NUMERICAL INVESTIGATION ON EFFICIENCY INCREASE IN HIGH ALTITUDE PROPULSION SYSTEMS USING PLASMA ACTUATORS

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Abstract. This paper describes the effects of Plasma actuators for the purpose of efficiency increase of propulsion systems. For solving the 3D steady/unsteady turbulent flows a numerical method based on the finite volume scheme by adopting the two-equation \(k-\omega\) turbulence model is used. Moreover, a body force treatment is devised to model the effect of plasma actuator and link the plasma and fluid dynamics. The body force can be derived from first principles. In order to compute this body force vector, the model solves two additional equations: one for the electric field due to the applied AC voltage at the electrodes; and the other for the charge density representing the ionized air. The numerical methodology is validated by solving transonic flows on a NASA rotor 67. Detailed comparisons between numerical results and the experimental data are made for the design condition in order to assess the overall quality the numerical solution. The predicted total pressure ratio and adiabatic efficiency agree fairly well with the experimental results. These results show that the electrode discharge can induce an important acceleration of the flow close to the surface, and therefore cause retardation of flow separation and consequently on enhancement of efficiency.
1 INTRODUCTION

For future huge airships, which are being designed to fly at very high altitude (as in the case of MAAT project [1]), efficiency increase is a crucial subject. For such airships, any increase in propulsion system efficiency will lead to a decrease in energy consumption through a decrease in size, length and mechanical complexity of propulsion system, thus also lowering the initial investment. At the blades of a propulsion system, separation causes significant total pressure loss causing a reduction in overall efficiency.

High-speed, high pressure ratio axial compression systems are widely used in propulsion applications. However they have a limited range of stable operations, especially at low-mass flow rates, because of fluid dynamic instabilities. These instabilities cause deteriorations in system operations when compressor reaches rotating stall or surge.

Throughout the aero-propulsion history much work has been done to broaden the operating range, by developing control strategies to alleviate the rotating stall and surge. In the past decades significant research on boundary layer control technologies, including active and passive flow controls, has been carried out. The control strategy is to generate micro-vortex inside the boundary layer thickness, to add flow momentum close to the wall and so cancel separation. Flow control methods are used to cause an advantageous change in the flow development with the purposes of delaying or advancing transition, suppressing or enhancing turbulence, and preventing excessive boundary layer growth and separation. Flow control devices can be categorized in two groups. Passive devices; which do not add energy to the air flow, such as winglets (as seen on some aircraft wings). They are designed to give compromise performance between each defined aerodynamic configuration, the best being usually during the cruise mission of the flight, the longest phase of a given flight where the greatest benefit in lift/drag ratio and hence fuel consumption is to be gained. Unfortunately, outside those of the mission profile, the aerodynamic performance is penalized. These passive devices may be rendered mobile, thus increasing the range of aerodynamic optimization, but they require complex mechanisms which are heavy both in terms of weight and power consumption.

A further optimization of these passive devices has been in the development of micro-electromechanical systems. They are small, require less power consumption, and allow the flow to be controlled. But their implementation can remain difficult and their response time is very slow, due to the need to move mechanical components to obtain the desired effect on the air flow.

An alternative is to use active devices which add energy to the air flow. These devices have been researched and shown their ability to control air flow for boundary layer transition, separation, wing tip vortex, shock/boundary layer interaction, also for engine exhaust jet, landing gear and cavity noise reduction. Different techniques are studied using jets or micro-jets to create fluidic vortex generators for separation control. The control strategy is the same as mechanical vortex generator but vortices are created by the interaction between the flow and the micro-jet generated by fluidic injection across the wall. For some applications, high velocity of the micro-jet can be required, requiring large amounts of energy and rendering the overall energy balance negative. Beside this, integration can be very complex with compressed air networks bringing the source of energy to a given delivery point. To combat these deficiencies, studies have shown that the pulsing of these ‘jets’ can be more effective in controlling the air flow than a continuous stream, thus improving the energy balance and the real-time control. Innovative solutions have thus been proposed like MEMS where pulsed frequencies can reach 1 kHz and jet velocities 150ms$^{-1}$. But the energy balance for these devices must be
improved. The efficiency of compressed air mass flow networks is essential to achieve the
desired jet velocity. The actual evolution of micro-jet devices is the ‘synthetic jet’, which re-
quire no external mass flow and have little power consumption. A detailed review on active
and passive flow control techniques can be found in [2,3].

