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NUMERICAL SIMULATION OF INTERACTION PROCESS BETWEEN DIELECTRIC BARRIER DISCHARGE AND DUCT FLOW

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Abstract. *Numerical procedure of DBD modeling based on RANS equations has been developed and tested in present study both for the standard DBD and DBD working in constricted mode. 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. Both DBD actuators models has shown up that required volume force magnitude has to be increased by 2-3 orders influence on flow separation in S-type engine ducts at relatively high inlet velocity Different 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 potential difference and charge density amplitude.*

1 INTRODUCTION

Modern aviation engine improvement requires high-level scientific maintenance of developing process and research of characteristics increase approaches for different operation stages. Therefore scientific research significance in modern engines design is increasing.

Short diffusers application with a high ratio between inlet and outlet areas with the strongly curved central line helps to reduce engine installation overall dimensions and mass. However, flow separation occurs in these ducts. Longitudinal pressure gradient from centrifugal force effect along with transverse pressure gradient induces secondary flows contorting pressure field.

A wide spectrum of different "passive" (e.g., interceptors) and "aggressive" (e.g., synthetic jets, DBD and SHF-discharges) methods is applying as a way of influence on these undesirable effects by its partial or total removal.

Use of electric discharge (DBD, SHF) influence on gas-dynamic flow has been studying intensively recently.

Interest in 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.

DBD discharge with its relatively low required power could be an example of significant flow changing (e.g., pressure loss decrease) with low energy contribution, this effect and its gas-dynamic application realization could be succeeded by reasonable placement on streamline surface.

DBD actuator consists of two electrodes placed on surface and divided by dielectric. High voltage alternating current on electrodes causes weak ionization in the nearby area. Ionized gas (plasma) under electric field gradient is exposed to volume force, it leads to additional external flow velocity distortions.

The most common approach to numerical simulation of aircraft construction external flow and engine internal flow currently is usage of different ways of Navier-Stokes equations solving. RANS/URANS is more fine-tuned computational procedure at present; LES requires greater computational powers, but allows obtaining fuller and more reliable separated flow characteristics. Perspective DNS - methods currently can be applied only to model problems due to its significant computational powers requirement. Therefore, integration of DBD flow influence models with CFD solvers seems to be perspective way of DBD numerical simulation.

The method of DBD actuator flow influence accounting by bringing in additional volume force vector in Navier-Stokes equation is largely used [1, 3, 4]. This force could be estimated as a product of charge density and electric filed 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 STANDARD DBD SIMULATION

Model duct studied both experimentally and numerically in [1] has been selected as an object for numerical procedure validation. In that paper two DBD actuators create vortex structure that helps to delay boundary layer transition from a laminar to a turbulent state. 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 (Fig.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.

The axisymmetric duct DBD flow control has considered as a two-dimensional problem. It helps to estimate to a first approximation possibility of flow separation partial or total removal and DBD influence effectiveness in principle and volume force magnitude required for such removal.

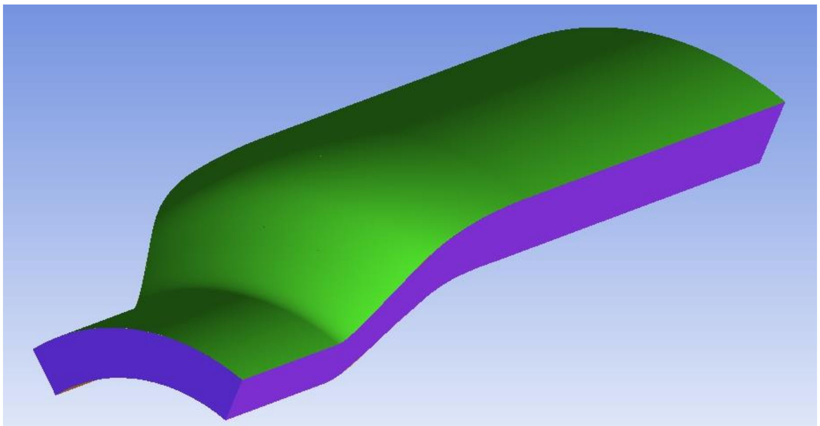


Figure 1: Simulated duct sector (60 degrees).

Volume force effect area is located in near-wall region when the flow separation is started (Fig. 2), size of this area is about 5 mm in a streamwise direction and 1 mm transversally. Exact volume force effect area x-coordinate, volume force magnitude and its vector direction has been considered as variable parameters in this research.

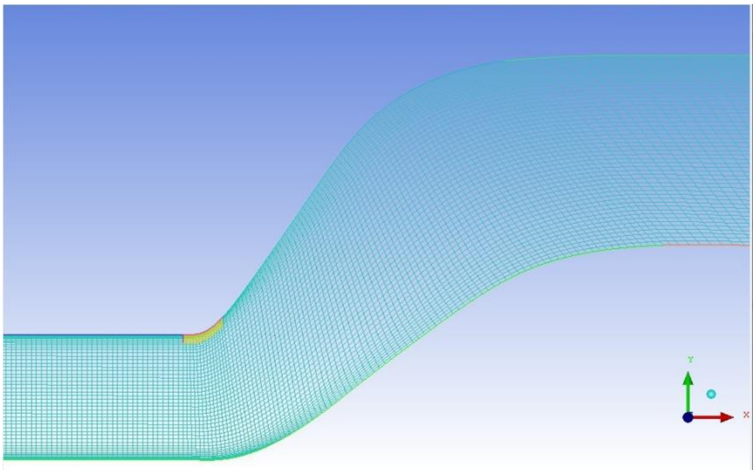


Figure 2: Calculation domain and mesh fragment example (orange area denotes volume force effect area).

