CFD simulation of DC-discharge in airflow

D A Tarasov and A A Firsov
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13, Bldg 2, Moscow 125412, Russian Federation
*af@jiht.org

Abstract. The main purpose of this work is to simulate a dynamics of DC discharge in a subsonic airflow. The calculations were performed in the FlowVision 3.12.01 software package. The single-fluid model (MHD approach) of equilibrium plasma was used while the initial discharge channel was set manually. Cylindrical coaxially arranged electrodes were located in the central part of the calculation area, in the core of the airflow. A 5A DC discharge at atmospheric pressure was considered, as well as a simple model of a re-breakdown between parts of discharge filament. In this work, three-dimensional distributions of temperature and current density were obtained during an evolution of discharge in a flow. Discharge channel extension by the airflow and partial channel decay after the re-breakdown process were shown.

1. Introduction
In recent years, active research has been carried out on the use of electric discharges in order to ignite fuel-air mixtures and stabilize combustion in high-speed flows [1]. Various locations and geometries of plasma modules and fuel injectors were studied. For example, the scheme of fuel injection directly into the discharge area was investigated in [2-4]. Another common solution for flame front stabilization is to use a cavity flameholder [5-6]. In [7], a high-voltage discharge was used in pair with such flameholder, and fuel was injected into the cavity. Consideration of a plasma system for both fuel ignition and flame front stabilization without the use of mechanical stabilizers was carried out in [8].

Compared to an experiment, computer simulation can provide complete three-dimensional distributions such properties like velocity, pressure, and temperature. That is why modeling in the field of plasma-assisted combustion is an urgent task. As a first approximation, the effect of the discharge on the flow can be simply modelled using volumetric heat source [9-10]. However, this approach has drawbacks - the impossibility of modeling a discharge of variable length, taking into account its interaction with the flow of the fuel-air mixture and further combustion modeling. More complex simulations of electric discharge have already been undertaken earlier using different electrodynamic models. In [11-13], a two-dimensional simulation of the discharge cross-section, which moves under the influence of constant magnetic field, was carried out. The discharge velocity, total current, and distributions in the simulation plane were compared with experimental data. In [14], three-dimensional distributions of discharge characteristics in a supersonic flow were obtained, where the problem was formulated axisymmetric, and a two-dimensional sector of the discharge was simulated for configuration with two electrodes located along the flow direction. However, the electric discharge channel is not a straight line, even if it is directed along the flow. Results of these two approaches do not fully describe the behavior of such essentially three-dimensional structure like an electric discharge in a flow: in experiments, the discharge channel often has parts directed both along and across the flow, which requires the use of 3D models in simulation.

In [15], a computational modeling of the Rail Plasma Actuator was performed. A fast moving arc discharge arising between two extended electrodes was considered. In this article, a re-breakdown of the discharge was simulated, but all calculations were carried out in the plane of the discharge.
In this work, the problem of three-dimensional modeling of a direct current electric discharge in a subsonic flow (excluding breakdown process) was solved as a preliminary stage for further modeling of discharge in supersonic flow. The evolution of the discharge channel in an airflow with electrodes located in the flow core was obtained by numerical simulation. In addition, a re-breakdown was simulated by setting a new current channel with a volumetric heat source.

2. Equations

In this work, a direct current discharge was simulated in a subsonic flow. FlowVision software package implements mathematical models of various processes [16]. Simulation were performed using three-dimensional unsteady Reynolds averaged Navier Stokes equations. The calculation also included heat transfer model using the energy equation written in terms of the total enthalpy. Joule heat was taken into account. In the FlowVision software, simulation of turbulent flows reposes on using turbulent viscosity in the equations describing physical processes. Modified k-ε FlowVision model was used in this simulation.

Used electrodynamic model is described by the following equations:

\[ \nabla \cdot \mathbf{j} = 0 \]
\[ \mathbf{j} = \sigma \mathbf{E} \]
\[ \mathbf{E} = \nabla \phi \]

Joule heat is calculated as:

\[ Q_{\text{joule}} = \mathbf{j} \cdot \mathbf{E} = \sigma \mathbf{E}^2 \]

In the current implementation of EHD process, it is assumed that dielectric permeability does not depend on the density of the medium. Then the Lorentz force is equal to:

\[ F_L = q \mathbf{E} - \frac{1}{8\pi} \mathbf{E}^2 \cdot \nabla \mathbf{E} \]

Following boundary conditions - electric potential and current density - were used for the electrodes. These boundary conditions are set by:

\[ \phi_b = \phi_{\text{ext}} \quad \text{and} \quad \left( \frac{\partial \phi}{\partial n} \right)_b = \frac{j}{\sigma} \quad \text{where index «b» means boundary.} \]