Although the traditional methods of boundary layer control are effective from an aerodynamic
point of view, their associated manufacturing and maintenance costs may limit their imple-
mentation, by introducing a significant increase in mechanical complexity and weight of the
airship. Therefore, the replacement of these conventional systems by a system utilizing active
flow control technology is a logical alternative. Plasma actuators are a relatively new flow
control technology. A plasma actuator consists of two offset thin electrodes that are separated
by a layer of dielectric insulator material. One of the electrodes is typically exposed to the air.
The other electrode is fully covered by a dielectric material. The electrode exposed to air is
assumed to be loaded by a high voltage, whereas an the electrode buried under dielectric is
expected to be grounded. Comprehensive reviews on plasma actuators for aerodynamic flow
controls have been published recently [3-5]. Corke et al [4] provides an overview of the phys-
ics and modeling of SDBD (single dielectric barrier discharge) plasma actuators. It highlights
some of the capabilities of plasma actuators through examples from experiments and simula-
tions. Caruana [5] has given a survey of methods of air flow control for aircraft performance
improvement. He has presented a short overview of non-plasma devices and studied ways for
flow control. Touchard [6] also made a detailed review of the designs and associated setups
for different aerodynamic plasma actuators developed these last twenty years, he further dis-
cussed the limits and the prospects of plasma actuators considered for airflow control.

The purpose of the present study is to apply the concept of Plasma Actuators to improve the
efficiency of the propulsion system that will be used in the European MAAT Project airships
[1]. In this work a numerical investigation of the flow control over a transonic fan blade (the
NASA Rotor 67 configuration) was performed, in order to determine the effect of a Dielec-
tric Barrier Discharge (DBDs) actuator on the aerodynamic efficiency of the propulsion sys-
tem component. The test case under consideration comprises the flow past a transonic fan,
NASA Rotor 67, with a single DBD actuator mounted at the blade suction side. Both near
stall and near peak efficiency conditions have been considered when evaluating the potential
of the plasma actuators for the purpose of efficiency increase. The overall performance of the
rotor, including the overall performance map and the spanwise distributions of total pressure
ratio, adiabatic efficiency and total temperature ratio agree fairly well with the measured data.
Maps of total pressure ratio and adiabatic efficiency versus mass flow rate have been obtained.
The impact of circulation control technique on axial compressor performance, particularly at
low mass flow rates is also investigated.

2 PLASMA ACTUATORS

Plasma-based devices exploit the momentum coupling between the surrounding gas and
plasma to manipulate the flow. Unlike other flow control techniques, such as suction and me-
chanical actuators, plasma actuators require low power consumption, involve no moving me-
chanical parts, and have a very fast frequency response that allows real-time control. For these
reasons, the plasma actuator has become a very promising and attractive device in the flow control community. Plasma actuators can be sub-categorized into two major families; the corona discharge, and the dielectric-barrier-discharge (the classification according to the class of discharges, may include corona discharge, dielectric barrier discharge (DBDs), glow discharge and arc discharge actuators; and also according to the conditions the classification can include the thermal and non-thermal plasma actuators). Different plasma actuators can be operated in various modes, depending on their geometrical configuration and the kind of high voltage applied (e.g., Nanosecond pulsed DBD, plasma synthetic jet, sliding DBD, Pulse DBD actuators). Very promising results for the application of plasma actuators have been observed in a wide range of aeronautical applications (boundary layer transition control [7], Separation control [8-10], control of a subsonic rotor blade wake [11], increasing the lift on a UAV [12], noise reduction [13] and pressure sensor [14], elimination of low Reynolds number separation in Low-Pressure Turbine flows [15] and reduction of the effects of turbine tip leakage [16]).

The specific plasma actuator which is considered for this study is the single-dielectric barrier-discharge (SDBD). In this configuration, two electrodes are typically separated by a dielectric barrier usually made of glass, Kapton or teflon as depicted in Figure 1. When a high AC voltage signal, of sufficient amplitude (5-40kVpp) and frequency (1-20 kHz), is applied between the electrodes the intense electric field partially ionizes the surrounding air, producing a nonthermal plasma on the dielectric surface. The collisions between the neutral particles and accelerated ions generate a net body force on the surrounding fluid. This body force is the mechanism for active aerodynamic control.