The structured 2D-mesh consists of 8 blocks and about 14000 elements. Wall boundary condition has been set on top and bottom domain boundaries (Fig. 3).

Boundary conditions on inlet (left boundary): total pressure 101325 Pa, turbulence intensity - 2%, turbulence scale - 0.001 m; on outlet (right boundary): static pressure 90000 Pa.

2D steady calculation with Roe-FDS flux type solution method has been used. RANS system of equations has supplemented by Spalart - Allmaras turbulence model with standard wall functions.

Volume force magnitude in DBD effect area has varied between 1 and 3•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 (Fig. 4). All these variations has been made for a particular volume force effect area location.

Calculation results have shown that volume force with 2•10^{6} N/m3 lowers flow separation and volume force with 3•106 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)

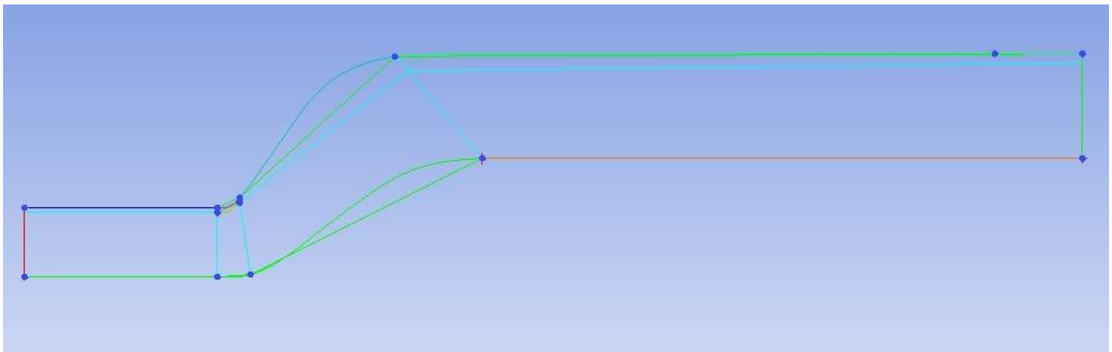


Figure 3: Computational domain block structure.

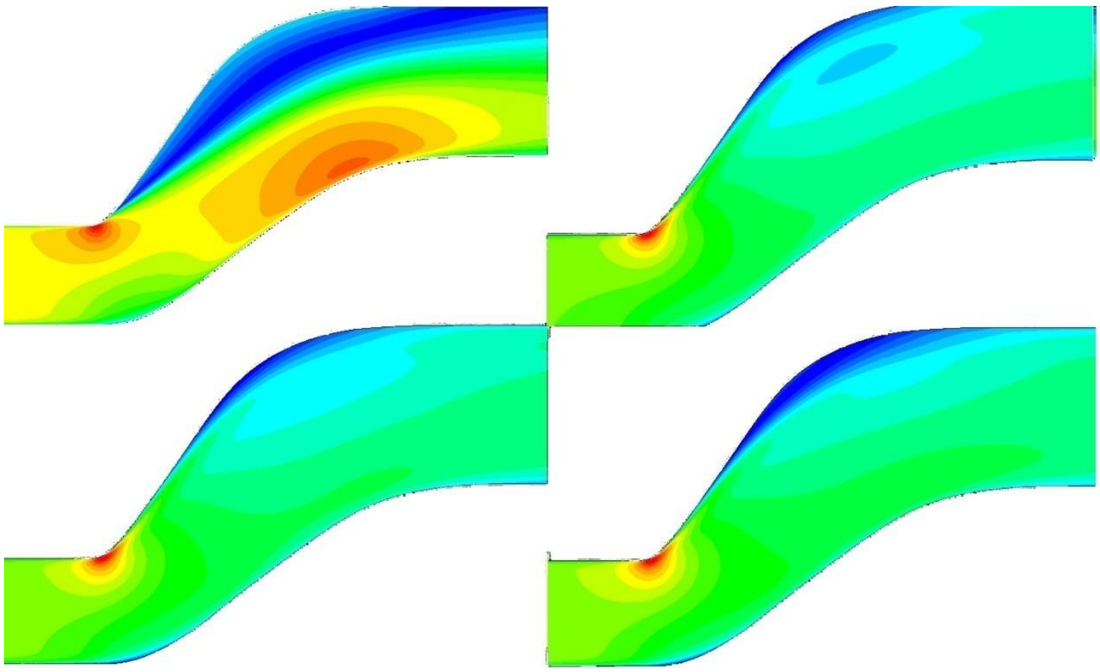


Figure 4: Velocity fields in separation flow area (left to right): zero volume force, volume force vector direction (relative to duct axis) 30 degrees, 45 degrees, 60 degrees with magnitude $3 \cdot 10^6$ N/m^3.

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 CONSTRICTED DBD SIMULATION

Along with standard DBD discharges simulation, which could be used for a flow control purpose, dielectric barrier discharges working in a constricted (saturated) mode or constricted DBD, has also considered in this paper.

