Numerical simulation of DBD-actuator influence on duct flow

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Abstract. Numerical procedure of modelling interaction between dielectric barrier discharge and duct flow based on RANS equations has been developed and tested in present study. Qualitative and approximate quantitative correspondence between known experimental data and numerical results has been achieved. Typical volume force and heat magnitudes has been evaluated, these values could be used as estimation in steady approximation calculations. DBD actuator model has shown up that required volume force magnitude has to be increased by 2-3 orders to influence on flow separation in S-type engine ducts at relatively high inlet velocity. Different method of volume force calculation using actuator operating parameters (Single Potential Method and Dual Potential Method) has been carried out. Continuous volume force components fields have been calculated as a function of DBD actuator applied voltage and surface charge density amplitude.

1. Introduction
Requirements for perspective aviation engines become more stringent, therefore different processes in engine units have to show higher performance and incorporate recent achievements in engine design technologies.

Short ducts with the strongly curved central line in compressor group and in pre-diffuser group before combustion chamber application helps to reduce engine overall length and mass. However, flow separation occurs in these ducts. A wide spectrum of different methods (e.g. synthetic jets, discharges) is applying as a way of influence on these undesirable effects by its partial or total removal. One of the promising methods is using of plasma formations produced by actuators.

Interest in dielectric barrier discharge (DBD) actuators application is connected with its advantages: small weight, no flow disturbance by mounted electrodes, absence of complicated mechanical or pneumatic systems, and electrodes ability of being placed in particular location of disadvantageous effects initiation, and also relatively simple active control system for critical regimes only could be created on basis of these actuators.

As it was shown earlier in many experimental and numerical studies, using of DBD discharge with its relatively low required power could lead to significant flow changing (e.g., pressure loss decrease) and this effect could be succeeded and optimized by reasonable placement of DBD device on wetted surface in the flow.

DBD actuator consists of two electrodes placed on surface and divided by dielectric. Alternating current with high amperage on electrodes induces weak ionization of the neighboring volumes of gas (air or other). Ionized gas (plasma) under electric field is exposed to volume force, it induced additional external flow velocity disturbances.
Process of interaction between DBD and gas flow is complicated multiphysical problem, which includes coupled areas of knowledge: gas dynamics, turbulence, heat transfer, plasma dynamics, and ion kinetics. The most common approach to numerical simulation of aircraft construction external flows and engine internal flows currently is usage of different ways of Navier-Stokes equations solving. The method of DBD actuator flow influence accounting by bringing in additional volume force vector and heat source in Navier-Stokes and energy equation correspondingly is largely used [1, 2]. The force could be estimated as a product of charge density and electric field potential. This approach requires Maxwell equation solving for electric field parameters obtaining or experimental data usage as an estimation of the volume force magnitude.

2. Constant volume force approach
Model duct from [1] has been selected as an object for numerical procedure validation. In [1] two DBD actuators are described, both of them create vortex structure that helps to delay laminar-turbulent boundary layer transition. Computational domain inlet velocity amounts 5 m/s, volume force magnitude nearby the DBD actuator amounts $10^3$ N/m³. An annular model diffuser duct (figure 1) has studied numerically as main simulation object; application of other ways of flow control such as interceptors and synthetic jets has been also studied in different works for this configuration.

The axisymmetric duct DBD flow control has considered as a two-dimensional problem. It helps to estimate in a first approximation possibility of flow separation removal and overall DBD influence effectiveness. Other important characteristic, which can be estimated in axisymmetric case, is volume force magnitude required for flow separation removal.

![Figure 1. Simulated duct sector (60 degrees).](image)

Volume force effect area (in 2D) is located in near-wall region where the flow separation zone is started; size of this area is about 5 mm in a streamwise direction and 1 mm transversally. Location of force area, volume force magnitude and its direction has been considered as variable parameters in this research. Volume force magnitude in DBD effect area has varied between 1 and $3 \cdot 10^6$ N/m³. At lesser volume force magnitudes no observable influence on the flow has been noticed. Volume force vector direction (relative to duct axis i.e. relative to inlet velocity direction) has varied between 30 and 60 degrees (figure 2). All these variations have been made for a particular volume force effect area location.