The advantages of DBD actuators include being surface-mounted (the ability to apply the actuators onto surfaces without the addition of cavities or holes), fully electronic, low power, high frequency-band devices, having a fast time response for unsteady applications, a very low mass and no moving parts. Moreover, flexible operation is possible by controlling the input voltage and waveforms. As DBD plasma actuators are thin, surface mounted, and do not require internal volumes or passages, they are particularly attractive for gas turbine and turbomachinery applications. Furthermore, plasma actuators like other active flow control devices can be driven either by open loop (not regulated by the output) or closed loop with feedback control [17].
It has been observed that plasma actuators are sensitive to a variety of atmospheric conditions, including air velocity, humidity and air pressure, at which they are exposed in many potential practical applications. There have recently been a number of investigations into the effect of pressure and temperature (in other word gas density) on the body force and velocity profiles produced by DBD plasma actuators [18-27]. Although air pressure has effect on the current used by Dielectric Barrier Discharge (DBD) plasma actuators, and the voltage limits for plasma production, in this study as a first attempt that effect is not considered.

3 THE NUMERICAL METHODS

The flow in the turbo-machinery of gas turbine engines is extremely complex. It is unsteady, viscous and three-dimensional, and in many cases, transonic with shock waves interacting with the surface boundary layers.

3.1 Governing equations

The three-dimensional, unsteady, compressible, Reynolds-averaged Navier-Stokes equations can be written for a rotating blade passage in conservative form presented in [28],

\[
\frac{\partial(Q)}{\partial t} + \frac{\partial(F - F_e)}{\partial x} + \frac{\partial(G - G_e)}{\partial y} + \frac{\partial(H - H_e)}{\partial y} = S, \quad (1)
\]

Where

\[
Q = \begin{bmatrix}
\rho \\
\rho u \\
\rho v \\
\rho w \\
\rho E
\end{bmatrix},
\]

\[
F = \begin{bmatrix}
\rho(u - u_g) \\
\rho u(u - u_g) + p \\
\rho v(u - u_g) \\
\rho w(u - u_g) \\
\rho H(u - u_g) + u_g p
\end{bmatrix},
\]

\[
G = \begin{bmatrix}
\rho(v - v_g) \\
\rho u(v - v_g) \\
\rho v(v - v_g) + p \\
\rho w(v - v_g) \\
\rho H(v - v_g) + v_g p
\end{bmatrix},
\]

\[
H = \begin{bmatrix}
\rho(w - w_g) \\
\rho u(w - w_g) \\
\rho v(w - w_g) + p \\
\rho w(w - w_g) + p \\
\rho H(w - w_g) + w_g p
\end{bmatrix},
\]

And
The variables $\rho, u, v, w, p, T, E$, and $H$ denote respectively the density, the absolute velocity components in the $x$, $y$, and $z$ directions of the Cartesian coordinate, the pressure, the temperature, the specific total energy, and specific total enthalpy. The Cartesian system $x, y, z$ is rotating about the $x$ axis with an angular velocity $\Omega$ and $\Omega = [u_\Omega, v_\Omega, w_\Omega] = [0, -\Omega z, -\Omega y]$ is the vector of velocity due to the rotation of the frame. The explanations of other terms can be found in [28] and are thus omitted in the present paper. These equations are closed by the equation of state for the perfect gas.

In the spatial discretization of the Navier-Stokes equations, the convective terms are computed with a second order upwind interpolation scheme. In the present paper, the Roe Riemann solver ([29-30]), is used to solve the 3D Navier-Stokes equations. The discrete equations are solved by implicit dual time-stepping method. Moreover, the turbulence model used in the present study is the two equation $k-\omega$ model [31]. The turbulent transport equations are solved using a scheme similar to that for solving the Navier-Stokes equations.

### 3.2 DBD Plasma Modeling

There have been several numerical studies on DBD plasma actuators. Two main different modeling approaches are commonly employed to describe the plasma actuators. The first consists of chemistry based models ([32-35]) that attempt to spatially resolve the plasma phenomena directly. The second are algebraic models that are based on the solution of a Poisson’s equation ([36-39],[10-11]). These algebraic models generally require assumptions regarding either the charge density or electric field produced by the actuator. The chemistry based family typically consists of drift diffusion type models. These models track the chemical species present in the plasma, such as electrons and ions, using a set of transport equations. The essential plasma physics such as ionization, recombination and streamer propagation are all modeled. Here in this study, the algebraic model of Suzen [39] is used for describing the effect of plasma actuation.

