zero charge. The inner boundary between the air and the dielectric material is defined by COMSOL when setting a relative permittivity to the two areas and applying a surface charge. For air $\varepsilon_{r,a} = 1$ and for the dielectric material $\varepsilon_{r,d} = 3$. The surface charge is defined using the Boundary ODEs and DAEs module and is described by equation . Initially all parts of the electrostatics module are zero.

### 2.2.3 Parameters and variables

For this simulation the parameters for mobility, diffusion and the reaction terms and how to calculate them are from reference [4]. Other sources include the reaction terms, but do not include the mobility and diffusion coefficients. This is due to that these coefficients are not constant in reality they depend on many things, such as the different molecules in the gas, the temperature, pressure, and so on. Hence, this simulation uses simplified coefficients. The applied voltage $\phi(t)$ and the wave frequency $\omega$ are set to somewhat replicate the values used during the experimental part. The applied voltage should ideally be much higher, at least 2 times higher, but at those values the simulation did not converge using the computer available. The electron and ion mobility coefficients are calculated from the following equations

\[
\mu_e = \frac{5600}{P} \quad (2.6)
\]

and

\[
\mu_i = \frac{30.4}{P} \quad (2.7)
\]

with the unit $m^2 V^{-1} s^{-1}$. The diffusion coefficients used are calculated according to the equations below from temperature and mobility coefficients

\[
D_e = \frac{T_e}{e} \mu_e \quad (2.8)
\]

\[
D_i = \frac{T_i}{e} \mu_i \quad (2.9)
\]

The local pressure used in equation 2.6 and 2.7 is calculated by

\[
P = \frac{P_0 T}{T_0} \quad (2.10)
\]
The temperatures, $T_e$, $T_i$, and $T$, the constant used for the mobility coefficients, $\mu_e$ and $\mu_i$, are from reference [4] as well as the equations used to calculate said parameters.

Table 2.2: A table of the values used for the different parameters and variables that are specified before the simulation begins.

<table>
<thead>
<tr>
<th>Set parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elementary charge</td>
<td>$e$</td>
<td>$1.6 \cdot 10^{-19}$</td>
<td>$[C]$</td>
</tr>
<tr>
<td>Epsilon zero</td>
<td>$\varepsilon_0$</td>
<td>$8.854 \cdot 10^{-12}$</td>
<td>$[F/m]$</td>
</tr>
<tr>
<td>Dielectric Epsilon</td>
<td>$\varepsilon_{r,d}$</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Air Epsilon</td>
<td>$\varepsilon_{r,a}$</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Temperature</td>
<td>$T_0$</td>
<td>293</td>
<td>$[K]$</td>
</tr>
<tr>
<td>Local Temperature</td>
<td>$T$</td>
<td>300</td>
<td>$[K]$</td>
</tr>
<tr>
<td>Electron Temperature</td>
<td>$T_e$</td>
<td>1</td>
<td>$[eV]$</td>
</tr>
<tr>
<td>Ion Temperature</td>
<td>$T_i$</td>
<td>0.026</td>
<td>$[eV]$</td>
</tr>
<tr>
<td>Pressure</td>
<td>$P_0$</td>
<td>$1.0133 \cdot 10^6$</td>
<td>$[Pa]$</td>
</tr>
<tr>
<td>Number of initial electrons/ions</td>
<td>$n_{o,e,i}$</td>
<td>$1 \cdot 10^{10}$</td>
<td>$[1/m^3]$</td>
</tr>
<tr>
<td>Voltage</td>
<td>$V_{ref, \Phi_{ref}}$</td>
<td>2500</td>
<td>$[V]$</td>
</tr>
<tr>
<td>Omega</td>
<td>$\omega$</td>
<td>50265</td>
<td>$[rad/s]$</td>
</tr>
<tr>
<td>Beta</td>
<td>$\beta$</td>
<td>$2 \cdot 10^{-13}$</td>
<td>$[m^3/s]$</td>
</tr>
<tr>
<td>$A$</td>
<td></td>
<td>10.95</td>
<td>$[s^2/kg]$</td>
</tr>
<tr>
<td>$B$</td>
<td></td>
<td>273.75</td>
<td>$[m^2/(sA)]$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculated parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron mobility</td>
<td>$\mu_e$</td>
<td>0.056588</td>
<td>$[m^2/(V s)]$</td>
</tr>
<tr>
<td>Ion mobility</td>
<td>$\mu_i$</td>
<td>$3.0719 \cdot 10^{-4}$</td>
<td>$[m^2/(V s)]$</td>
</tr>
<tr>
<td>Local Pressure</td>
<td>$P$</td>
<td>98961</td>
<td>$[Pa]$</td>
</tr>
<tr>
<td>Electron diffusion</td>
<td>$D_e$</td>
<td>$0.056665$</td>
<td>$[m^2/s]$</td>
</tr>
<tr>
<td>Ion diffusion</td>
<td>$D_i$</td>
<td>$7.9979 \cdot 10^{-8}$</td>
<td>$[m^2/s]$</td>
</tr>
</tbody>
</table>