This mode is connected with significant power input (voltage amplitude increase) which leads to the constriction of the discharge due to overheating instability. A local increase in the conductivity leads to the increase in the current density, and a bright highly conductive filament is formed. (Fig. 5, [2])

Formation of a region with a higher conductivity in the discharge should significantly disturb electric field and charge distribution, providing body force to be radial relatively to a discharge channel (filament) to a first approximation (real structure is more complicated)

Constricted DBD disturbance structure in practically immobile gas is presented in [2]. It has shown that flow structure induced by constricted DBD includes jets perpendicular to dielectric surface, which is placed between discharge channels (Fig. 5)

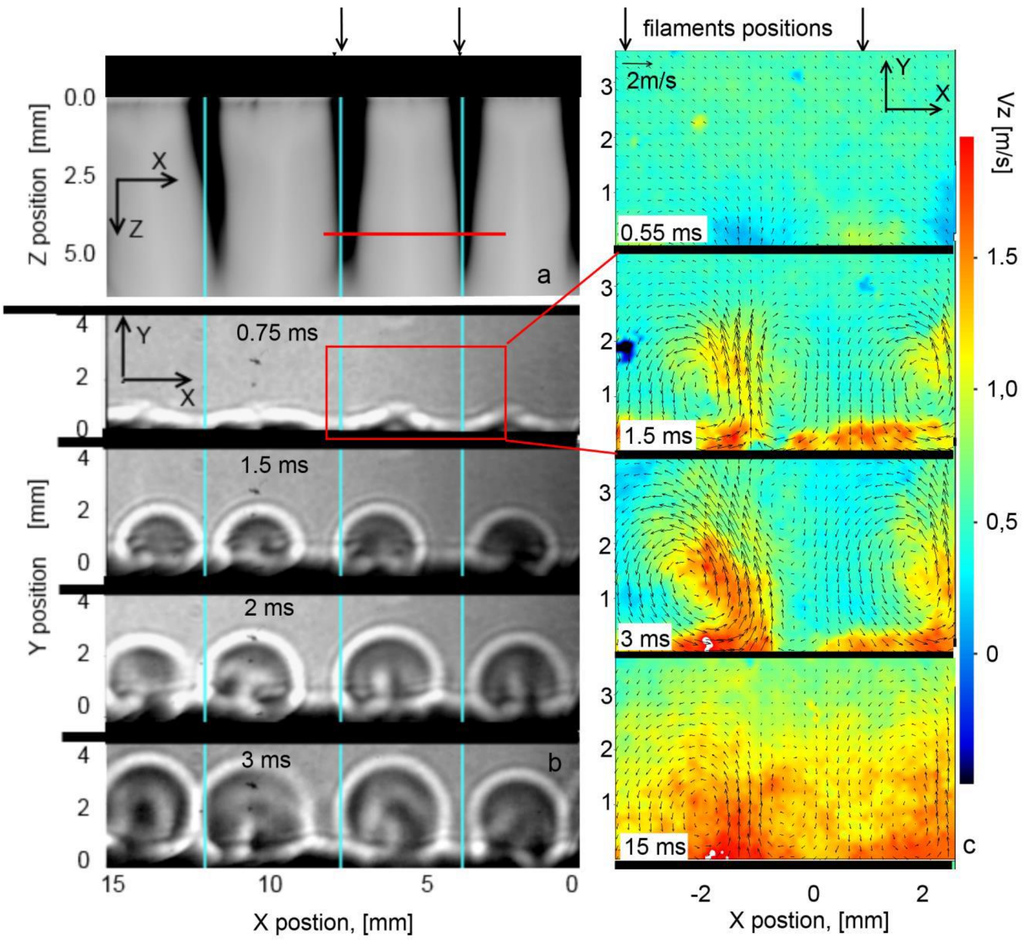


Figure 5: "a": top view (X–Z) of the discharge (negative image). Red line marks the position of the cross section for PIV measurements, "b": shadow pictures of discharge-induced disturbances and "c": enlarged PIV images of the flow in the X–Y plane at the position Z = 4 mm. [2].

Jets forming occur with gas suction from the upper layers. At next stage vortex pairs rotating in different directions are forming attached to discharge channels positions.

An interaction between formed discharge plasma channels and a medium could be described by two mechanisms: energetic mechanism (volume heat release inside the discharge channel and nearby regions), which has sufficiently larger intensity than standard DBD and force (momentum) mechanism which has lesser intensity than standard DBD. These interaction mechanisms are simulating in this study for the purpose of recreating pair vortex structures numerically and estimation of mechanisms intensity.

A validation of numerical procedure along with volume force and volume heat magnitude estimation has been carried out at 3D model of DBD actuator from [2]. Three domain versions ("a" - "c") which help to estimate necessary domain width are presented at Fig.6.

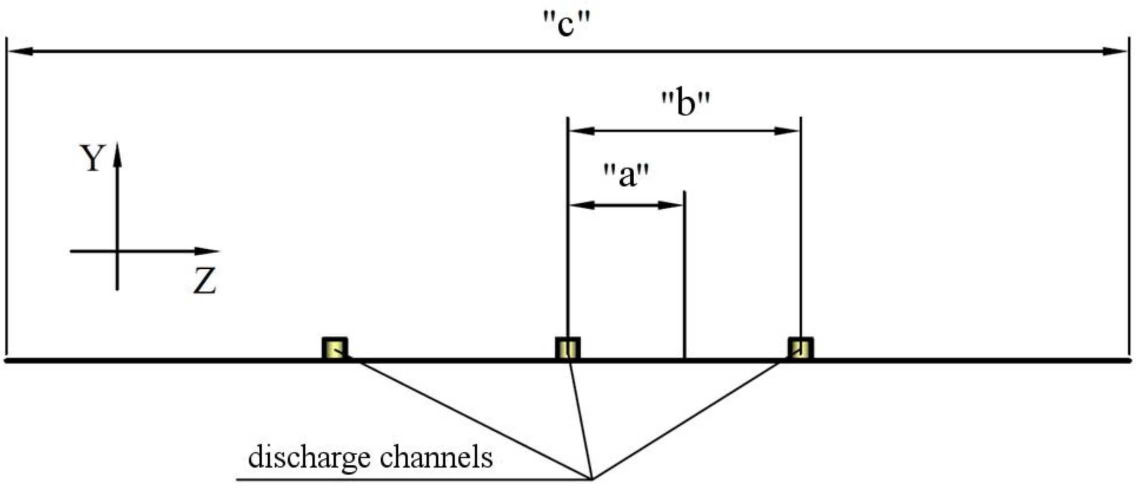


Figure 6: Three computational domain types which differ in Z-dimension: "a" - half inter-channel space, "b" - one inter-channel space, "c" two inter-channel spaces with left and right boundaries moved aside.