**Split potential field model**

The electrostatic formulation is based on the assumption that the plasma formation and fluid flow response can be decoupled due to the disparities in the characteristic velocities associated with each process. This is a reasonable assumption since the characteristic velocities of the...
transport fluid under consideration are between 10 m/s and 100 m/s and, for electron temperatures between 1000 K and 10000 K, the electron velocities, which present the characteristic velocities of the plasma, are of the order of $10^5$-10$^6$ m/s.

The plasma actuators are formed by a pair of electrodes separated by a dielectric material. The actuator is placed in the surface with one electrode exposed to the surroundings and the other one embedded in the surface below the dielectric material (Figure 1). When a high AC voltage is supplied to the electrodes, this arrangement causes the air in their vicinity to weakly ionize. The ionized air, in the presence of the electric field gradient produced by the electrodes, results in a body force vector acting on the external flow that can induce steady or unsteady velocity components. This body force can be expressed in terms of the applied voltage and incorporated into the Navier Stokes equations. By neglecting magnetic forces, the electrohydrodynamic (EHD) force can be expressed as

$$\tilde{f}_b = \rho_e \tilde{E}, \quad (4)$$

where, $\tilde{f}_b$ is the body force per unit volume, $\rho_e$ is the net the charge density and $\tilde{E}$ is the electric field. This body force is a body force per volume of plasma, which is the basis of the plasma actuator effect on neutral air. Considering the Maxwell equations (respectively Gauss law, Gauss law for magnetism, Faraday’s law of induction and Ampere’s circuit law):

$$\nabla \cdot \tilde{D} = \rho_e, \quad \nabla \cdot \tilde{B} = 0, \quad \nabla \times \tilde{E} = -\frac{\partial \tilde{B}}{\partial t}, \quad \nabla \times \tilde{H} = \tilde{J} - \frac{\partial \tilde{D}}{\partial t}, \quad (5)$$

where $\tilde{H}$ is the magnetic field strength, $\tilde{B}$ is the magnetic induction, $\tilde{E}$ is the electric field strength, $\tilde{D}$ is the electric induction and $\tilde{J}$ is the electric current. We assume that the charges in the plasma have sufficient amount of time for the redistribution process to occur and the whole system is quasi-steady, and that the time variation of the magnetic field is negligible, as is often the case in plasma. These assumptions imply that the electric current $\tilde{J}$, the magnetic field $\tilde{H}$, and the magnetic induction $\tilde{B}$ are equal to zero, as well as the time derivatives of the electric $\frac{\partial \tilde{D}}{\partial t}$ and the magnetic induction, $\frac{\partial \tilde{B}}{\partial t}$. Therefore, the Maxwell’s equations give rise to

$$\nabla \cdot \tilde{D} = \rho_e, \quad \nabla \times \tilde{E} = 0, \quad (6)$$

The relation between the electric induction and the electric field strength is given by:

$$\tilde{D} = \varepsilon \tilde{E}, \quad (7)$$

where $\varepsilon$ is the permittivity. The permittivity can be expressed as $\varepsilon = \varepsilon_0 \varepsilon_r$, where $\varepsilon_r$ is the relative permittivity of the medium, and $\varepsilon_0$ is the permittivity of free space. Using Eq. (7), Eqs (6) can be rewritten as,

$$\nabla \cdot (\varepsilon \tilde{E}) = \rho_e, \quad \nabla \times \tilde{E} \approx 0 \quad (8)$$

This implies that the electric field can be derived from the gradient of a scalar potential:

$$\tilde{E} = -\nabla \Phi, \quad (9)$$

Therefore,
\[ \nabla \cdot (\varepsilon_r \nabla \Phi) = -\frac{\rho_c}{\varepsilon_0}, \]  

(10)

If we use the Boltzmann relation we have:

\[ n_{e,j} = n_0 \exp \left( \pm \frac{e\varphi}{k_b T} \right) \approx n_0 \left[ 1 \pm \frac{e\varphi}{k_b T} \right], \]