### 2.2.4 Study and solver setup

The simulation is solved using one of the built-in time-dependent solvers, for two periods of the applied voltage sinus wave. The frequency, is $\omega = 50265 \ [rad/s]$, or $\omega = 8000 \ [Hz]$, giving a period of 0.000125 seconds, or 125 $\mu$s, according to equation 2.11 below.

$$T = \frac{1}{\omega} = \frac{1}{8000} = 0.000125$$

Where $T$ is the time of one period and $\omega$ is the frequency of the sinus wave. The time range of the simulation is thus $2T = 250 \mu$s. By simulating over more than one period the second period indicates how the problem behaves when the volume charge is non-neutral, as it is at initialization.
The solver used for this simulation is the MUMPS-solver. MUMPS is short for Multifrontal massively parallel sparse direct solver, which implements the multifrontal method a variant of the Gaussian elimination method. The time stepping method used by the solver is a free step backward differentiation formula, BDF for short, with a maximum order of 5 and minimum order of 1. For the solver the relative tolerance, absolute tolerance and the event tolerance is set to 0.001. A backward Euler consistent initialization is used. Most of the settings are the default settings, some parameters have been changed or mixtured with to obtain a converging result.

2.3 Results

2.3.1 Electric field and voltage distribution

The movement of the charged species behaved as expected, when the exposed electrode had a positive voltage the ions moved away from it and the electrons moved towards it. Due to the surface charge on the dielectric material to the right of the exposed electrode the behaviour changed for the charged species and the electric field during the simulation. As the charged species movement depend on the electric field distribution the voltage and electric field is described first. At \( t = 0 \) there is no electric field present, but at \( t = 125 \mu s \) the electric field looks in figure 2.5. For the electric field plots, figures 2.5 - 2.7, the electric field is described by the black lines and the voltages are described by the different colors. The green color indicates zero voltage, the dark red color a positive voltage and the blue dark color indicates a negative voltage. The covered electrode is the ground and is therefore always zero in the simulation. The electric field is stronger if the black lines (electric field lines) are closer together and weaker if they are further apart.

![Figure 2.5: The voltage distribution and electric field at \( t = 125 \mu s \) after one period.](image)
There is also a difference in the electric field for the maximum applied voltage times, \( t = 31.75\mu s \) and \( t = 156.25\mu s \). The electric field lines are perpendicular to the dielectric surface a longer distance during the second period compared to the first period, see figure 2.6 for the first period max voltage and figure 2.7 for the second period max voltage.

![Figure 2.6](image1.png)

**Figure 2.6:** The voltage distribution and electric field at \( t = 31.75\mu s \) during the positive voltage peak of the first period.

![Figure 2.7](image2.png)

**Figure 2.7:** The voltage distribution and electric field at \( t = 156.25\mu s \) during the positive voltage peak of the second period.