Inside the constricted discharge channels matter is in plasma state (temperature experimental estimation is 1500 K at the basis of channel) hence it does not pass electric field inside and volume force magnitude equates zero; experimental estimation of heat source is 10^{10} W/m^3.

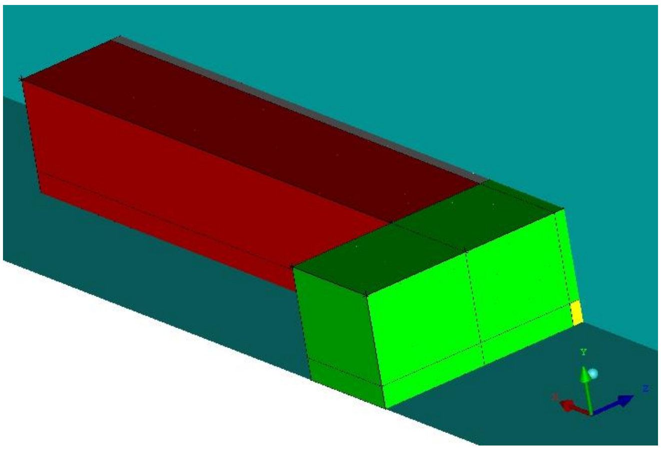
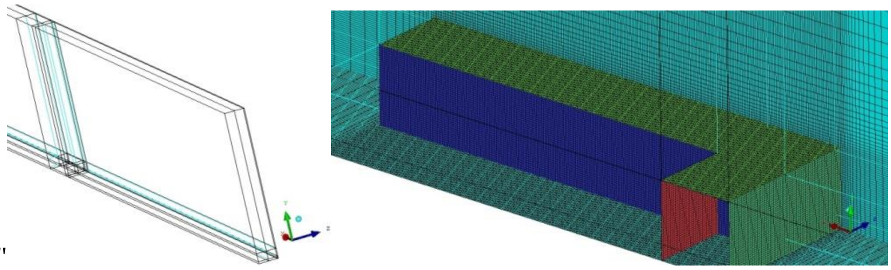


Figure 7: Configuration of computational areas with the source terms ("a" - domain type): green color denotes an area with the longitudinal volume force (X-direction), red color denotes the transversal volume force (Z-direction), and yellow color denotes discharge channel with heat sources and zero volume force.

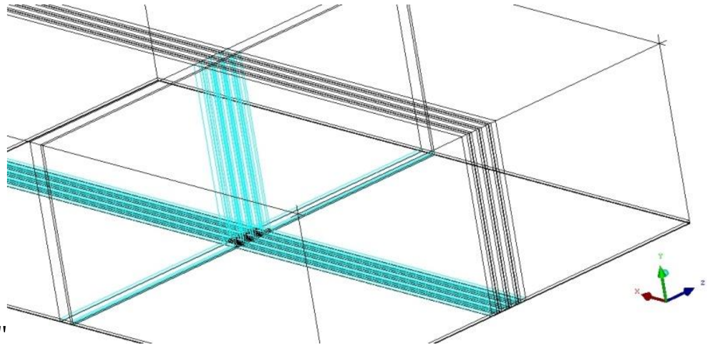
The volume force effect area size has selected on the ground of experimental and numerical research data [1-4]. An area with longitudinal volume force (X-direction) has been set at the basis of the channel (Fig. 7); an area with transversal volume force (Z-direction) has been set along the discharge channel region.

Exact value of volume force magnitude has been clarified during the validation simulations. As a first estimation results from [1-2] has been used, qualitative correspondence to experiment [2] was the main criteria during the volume force magnitude refinement.

Three computational domain structural 3D-meshesconsist of 36 blocks and about 2 million elements, 72 blocks and about 4 million elements, 180 blocks and about 4 million elements for "a", "b" and "c" domain types respectively (Fig.6). Mesh and block structure fragments are shown at Fig. 8.



"a"



"c"

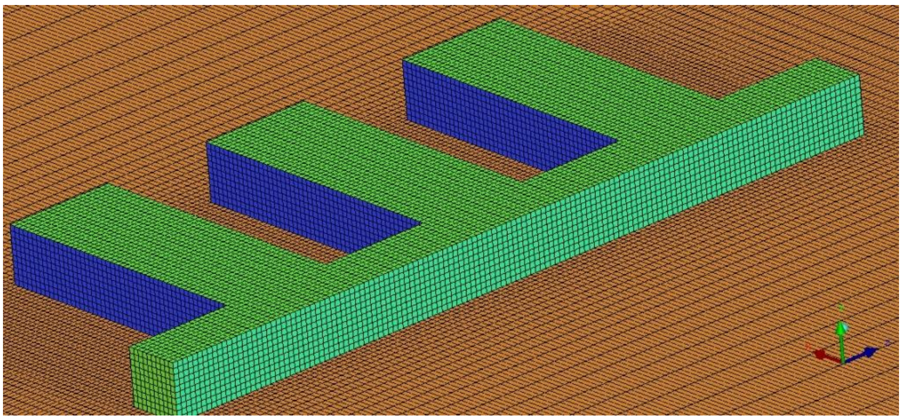


Figure 8: Computational mesh and block structure fragments for "a" and "c" domain types.