To calculate an electric discharge in an airflow using a single-fluid model, it is necessary to know the thermodynamic characteristics and transfer coefficients of the air. In addition, all the physical characteristics of the gas are required in a wide range of temperatures and pressures, since the temperature in the discharge could reach 8000 K at atmospheric pressure [4]. The temperature dependences of thermal conductivity \( \lambda (T) \) and specific electrical conductivity \( \sigma_e (T) \) are especially important for modeling the discharge channel. In this work, data on the physical characteristics of air from [17] were used, where calculated values have been fitted by closed forms. The range of their applicability, according to [17], is air at pressures of 0.01 – 100 atmospheres and temperatures of 50 - 60,000 K, which is several times larger than the range of values required for calculations. Copper was used as the electrode material, the physical characteristics of which were loaded from the FlowVision standard library of substances.

3. Discharge in a subsonic flow

3.1. Calculation domain

To simulate a discharge in a subsonic flow, a rectangular parallelepiped with dimensions of 20 cm × 10 cm × 10 cm was used as the computational domain. Two vertical cylinders with a diameter of \( D = 2 \text{ mm} \) and a height of \( h = 20 \text{ mm} \) located coaxially in the core of the airflow were used as electrodes. The interelectrode gap was 5 mm. Figure 1 shows the computational domain of the project.
In Figure 1, the entry boundary condition is marked in red. Inlet boundary conditions were $P_e = 1$ atm, $v = 100$ m/s, $T_g = 170$ K. At the exit from the computational domain, the free outlet boundary condition was used. This surface is shown in blue in Figure 1. On the surface of the electrodes and on the remaining faces of the domain, the no slip wall boundary condition with wall functions and zero temperature gradient was used.

All parallelepiped faces have zero potential boundary condition. In addition, a boundary condition was used on the walls of the electrodes, which ensures the continuity of the electric current. At the far ends of the electrodes, the boundary conditions responsible for direct current were used. Boundary condition of the top electrode was set to a constant current of 5 A using fixed current density, while the bottom electrode was set to a constant zero electric potential. The simulation is based on the experiments where a constant current was obtained by applying a high voltage to a system of electrodes, connected in series with ballast resistance. This resistance was much higher than the plasma channel resistance; therefore, the discharge current was almost constant. That is why constant current density boundary condition was used in this work.

The initial conditions set the temperature, velocity, and pressure in the entire volume, corresponding to the input boundary conditions. The initial current channel was established by setting the temperature $T_d = 8000$ K in the thin cylinder connecting the nearest ends of the electrodes.

The calculation used a rectangular Cartesian grid with adaptation. The project used both adaptation in a predetermined area and adaptation according to temperature and electric current density. Thus, the total number of cells was kept at the minimum required level for maximum efficiency of the calculation. The maximum number of calculation cells in a project was approximately two million. The cross section of the grid with temperature field in the plane of the discharge can be seen in Figure 2.

### 3.2. Simulation result

The results of discharge modeling in a subsonic flow are shown in Figure 3. The figure presents the dynamics of the current channel in the flow. It can be seen that the channel is lengthened by the airflow,
and its connection points are gradually shifted from the ends of the electrodes to the downstream surface of electrodes. During this movement, the thickness of the filament near the touching points increases, which led to the instability of these point positions (155 - 211 \( \mu s \)).

![Figure 3. Current distribution at different time moments.](image)

In a real experiment, the discharge channel will not lengthen infinitely. Increase of discharge length results in increasing of plasma resistance that cause the voltage rise on the top electrode at constant current. When a certain discharge voltage is reached, a re-breakdown could occur, mainly between the existing current channels, which will reduce the channel length. In an attempt to simulate this process in this calculation, a simple approach of a new current channel formation was used: its position was manually set based on the experimental images using a volumetric heat source. This short-range (less than a microsecond) heat source was turned on until the current through it was sufficient to maintain its existence. Figure 4 shows a temperature distribution overlaid with current density distribution to show the simulated re-breakdown process. It can be seen in this figure that after the breakdown the current through the longer channel becomes zero. It could no longer maintain its integrity and began to gradually cool down and decay.

![Figure 4. Temperature distribution with the current channel overlay (in red).](image)

During the simulation, the electrical characteristics of the discharge were recorded. The voltage measurement results can be seen in Figure 5. The voltage graph clearly shows a re-breakdown that occurred at 340 \( \mu s \). The same behavior shows an oscillogram taken from [8] and a photograph of the re-breakdown, obtained experimentally. This nature of the discharge behavior was discovered quite a long time ago, but research in this area continues and the topic is still actual [18].
Figure 5. Voltage time dependency obtained in this work (a), the graph of the voltage measured in the experiment [8] (b) and the photograph of the re-breakdown (c).