When the voltage applied to the exposed electrode is negative the electric field in the area is very weak, see figure 2.8. These distributions are similar for both periods of the sinus voltage wave.
For all times the electric field strength is larger inside the dielectric material than in the air or gas above it. The unsymmetrical geometry and the difference of relative permittivity together with the surface charge contributes to how the electric field changes during the two periods.

\subsection*{2.3.2 Charged species movement}

When looking at the movement and distribution of the charged species the most important value for the end result is the volume charge, as this directly applies to the volume force which is the driving motion of the air or gas. However the individual movement of electrons and positively charge particles is important to follow to ensure that they move in a correct fashion as this is an indicator of if the equations and parameters are correctly applied in the simulation.

The plots describing the electron and ion distributions, figure 2.10 to 2.15, below are snapshots at times where there are clear areas with either electrons or ions. Said figures are in chronological order and the times are plotted in figure 2.9 to indicate at what part of the period the figure is from, the maximum and minimum points are also included in the figure.
Figure 2.9: An image of at what times the species distribution plots are taken at. The Amplitude of the sinus wave is normalized to one.

Figures 2.10 and 2.13 show where the ions are positioned when the voltage is at or going towards the maximum voltage peak. The ions depend on the electrons, equation 1.6, the ions are created at close to the exposed electrode where there is a high concentration of electrons. As they are created they move away from the positive voltage of the exposed electrode. During the second period, figure 2.13, the process is more diffuse. The electrons at the same times are very close to the exposed electrode and when plotted they are only seen if zoomed in very close proximity to the surface of the electrode.

Figures 2.12 and 2.14 show the distribution of electrons close the negative peaks. During the first peak the electrons are gathered in a clump far away from the exposed electrode, but during the second negative peak the electrons are spread out more even along the dielectric surface. Another thing seen is that in the first figure 2.12 is slightly after the negative peak so that the direction of the electric field is changing and the electrons are starting to move towards the exposed electrode.

The difference in electron distribution can also be seen in the ion distribution at times $t = 77\mu s$ and $t = 226\mu s$, see figures 2.11 and 2.15. In these figures the ions seen are created through reactions with electrons, after they are created they start moving towards the exposed electrode with a negative voltage.

The concentration of ions is always largest where the concentration of electrons is largest, but the ions and electrons move differently in the electric field, equations 1.8 and 1.12. As mentioned the surface charge affect the electric field and thus affect the movement of the ions and electrons. The charged species move perpendicular to the electric field lines, thus a longer distance with perpendicular electric field lines along the dielectric surface increases the wanted effect of the plasma actuator.
Figure 2.10: The concentration plot of ions at $t = 17\mu s$.

Figure 2.11: The concentration plot of ions at $t = 77\mu s$. 
Figure 2.12: The concentration plot of electrons at $t = 97\mu s$.

Figure 2.13: The concentration plot of ions at $t = 152\mu s$. 
2.3.3 Volume force

To see how much and in what area the modeled plasma actuator has a direct affect on the neutral gas or air in the surrounding area. The volume force is calculated by taking the volume charge and multiplying it with the electric field. The volume force of interest is the average volume force over the whole time period, thus the average volume force is multiplied with the average electric field. The result can be seen in figure 2.16, this is a quiver plot showing the direction and magnitude of the volume force. This figure is manipulated to accentuate
in what area there is an effect, in the bottom left corner the white area is the exposed electrode. It is clear that the direction is away from the electrode in the positive x-direction.

Figure 2.16: A quiver plot of the volume force due to the simulated plasma actuator.

To highlight the area affected figure 2.17 shows a contour plot of the volume force. The largest magnitude of the volume force from this simulation is:

\[ f = 752 \text{ [N/m}^3\text{]} . \]

Figure 2.17: A contour plot of the mean volume force, illustrating where the effect is the strongest.
2.4 Scope of the problem

The simulation described in this report took 17 hours 27 minutes and 36 seconds to complete, using a home computer with a 3.2 GHz six-core processor, 32 GB of RAM and a SSD as the main hard drive. After the simulation the COMSOL Application File became almost 23.6 GB in size, note that this size is with the mesh and all the results included.