Boundary conditions on domain inlet : total pressure 101325 Pa, temperature 300K turbulence intensity - 2%, turbulence scale - 0.001 m; on outlet : static pressure 101324,7 Pa. Co-current flow velocity has value of 0,5 m/s under this conditions and equals experimental flow velocity.

3D steady calculation with Roe-FDS flux type solution method has been used. RANS system of equations has supplemented by Spalart - Allmaras turbulence model with standard wall functions.

Experimental estimation of heat source (1010 W/m3) has been based on one-channel power input estimation (5 W). The value of volume heat source magnitude has been also refined for a steady numerical problem in b domain type (Fig. 6). A correspondence of experimental and numerical temperature (600...1500 K) was the refinement criteria. The corrected volume heat source magnitude has been set at $2•10^9$ W/m3 for the further calculations.

The selected volume force magnitude value has been set at $6•10^3$ N/m3 for the further calculations. At this force (momentum) intensity in "b" and "c" domain types experimental pair vortex structures have been reproduced numerically. It has to be mentioned that "c" domain type shows the best experiment approximation of three options (Fig. 9).

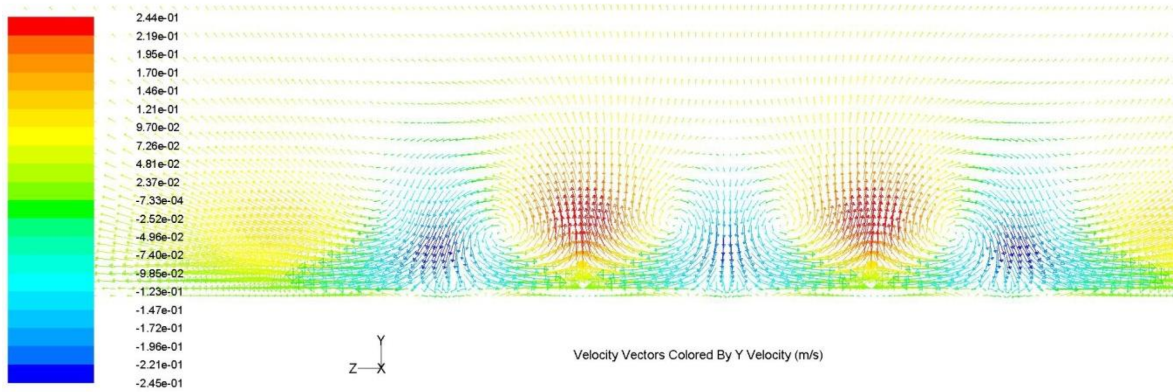


Figure 9: Y-velocity vector field at the last third of discharge channel cross-section ("c" domain type).

Actuators based on constricted DBD are perspective device for the real engine duct separation and pressure loss control. An annular model diffuser duct (Fig.1) with constricted DBD actuators has studied numerically as an application effectiveness estimation of this device.

Z-curvature of the segment of annular model duct (Fig.10) was disregarded due to small computational region width.

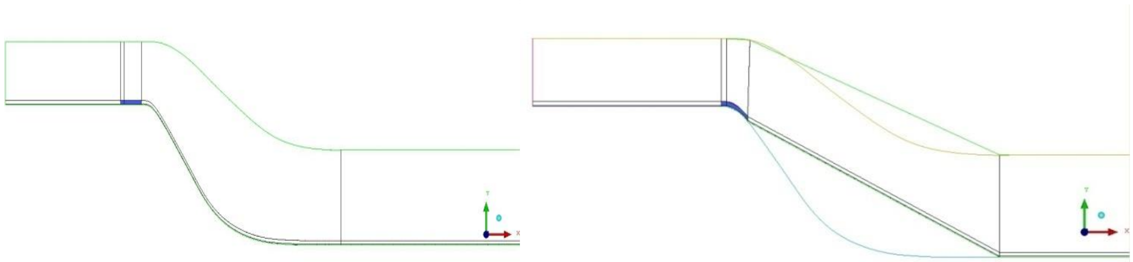


Figure 10: Geometry and block structure of the aggressive model duct, blue areas denote to different actuator and volume force effect area locations (left to right: #1 and #2).

Domains with two different actuators (hence, the volumes force area) location has considered (Fig. 10): #1 – directly before the separation zone, #2 – at the beginning of the separation zone.

Volume force and heat areas topology and channel quantity is similar to a validation problem "c" domain type with three discharge channels in Z-direction.

Solver type, boundary conditions, turbulence model and source terms magnitudes has been taken from a validation problem. Computational consists of 180 blocks and 4 million elements (Fig. 11).