(11)

with \( \varphi \) being the local electric potential, \( n_0 \) the background plasma density, \( T \) the temperature of the species, \( e \) the elementary charge, and \( k_b \) the Boltzmann constant. In the above equation, the positive sign applies to electrons and the minus sign applies to the ions. The net charge density at any point in a plasma is defined as the difference between the net positive charge produced by ions and the net negative charge of electrons. The difference can be related to the local electric potential \( \varphi \) by the Boltzmann relation (11). Assuming a quasi-steady state with a time scale long enough for the charges to redistribute themselves, the following relation can be written

\[ \frac{\rho_c}{\varepsilon_0} = \frac{e}{\varepsilon_0} (n_i - n_e) \approx -\frac{e n_0}{\varepsilon_0} \left( \exp \left( \frac{e\varphi}{k_b T_i} \right) + \exp \left( \frac{e\varphi}{k_b T_e} \right) \right), \]

(12)

Where \( n_i \) and \( n_e \) being the ion and electron densities in the plasma. Expanding the exponential functions in a Taylor series for \( \varphi \ll T \), Equation (12) becomes, for the lowest order of \( \varphi / T \),

\[ \frac{\rho_c}{\varepsilon_0} \approx -\frac{e^2 \varphi n_0}{\varepsilon_0} \left( \frac{1}{k_b T_i} + \frac{1}{k_b T_e} \right). \]

(13)

The Debye length, which is the characteristic length for electrostatic shielding in a plasma, is defined as,

\[ \lambda_d = \left[ \frac{e^2 n_0}{\varepsilon_0} \left( \frac{1}{k_b T_i} + \frac{1}{k_b T_e} \right) \right]^\frac{1}{2}, \]

(14)

The free charges in the plasma are shielded out in a distance given by the Debye length. The Debye shielding is valid if there are enough particles in the charge cloud. The criteria for this is the dimensionless plasma parameter, \( \Lambda \), that characterizes unmagnetized plasma systems, defined as

\[ \Lambda = \frac{4}{3} \pi \lambda_d^3 n_e, \]

(15)

If the plasma parameter is \( \Lambda \gg 1 \), then it means that the plasma is weakly-coupled, and the Debye shielding is valid. For plasma with the Debye length of approximately 0.00017 m, and the density of the charged particles is on the order of \( 10^{16} \) particles/m\(^3 \), the criteria is \( \Lambda = 3.5 \times 10^5 \), indicating that the assumption of the Debye shielding is true. With the present definition of Debye length we have,
\[
\frac{\rho_c}{\varepsilon_0} \approx -\frac{1}{\lambda_d^2} \Phi, \tag{16}
\]

Experiments indicate that independently of which electrode the voltage is applied to, and independently of the polarity of the applied voltage, the resultant body force and the induced flow is in the direction towards the embedded electrode. The exposed surface of the dielectric plays a critical role. Even before the air ionizes, the dielectric surface communicates the potential charge from the covered electrode. When the voltage potential is large enough to ionize the air, the surface of the dielectric collects or discharges additional charge. As a result the dielectric surface is referred as a virtual electrode. Therefore there is the need for a better model that can account for these effects. According to [38] and [39] (split potential field model), since the gas particles are weakly ionized, we can assume the potential \( \Phi \) can be decoupled into two parts: one being a potential due to the external electric field, \( \phi \), and the other being a potential due to the net charge density in the plasma, \( \bar{\phi} \),

\[
\Phi = \bar{\phi} + \phi, \tag{17}
\]

Assuming that the Debye length is small, and the charge on the wall above the encapsulated electrode is small, the distribution of charged particles in the domain is governed by the potential due to the electric charge on the wall, and is unaffected by the external electric field. Note that the grid spacing should not be larger than the Debye length. The smaller the Debye length, the narrower it becomes the plasma region located near the electrode and dielectric surface becomes. For the potential due to the external electric field, we have,

\[
\nabla \cdot (\varepsilon_c \nabla \phi) = 0 \quad \tag{18}
\]

and for the potential due to the net charge density, we have,

\[
\nabla \cdot (\varepsilon_c \nabla \bar{\phi}) = -\frac{\rho_c}{\varepsilon_0} \quad \tag{19}
\]