Considering that the simulation area is 4.2 cm\(^2\) and the simulation time-range is 250\(\mu\text{s}\) the computation power needed for such a simulation is very high. Tries were made to simulate a larger time-range, using a different mesh both finer and coarser, a different area both smaller and larger, but the current configuration seemed to be the best combination for the computer used. A too fine mesh resulted in a too large problem size (not enough RAM) and a too coarse mesh resulted in a unsatisfactory simulation result. Changing the simulation area had limited effect, a too small area resulted in a unsatisfactory electric field.

To improve or expand the problem by using a wider time span, higher electrode voltages, including more species, or using less simplifications a more powerful computer is desired. Working with the result file is time consuming even for this simulation.
Chapter 3

Experimental work

The following chapter will contain information about how the experimental work was conducted, as well as a description of the equipment and components used to perform the experimental work. Also a short explanation on why and how these products were used. The experimental work was done as a complement to the simulation, to verify that a plasma actuator works in the intended way. This chapter mostly contains descriptions of the equipment used, but there are some results to show for too.

3.0.1 Electronics

To perform the experimental tasks during the thesis an electrical circuit with specific conditions was needed. According to many previous works [1][2][8][9] on plasma/DBD-actuators a sinusoidal wave is used to drive the actuator. The values for the frequency is in the range of 0.5 - 20kHz and for the output voltage in the range of 1 - 20kV [2]. Orlov [8] states that higher frequencies and voltages are preferred, hence the aim with our electrical circuit is to obtain as large values of both voltage and frequency possible.

The final schematic of the electrical circuit design used is shown in figure 3.1. The DC voltage source is a TENMA 72-10500 and it could deliver 0-30V and 0-3A, this voltage source was connected to a cooling fan through a voltage regulator, L7812/TO22, and also connected to the transformer. To have the correct waveform over the plasma actuator the transformer is also connected to a signal generator, Agilent 33210A, through a MOSFET-transistor, BUZ11, mounted with an extra heat sink and a diode, 1N4007. The transformer used is an ignition coil initially made for the electric system of a car. As an output the transformer produces an alternating current which is connected to the plasma actuator. A small LED-light, Q12P1CXXR12, was added to indicate when the system was on as a safety precaution. To measure voltages to different oscilloscopes were used. A two channel Tektronik TDS 220 was used during the experiments to read and check voltages. During the testing of electrical components a four channel Agilent technologies MSO-X 3054A was used. To read the high voltage a special 1000:1 high voltage probe was connected to the oscilloscope.
Figure 3.1: The final schematics of the electrical circuit used during the experimental work.

An illustrated image of how the Plasma actuator is built is found in figure 3.2. In these experiments the electrodes are 1 cm wide and 10 cm long copper tape strips parted by a 0.2 mm thick Kapton polyimide film layer as the dielectric material. The independent layer thickness of the polyimide film tape was 0.05 mm, thus four layers were used to obtain the total thickness. Figure 3.2 also indicates where on the actuator the plasma field is positioned.
During the testing and configuration of the electrical system and components a decision to keep the alternating frequency set at 8 kHz was made. Due to the limitations of the transformer, the visual plasma was the strongest at this frequency when the system was tested at maximum voltage. Also the waveform was out from the transformer was closest to a pure sinus wave at this frequency. This is due to the recharging and discharging properties of the transformer.

The in house built circuit board with the components were mounted inside a 3D-printed box with Plexiglas sides portrayed in figure 3.3. On the outside of the box the LED-indicator as well as banana plug connections for the input from the signal generator, the input from the DC-voltage source and the output to the transformer. Having all the components in a box allowed for an easy transfer when moving between different places, such as PIV system and wind tunnel. It also minimized to risk of interference from careless handling.
3.1 Wind tunnel