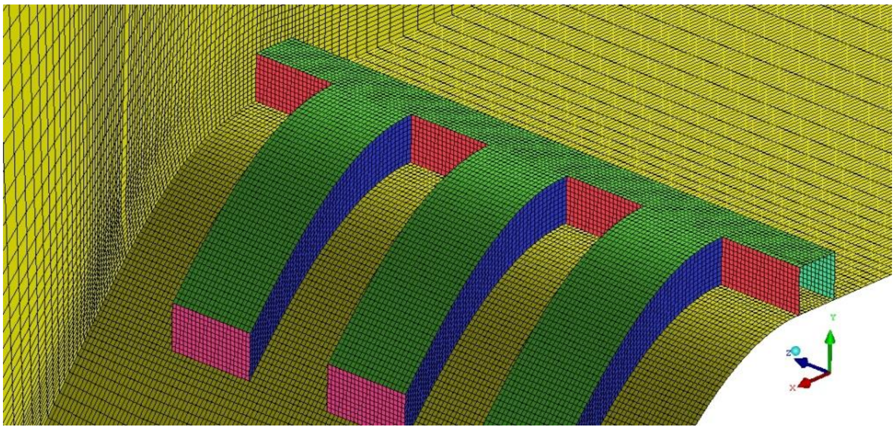


Figure 11: Computational mesh fragment for #2 volume force area location.

Z-direction volume force magnitude was the variable parameter. Duct pressure differential has been set at the value of 7825 Pa (101325 Pa and 93500 Pa, total inlet pressure and static outlet pressure respectively), inlet velocity has the value of 93 m/s under this conditions.

Velocity magnitude fields have presented on Fig.12. Volume force magnitude has been increased from zero (Fig.12, a) to a considerably large value, which affects flow separation zone (Fig.12, b, c).

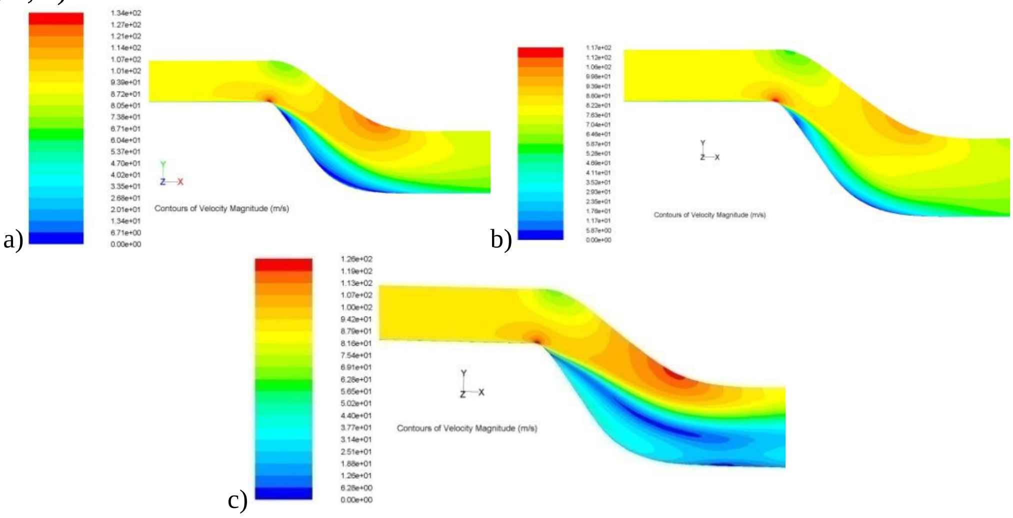


Figure 12: Velocity magnitude fields in longitudinal section: a) – zero volume force magnitude; b) – scheme #1 (Fig.10) volume force area location, c) – scheme #2 volume force area location.

The increased volume force magnitude value has been set at value of $2\cdot10^6$ N/m3.

DBD actuator #1 location has practically removed flow separation, except small region with reverse current (Fig.12, b). DBD actuator #2 location has partially promoted flow separation, because force (momentum) influence is located in separation zone mostly. It has to be mentioned that even a considerably large volume force magnitude value does not lead to a total flow separation zone removal in Z-direction (Fig. 13). It is presumably connected with pair vortex structures influence on the flow, which creates nonuniform flow structure.

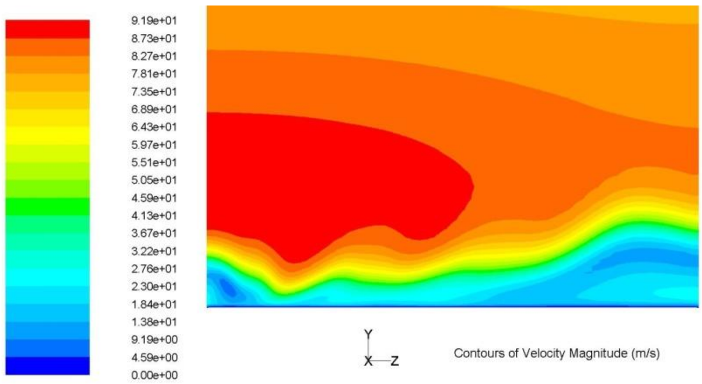


Figure 13: Velocity magnitude field in a cross section after DBD actuator location at the beginning of the diffuser part (scheme #1).

Constricted DBD flow control research results are similar to standard DBD ones. Significant effect on the flow separation zone could be reached only by applying large force (momentum) influence, which has not reached experimentally yet.

4 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. Main advantage of this more complicated approach is achievement of continuous volume force field which corresponds to features of physical processes near actuator.

Computational domain was analogous to previous calculations (Fig.14). The only difference is additional area 2 mm depth (black boundaries on Fig.14) modeling the dielectric material of actuator. Distance between the electrodes in streamwise direction is 0.5 mm, electrodes length – 1 mm.