Using Eq. (16) we can rewrite Eq. (19) as follows,

\[
\nabla \cdot (\varepsilon_c \nabla \rho_c) = \frac{\rho_c}{\varepsilon_0} \quad \tag{20}
\]

Equation (18) is solved for the electric potential, \( \phi \), using the applied voltage on the electrodes as boundary condition. The applied AC voltage is imposed at the exposed (upper) electrode as a boundary condition

\[
\phi(t) = \phi_{\text{max}} f(t), \quad \tag{21}
\]

The waveform function \( f(t) \) can be either a sine wave or a square wave given by,

\[
f(t) = \begin{cases} 
sin(2 \pi \omega t) & \text{ (sine wave)}, \\
1; & \sin(2 \pi \omega t) \geq 0 \\
-1; & \sin(2 \pi \omega t) < 0 & \text{ (square wave)},
\end{cases} \tag{22}
\]
where $\omega$ is the frequency and $\phi_{\text{max}}$ is the amplitude. The embedded electrode is prescribed as ground by setting the electric potential to zero on that electrode. At the outer boundaries $\partial \phi / \partial n = 0$ is assumed. The waveform function $f(t)$ is a time dependent boundary condition and can be used to model both steady and unsteady actuator arrangements. For the steady case, $f(t)$ can be set to be a square wave. For unsteady cases, different frequencies and wave forms can be used to simulate actuation with different duty cycles. Equation (20) is solved for the net charge density $\rho_c$, only on the air side of the domain. A zero normal gradient for the net charge density is imposed on the solid walls except in the region covering the lower electrode. The charge density is set to zero on the outer boundaries. On the wall, downstream of the exposed electrode, where the embedded electrode is located (virtual electrode), the charge density is prescribed in such a way that it is matched with the time variation of the applied voltage $\phi(t)$ on the exposed electrode,

$$\rho_{c,w}(t) = \rho_{c,\text{max}} G(x)f(t),$$

(23)

where $\rho_{c,\text{max}}$ is the maximum value of the charge density allowed in the domain ($\text{C/m}^3$). The variation of the charge density on the wall, $\rho_{c,w}$ in the streamwise direction $x$, is prescribed by a function $G(x)$ chosen to resemble the plasma distribution over the embedded electrode. Experimental results [40] suggest that this distribution is similar to a half Gaussian distribution given by

$$G(x) = \exp(-\frac{(x - \mu)^2}{2\sigma^2}) \quad \text{for} \quad x \geq 0,$$

(24)

In equation (24) $\mu$ is the location parameter indicating the maximum $x$ location, and $\sigma$ is a scale parameter determining the rate of decay. The location parameter $\mu$ is chosen such that the peak corresponds to the left edge of the embedded electrode. Moreover, it is assumed that $\sigma$ takes a value of 0.3 to allow a gradual decay of the charge density distribution from the left edge to the right edge. It should be noted that in order to solve the above equation, it is necessary to specify two parameters, namely $\rho_{c,\text{max}}$ and $\dot{\lambda}_d$. These parameters control the strength of the plasma actuator's effects on the flow field and the extent of these effects into the flow field. These two parameters should be calibrated using available experimental data. The values for $\rho_{c,\text{max}}$ and $\dot{\lambda}_d$ were empirically defined by Suzen et al. (2005) [39] as $8 \times 10^{-4} \text{C/m}^3$, and 0.001m. Since Eqs (18) and (20) do not contain a time derivative term. Then, Equation (18) can be normalized using the value of voltage of the exposed electrode $\phi_{\text{max}}f(t)$, and be solved by imposing a constant boundary condition equal to unity at the upper electrode. Once the dimensionless distribution is determined, the dimensional values at any given time can be obtained by multiplying this distribution with the corresponding value of $\phi_{\text{max}}f(t)$. Similarly, equation (20) can be solved by normalizing with $\rho_{c,\text{max}}f(t)$. This implies that the boundary condition for the dimensionless charge density on the wall region covering the embedded electrode is $G(x)$. The non-dimensional form of Eqs (18) and (20) is as follows,
\[ \nabla \cdot (\varepsilon_r \nabla \phi^*) = 0, \quad \phi^* = \frac{\phi}{\phi_{\text{max}} f(t)}, \]  