4. Summary

In this work, for the first time, a three-dimensional simulation of a direct current electric discharge in high-speed subsonic flow was carried out in the approximation of a single-fluid model of equilibrium plasma. The initial channel obtained after air breakdown was set manually. The calculation was carried out using the FlowVision software package. Using the analytical formulas from [17] the physical characteristics of air were calculated in a wide range of temperatures and pressures to improve modeling accuracy. As a result of modeling, three-dimensional distributions of temperature and current density were obtained during the evolution of discharge in a flow. Re-breakdown between parts of the electric discharge in subsonic airflow was manually initiated using volumetric heat source and its influence on the discharge channel and on the electrical characteristics was obtained.

References

[1] Leonov S B - Electrically Driven Supersonic Combustion Energies 2018 11(7) 1733
[2] Shibkov V M, Shibkova L V, Kopyl P V et al. Stabilization of Supersonic Combustion of Propane in an Expanding Aerodynamic Channel with the Use of Low-Temperature Plasma High Temperature 2019 V 57 164–176
[3] Inshakov S I, Skvortsov V V, Rozhkov A F et al. Spectroscopic Studies of Longitudinal Discharges in a Supersonic Air Flow during the Injection of Propane, Ethylene, and Oxygen into the Discharge Zone High Temperature 2019 V 57 798–807
[4] Firsov Alexander, Savelkin Konstantin V., Yarantsev Dmitry A. and Leonov Sergey B Plasma-enhanced mixing and flameholding in supersonic flow Philosophical Transactions of the Royal Society A 2015 373 2048 20140337
[5] Oamjee A and Sadanandan R Effects of fuel injection angle on mixing performance of scramjet pylon-cavity flameholder Physics of Fluids 2020 11 32
[6] Daniel Montes, Paul King, Mark Gruber, Campbell Carter and Mark Hsu Mixing Effects of Pylon-Aided Fuel Injection Located Upstream of a Flameholding Cavity in Supersonic Flow 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 2005 AIAA 2005-3913
[7] Sergey B. Leonov, Skye Elliott, Campbell Carter, Alec Houpt, Philip Lax, Timothy Ombrello Modes of plasma-stabilized combustion in cavity-based M = 2 configuration Experimental Thermal and Fluid Science 2021 124 110355
[8] Firsov A A et al Advanced Ignition in Supersonic Airflow by Tunable Plasma System IOP Conference Series: Materials Science and Engineering 2017 249 012022
[9] Falempin F, Firsov A A, Yarantsev D A, Goldfeld M A, Timofeev K, Leonov S B Plasma control of shock wave configuration in off-design mode of $M = 2$ inlet. *Experiments in Fluids* 2015 56 54

[10] Firsov A A, Yarantsev D A, Leonov S B, Ivanov V V Numerical simulation of ethylene combustion in supersonic air flow. *Computer Research and Modeling* 2017 9 1 75-86

[11] Toktaliev P.D., Semenev P.A., Moralev I.A., Kazanskii P.N., Bityurin V.A. and Bocharov A.N Numerical modeling of electric arc motion in external constant magnetic field. *Journal of Physics: Conference Series* 2020 1683 032009

[12] Ivan Moralev, Pavel Kazanskii, Valentin Bityurin, Alexey Bocharov, Alexander Firsov, Eugenii Dolgov and Sergey Leonov Gas dynamics of the pulsed electric arc in the transversal magnetic field. *Journal of Physics D: Applied Physics* 2020 V 53, N42, 425203

[13] Rakhimov R.G., Moralev I.A., Firsov A.A., Bityurin V.A. and Bocharov A.N. On the gas dynamics of the electric discharge in external magnetic field. *Journal of Physics: Conference Series* 2019 V 1147 012128

[14] Bityurin V.A., Bocharov A.N., Kuznetsova T.N. Numerical simulation of an axisymmetric discharge in a supersonic air co-flow. *Journal of Physics: Conference Series* 2020 V 1698 012027

[15] Computational Modeling and Physical Analysis of Rail Plasma Actuator Arc. *AIAA Aerospace Sciences Meeting* 2018 AIAA 2018-0935

[16] Aksenov A.A. - FlowVision: Industrial computational fluid dynamics. *Computer Research and Modeling* 2017 V 9, N 1, PP. 5-20

[17] D’Angola A., Colonna G., Gorse C. et al Thermodynamic and transport properties in equilibrium air plasmas in a wide pressure and temperature range. *The European Physical Journal D* 2008 V 46, PP. 129–150

[18] Logunov A.A., Kornev K.N., Shibkova L.V., Shibkov V.M. Influence of the Interelectrode Gap on the Main Characteristics of a Pulsating Transverse-Longitudinal Discharge in High-Velocity Multicomponent Gas Flows. *High Temperature* 2021 V 59, N 1, PP. 19-26