To visually test the effect of a plasma actuator a wind tunnel test was conducted. The test area of the wind tunnel is approximately 30x30x60 cm where a 3d-printed NACA0012 profile was placed. The plasma actuator was placed on 0.25c, where c is the chord length of the wing. The NACA0012 wing profile had a 10 cm chord and a 10 cm width, the mounted plasma actuator was 8 cm long. The wing used in the wind tunnel can be seen in figure 3.4. A smoke machine was used for visualization of the air flow over the wing. During the visualization the wind tunnel was running at approximately 1-2 m/s, a steady flow of smoke was induced 10-20 cm in front of the leading edge. The angle of attack was approximately 15-20 degrees; enough to get a separated/turbulence flow with re-circulation on the wing. No exact angle was measured due to visualization being more important than measurements during this test. The test where filmed using a Gopro camera standing inside the wind tunnel to reduce mirroring in the plexiglas casing. A mobile phone flashlight was used in a darkened room to get a clearer view of the smoke when filming. The setup with the wing, and camera in the wind tunnel test area can be seen in figure 3.5, the smoke was inserted into a small hole in the side panel.
Figure 3.4: The 3D-printed NACA0012 wing profile used in the wind tunnel experiments.

Figure 3.5: The setup during the wind tunnel experimental work.
3.2 PIV

PIV stands for Particle Image Velocimetry and is a method to measure instantaneous velocity fields by using lasers, seeding particles and high speed cameras [10]. The inserted seeding particles need to be small enough so that they faithfully follow the flow of the fluid. These particles can for example be small glass beads, aluminum flakes or oil droplets, what kind of seeding particles used depend on the experiment. The laser or strobe light used to illuminate the seeding particles is pulsed at a short duration that freezes the particles without streaks behind them and with long enough intervals between the pulses to be able to establish the movement of the particles. Some synchronizer is used between the light and camera to get the correct timing between light ant photo. The footage is then analyzed by some PIV-software that calculates the flow field of the fluid.

To perform this experiment an enclosed box with Plexiglas casing was used, as can be seen in figure 3.6. Inside this casing a platform with the plasma actuator was placed together with the transformer directly underneath it. For gaseous flows oil droplets or smoke is the preferred seeding particle, therefore a smoke machine was used as seeding particles. The smoke was inserted into the box and was left to settle a couple of minutes before the PIV measurements begun. Only one or two small puffs from the smoke machine was inserted, this smoke could not be seen when the smoke had settled by the naked eye but was plenty for the PIV measurements to work.

![Figure 3.6: The setup of the PIV experimental work, showing the plexiglas casing, the box with electronics, the signal generator and the PIV high speed camera. Not pictured is the DC-voltage source, the smoke machine and an oscilloscope.](image-url)
The goal of the PIV experiments was to obtain information of the velocities and profiles of the effects from the in-house built DBD actuator. The results are used to see if the simulation has an effect in the right region behind the electrodes. The measurement area was a square area which started behind the exposed electrode and stretched back 5 cm. Some measurements were made with a larger area, 10x10 cm square, these were good to see the initialization movement of the are, but not quite accurate enough close to the wall.

For the PIV experimental work the voltage applied to the exposed electrode was varied from the lowest voltage where a steady uniform plasma was obtained to the maximum voltage the equipment could handle. The lowest peak-to-peak voltage was 5400 volt and the highest peak-to-peak voltage was 15600 volt. Below 5400 volt the plasma created was uneven and unsteady.

3.3 Experimental Results

3.3.1 Wind tunnel

The main goal of the wind tunnel test was to ensure that the plasma actuator performed the designed task, re-energizing turbulent flow. Figures 3.7 and 3.8 show the flow before the plasma actuator is activated. The first figure is a snapshot from a video recording inside the wind tunnel, the turbulent vortexes can be seen clearly here. The second figure is taken with a longer exposure from the outside of the wind tunnel, here no clear vortex is seen.

![Figure 3.7: A snapshot from the video recording of the turbulent flow around the wing profile.](image-url)
Figure 3.8: The turbulent flow seen from the outside, taken with longer exposure time.