(25)

\[ \nabla \cdot (\varepsilon_r \nabla \rho_c^*) = \frac{\rho_c^*}{\lambda_d}, \quad \rho_c^* = \frac{\rho_c}{\rho_{c\text{\text{max}}} f(t)}, \]  

(26)

### 3.3 Fluent Configuration Computational Grid

The flow control capability of plasma actuators is studied NASA Rotor 67 configuration [41]. The design pressure ratio for the Rotor 67 configuration is 1.63, at a mass flow rate of 33.25 kg/sec. The rotor has 22 blades with an aspect ratio of 1.19, hub to tip ratio of 0.70, and a tip solidity of 1.288. The running tip clearance was estimated to be 0.356 mm (0.5% span). The tip relative Mach number at the inlet is 1.38 at the design rotational speed of 16,043 rpm, which gives a tip speed of 429 m/s. A number of numerical studies have been performed to investigate the flow field in Rotor 67 over recent years ([42-46]). An electrode with length 12.7mm and a thickness of 1mm is mounted on the suction side of blade, near trailing edge. Another electrode, with the same thickness and length, is grounded in the blade and separated from the mounted electrode with the 3mm thick layer of Kapton as dielectric material. The center line of the actuators was placed at \( x/C = 0.016131 \), see Fig 1.

A commercial solver package, FLUENT [47], was utilized for the present work. A user-defined function (UDF) has been coded and used for calculation of electric fields and body force. In the present numerical simulation, A structured grid with totally 614,880 cells in a multi-block arrangement was used. The grid used for this study is shown in figure 2.

The flow domain is composed of different types of boundary conditions. Walls are treated using non-slip and adiabatic conditions. The velocity on the casing is set to zero, while the rotational velocity for grid points on the compressor blades and hub, which are moving, is set equal to \( \Omega \). Using rotationally periodic boundary conditions allows reducing the spatial com-
putation requirements from that of the entire rotor (22 blades) to the space between 2 blades. Moreover, total pressure, total temperatures were imposed uniformly at the inlet boundary. At outlet, static pressure is prescribed at the hub, and its radial variation is computed according to the radial equilibrium equation [48]. To investigate the different design conditions, the outflow static pressure is varied in order to set the mass-flow. The convergence of the numerical simulation is checked through the convergence histories of mass flow rate and pressure ratio, as well. The implementation of the mathematical model of plasma actuator was validated in a previous published work [49] in comparison with numerical simulation of plasma-driven flow in a quiescent environment as proposed by by Suzen et. al. [39].

4 RESULTS AND DISCUSSIONS

First we present the result of rotor without any plasma effect. This is for the purpose of validating the flow calculation. The relative Mach number distribution of different spanwise sections of the blade is presented in Fig 4 and 5 both for near peak efficiency and near stall operation condition.
Fig. 3 relative Mach number distributions on different spanwise sections at near peak efficiency.
In a subsequent, we have computed the rotor with plasma actuator on. For the entire configuration, a voltage difference of 5kV with frequency of 120Hz is applied to the plasma actuator. The distribution of electric potential and charge density around the electrodes is shown in Fig 6. As was explained before, the solution of the electrostatic equation (Eqs. 18 and 20) is done by solving the non-dimensional electrostatic equations (Eqs. 25 and 26) which prevents the necessity to solve these equations in unsteady manner.

The predicted overall performance for both near peak efficiency and near stall operation conditions and with, and without, plasma actuation at the design speed is presented in Fig.6. As it is clear in this figure, the predicted total pressure ratio is in good agreement with the experiment data. From this figure, it is clear that in the presence of plasma actuation the adiabatic efficiency increases to a slightly higher (1% increase) value in comparison to the cases without plasma actuation.
This paper presents a preliminary study aimed to study the potential of plasma actuators to enhance the efficiency of transonic fan blades. A three-dimensional unsteady, compressible, Reynolds-averaged Navier-Stokes equation has been solved in conjunction with simple electrostatic model to simulate the flow field around the NASA rotor 67 blade. The innovative active flow control of plasma actuators is adopted in the surface of fan blade to enhance the performance of considered rotor. According to the numerical results, it can be concluded that plasma actuators have the potential to be used in transonic fan blades to increase the efficiency.

5 CONCLUSIONS

Fig.6 Comparison of overall performance at design speed of the present computation as compared with the experimental results of [41]
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