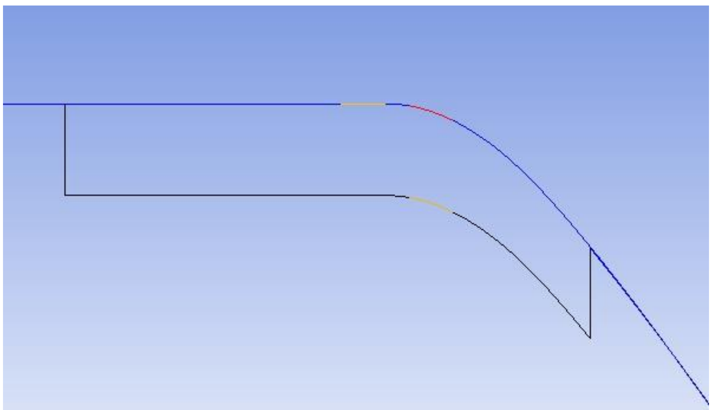


Figure 14: Boundary conditions in computational domain: orange color denote to electrodes, red color denote to area of variable charge density.

Computational 2D-domain consists of $5 \cdot 10^4$ elements. Dual-potential Method (DPM) was used for electrical characteristics (electrical potential φ and charge density ρ_C) calculations. This approach connected with solving a two-equation system for two components of electrical potential:

$$\varphi = \Psi + \Phi \tag{1}$$

Equations for both components are of the form:

$$\nabla \cdot (\varepsilon_r \nabla \varphi) = \frac{1}{\lambda_D^2} \varphi \qquad (2)$$

Connection between charge density and electrical potential is of the form:

$$\rho_c = -\frac{\varepsilon_0}{\lambda_D^2} \varphi \qquad (3)$$

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

Boundary conditions for two scalar values are:

$\varphi = \varphi_0 sin(wt),\ \rho_C = 0$ - for exposed electrode,

$\varphi = 0$ - for buried electrode,

$\frac{\partial \varphi}{\partial \vec{n}} = 0,\ \rho_C = \rho_{C0} sin(wt)$ - for variable charge density area,

$\frac{\partial \varphi}{\partial \vec{n}} = 0,\ \frac{\partial \rho_C}{\partial \vec{n}} = 0$ - for the wall above the dielectric,

$\frac{\partial \varphi}{\partial \vec{n}} = 0, \rho_C = 0$ - for the rest boundaries.

Typical fields of electrical potential φ and charge density ρ_C near the electrodes is presented on Fig.15 and 16.

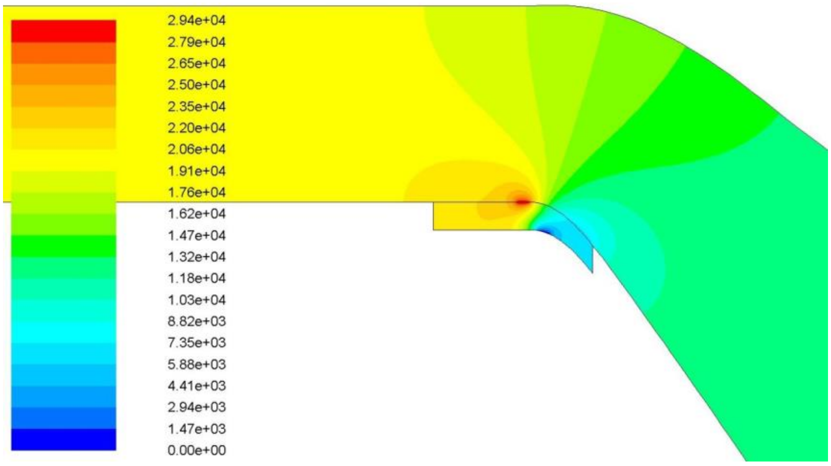


Figure 15: Typical instantaneous electrical potential φ (V) field.

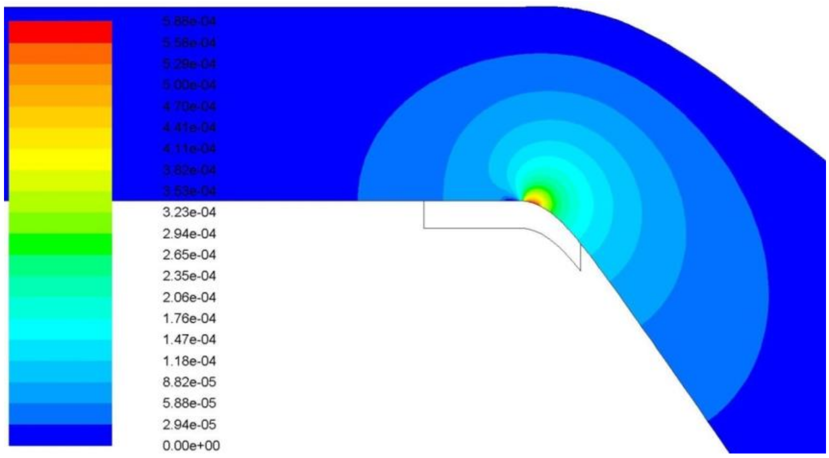


Figure 16: Typical instantaneous electrical potential ρ_C (C/m^3) field.

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 Fig.17 and 18.