Figure 3.9 and 3.10 show the flow after the plasma actuator has been activated and the flow has re-established around the wing profile. As for the before activation pictures the first figure is taken from inside the wind tunnel test area and the second picture from the outside. In both figures it is clear that the plasma actuator re-establishes the flow around the wing profile. The plasma itself is also very clear, it is the purple glowing light situated at 25 percent of the chord. This confirms that the plasma actuator works as predicted beforehand.
Figure 3.9: A snapshot from the video recording of the flow around the wing profile with the plasma actuator activated.

Figure 3.10: The re-established flow seen from the outside, taken with longer exposure time.
3.3.2 PIV
When performing the PIV experimental work a Kapton polyimide film used as dielectric covered the whole area. This resulted in reflections of the laser applied giving inaccurate results close to this boundary. Hence the figures below do not start from \( y = 0 \). The generated plasma from the plasma actuator used can be seen in figure 3.11 below.

![Plasma created for PIV experimental work](image)

Figure 3.11: The plasma created for the PIV experimental work, a more detailed picture is hard to take.

The measured velocity magnitudes for different peak-to-peak voltages are illustrated in figure 3.12 to figure 3.15. For the highest voltage the data is uncertain close to the generated plasma, which means that the maximum velocity stated most likely is inaccurate. However, the plot is included to give a better picture of how the flow changes with a higher voltage. The plasma actuator is positioned at \( x = 0 \) and the generated plasma disturbs the measurement of the particle movement due to the emitted light.
Figure 3.12: The velocity magnitude field for a voltage peak-to-peak of 5400 volt. Max velocity: 0.4 [m/s]

Figure 3.13: The velocity magnitude field for a voltage peak-to-peak of 8400 volt. Max velocity: 1.2 [m/s]
Figure 3.14: The velocity magnitude field for a voltage peak-to-peak of 10200 volt. Max velocity: 2.2 [m/s]

Figure 3.15: The velocity magnitude field for a voltage peak-to-peak of 15600 volt. Max velocity: 4.3 [m/s]

The velocity figure above do not show the direction of the flow, only magnitude of the velocity and where this velocity is reached. The direction of the flow for figure 3.12 can be found in figure 3.16 below. This figure is zoomed in to better show the effect of the plasma actuator. The air moves down towards the plasma and is then pushed away in the positive x-direction.
Figure 3.16: Zoomed in image of the velocity vectors for a voltage peak-to-peak of 5400 volt. To show the direction of the movement due to the plasma actuator.
Chapter 4

Final words

4.1 Conclusion

The performed simulation result describe that the volume force applied onto the neutral gas in its surrounding is in the correct direction. To do a better comparison with experimental work the simulated volume force should be included into the Navier-Stokes equations and from there obtain a velocity to compare with the PIV measurements. The simulation has given a better understanding of how the movement of the charged species is described and the importance of the surface charge that amplifies the wanted effect. However, these simulations are very time-consuming and computationally heavy. They are probably not great at simulating the active actuator together with an external flow due to this.

The practical experiments gave a better understanding of the practical aspects of the plasma actuator usage. There are some limitations that need to be considered to be able to use it to the best effect. The velocities the plasma can generate are limited, and the have a re-energizing effect the introduced velocity from the plasma actuator should ideally be higher than the surrounding flow. If the plasma actuator is applied in the same direction as it was in this work.

Today, to use plasma actuators for active flow control is not recommended. At the current state they are too ineffective for any practical use, but the idea to use similar devices to decrease drag around a body is a great idea.

4.2 Future work

There are several ideas for future work with this subject. The simulations could be re-done with an increased amount of charged species, more accurate reaction terms to see how these parameters effect the result. Simulations could also be performed with variable peak-to-peak voltage and variable voltage frequency to see how the volume force changes with these parameters. If there is no huge performance increase in computational power these things may be hard to simulate in a time effective way. Simulations such as these could perhaps be used to find ways to increase the effectivity of a single plasma actuator.

To simulate how the plasma actuator is most effectively applied to fluid dynamics a faster and simpler model needs to be found, such a model could be
to find the volume force only dependent on the voltage and frequency to reduce computation time.
Bibliography