Calculation results have shown that volume force with $2 \cdot 10^5$ N/m³ lowers flow separation and volume force with $3 \cdot 10^6$ N/m³ practically removes it. Volume force vector direction variation (due to X and Y components alteration with the constant magnitude) appears to be insignificant in comparison with force (momentum) effect. Therefore volume force vector direction has been set at a value of 45 degrees (approximately parallel with the nearby upper duct wall).
Flow separation appears to be unresponsive to a small volume force effect area movements in a streamwise direction (1...3 mm) also. On the contrary, force (momentum) influence intensity is the most significant parameter. However, intensity of force (momentum) influence that requires for flow separation removal has considerably large volume force magnitude in comparison with experimental data [1,2]. The experimental upper limit of this force is connected with DBD actuators voltage limitations due to dielectric properties.

3. DPM approach

Besides constant volume force regions approaches there are alternative methods connected with DBD actuator electrical potential calculation. These approaches also imply more or less detailed mathematical model of plasma formation and its interaction with the flow [3]. Main advantage of this more complicated approach is achievement of continuous volume force field which corresponds to features of physical processes near actuator. One of the examples of charged species transport equations and reduced Maxwell equations solving for system with electric field and medium convective-diffusion flow can be found in [4].
One of the promising approaches, that compromised numerical complexity and physical validity of the mathematical model of DBD system, is Dual Potential Method. This approach connected with solving a two-equation system for two components of electrical potential.

Equations for both components are of the form:
\[ \nabla \cdot (\varepsilon_r \nabla \varphi) = \left( \frac{1}{\lambda_D^2} \right) \varphi \]

where \( \lambda_D \) is Debye radius and \( \varepsilon_r \) is dielectric constant.

Connection between charge density and electrical potential is of the form:
\[ \rho_c = -\left( \varepsilon_0 / \lambda_D^2 \right) \varphi \]

All empirical constants and solution method has been taken from [5].

Boundary conditions for two scalar values are:

- \( \varphi = \varphi_0 \sin(\omega t) \), \( \rho_c = 0 \) - for exposed electrode.
- \( \varphi = 0 \) - for buried electrode.
- \( \frac{\partial \varphi}{\partial \mathbf{n}} = 0 \), \( \rho_c = \rho_{c0} \sin(\omega t) \) - for variable charge density area.
- \( \frac{\partial \varphi}{\partial \mathbf{n}} = 0 \), \( \frac{\partial \rho_c}{\partial \mathbf{n}} = 0 \) - for the wall above the dielectric.
- \( \frac{\partial \varphi}{\partial \mathbf{n}} = 0 \), \( \frac{\partial \rho_c}{\partial \mathbf{n}} = 0 \) - for the rest boundaries.

Numerical simulations for configuration from figure 1 were performed. Dual-potential Method (DPM) was used for electrical characteristics (electrical potential \( \varphi \) and charge density \( \rho_c \)) calculations. Typical fields of electrical potential \( \varphi \) and charge density \( \rho_c \) near the electrodes is presented on figures 4 and 5.

Using data of this calculation during one period of potential calculation of time-averaged volume force has been performed. The result time-averaged field of \( F_x \) and \( F_y \) force component for \( \Delta \varphi = 50000 \) V, \( f = 5000 \) Hz case is presented on figure 6 and figure 7.

First results of DPM approach application are in qualitative agreement with other authors’ results [6-7].
Maximum values of volume fields components for potential difference $\Delta \phi = 50000$ V, charge density amplitude $\rho_{0C} = 0.1$ C/m$^3$, and voltage frequency 5000 Hz are: $F_{x\text{max}} = 1.859 \cdot 10^6$ N/m$^3$, $F_{y\text{max}} = 1.892 \cdot 10^6$ N/m$^3$. Significant difference between constant volume force approach means that it could be used mostly only as a first approximation.

4. Conclusions

Numerical procedure of DBD modelling has been developed and tested in present study. Qualitative and approximate quantitative correspondence between known experimental data and numerical results has been achieved. Typical volume force and heat magnitudes has been evaluated, these values could be used as estimation in steady approximation calculations.

Calculations have shown that experimental force (momentum) and heat influence intensity levels appears to be enough for a low velocity flow control (Mach number about 0.1 and lower). However both DBD actuators models has shown up that required volume force magnitude has to be increased by 2-3 orders (in comparison with validation problems) to influence on flow separation in S-type engine ducts at relatively high inlet velocity (about 100 m/s).

Alternative method of volume force calculation using actuator electrical parameters (DPM) has been carried out. Continuous volume force components fields have been calculated as a function of DBD actuator applied voltage and charge density amplitude.

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