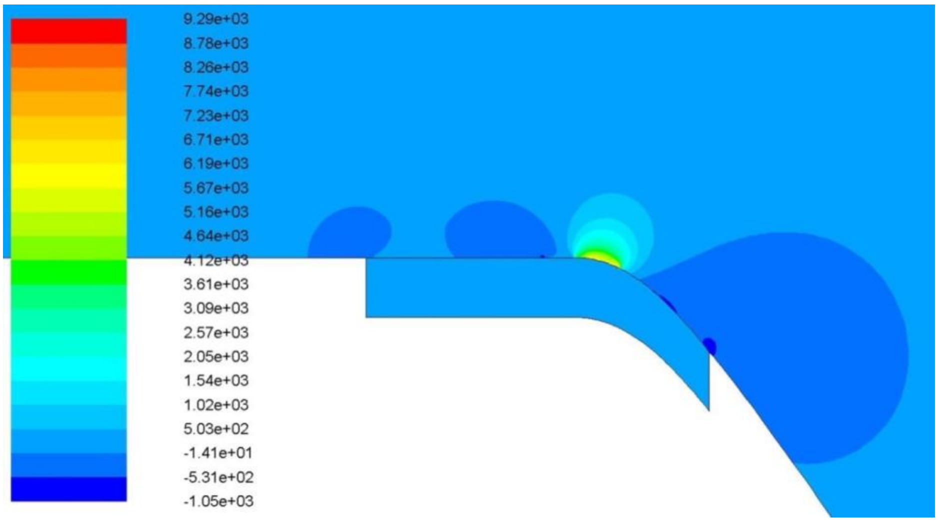


Figure 17: Time-averaged field of F_x force component for $\Delta\varphi$=50000 V, *f*=5000 Hz case (N/m^3).

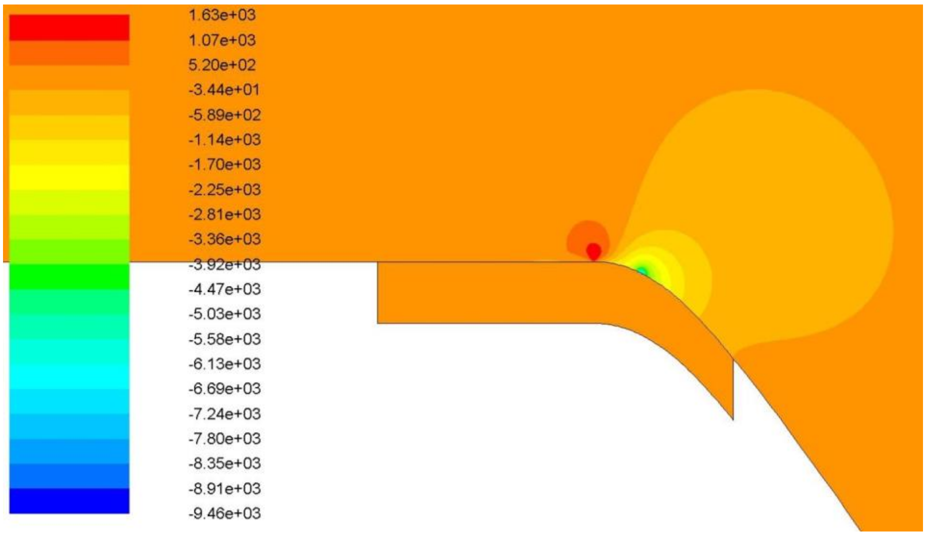


Figure 18: Time-averaged field of F_y force component for $\Delta\varphi$=50000 V, *f*=5000 Hz case (N/m^3).

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 $\Delta\varphi$=50000 V, charge density amplitude ρ_{0C}=0.1 C/m^3, and voltage frequency 5000 Hz are: $F_{xmax}=1.859*10^6$ N/m^3, $F_{ymax}=1.892*10^6$ N/m^3.

Significant difference between piecewise constant volume regions approach means that it could be used mostly only as a first approximation.

5 CONCLUSIONS

Numerical procedure of DBD modelling has been developed and tested in present study for both the standard DBD and DBD working in constricted mode. 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 potential difference and charge density amplitude.

REFERENCES

[1] Brandt A. Belson, Ronald E. Hanson, Denis Palmeiro, Phillip Lavoie, Katelyn Meidell, Clarence W. Rowley. Comparison of plasma actuators in simulations and experiments for control of bypass transition. *In:50th AIAA Aerospace Sciences Meeting*, 9–12 January 2012, Nashville, Tennessee.

[2] I. Moralev, S. Boytsov, P. Kazansky, V. Bityurin. Gas-dynamic disturbances created by surface dielectric barrier discharge in the constricted mode. *Exp Fluids 55:1747*, 2014.

[3] Y. B. Suzen, P. G. Huang, J. D. Jacob, D. E. Ashpis. 2005. Numerical Simulations of Plasma Based Flow Control Applications. *35th Fluid Dynamics Conference and Exhibit*. AIAA 2005-4633

[4] Arvind Santhanakrishnan, Daniel A. Reasor Jr.y, and Raymond P. LeBeauJr.z.2008. Unstructured Numerical Simulation of Experimental Linear Plasma Actuator Synthetic Jet Flows.*46th AIAA Aerospace Sciences Meeting and Exhibit, Jan.* 7-10, 2008, Reno, NV. DRAFT.

[5] B.E. Mertz, T.C. Corke, Time-dependent dielectric barrier discharge plasma actuator modeling. *47th AIAA Aerospace Sciences Meeting, Orlando, FL*, AIAA Paper, vol.1083, 2009

[6] Sheng-ji Dai , Yang Xia , Li-ming He, Tao Jin, Qian Zhang , Peng-hui Hou, Zi-chen Zhao. Film-cooling of cylindrical hole with downstream surface dielectric barrier discharge actuators. *International Journal of Heat and Mass Transfer 90* (2015) p.825–837

[7] E. Pescini, D.S. Martínez, M.G. De Giorgi, A. Ficarella. Optimization of micro single dielectric barrier discharge plasma actuator models based on experimental velocity and body force fields. *Acta Astronautica 116* (2015) p. 318–332