On the gasdynamics of the electric discharge in external magnetic field

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Abstract. The motion of an arc discharge in an external transverse magnetic field has been investigated experimentally and numerically. Two-dimensional modeling was carried out within the framework of the magnetoplasmadynamic approximation in the programs PLASMAERO and Comsol Multiphysics 5.3. A comparison of the calculation results with the experimental data shows a qualitative agreement between the observed temperature and velocity fields for both cases. At the same time, it was shown that the difference in the numerical approaches, used in either package, for a given problem leads to a significant difference in quantitative characteristics, such as arc diameter, peak temperature and arc channel velocity.

1. Introduction

The movement of the arc discharge (contracted current channel) in an external magnetic field occurs in a number of applications such as magnetic mixers, circuit breakers, advanced flow control apparatus (plasma actuators). In the latter case, certain expectations are associated with the use of pulsed arc in new high-speed flow control methods, as well as to intensify the mixing of fuel and oxidizer in high-speed ramjet combustors [1,2]. However, the understanding of the detailed processes responsible for the specific characteristics of the arc channel in a magnetic field is far from ideal now. This is partly due to the fact, that the contracted channel moving in the magnetic field is a rather complex object [3], in which the discharge characteristics (such as the current density and the current channel diameter) are inextricably linked with the gas dynamics of the process. Existing models (such as the solid rod model [3]) are not suitable for a self-consistent description of arc motion, and therefore development and verification of numerical models of the arc in a magnetic field is of some practical and scientific interest. The purpose of this paper is to study the dynamics of an arc channel in a magnetic field, as well as to verify the numerical models and procedures used in two different programs (JIHT RAS numerical code [1] and commercial software Comsol Multiphysics 5.3), by comparing the results obtained with experimental data.

2. Experimental part

The principal scheme of the experiment is shown in figure 1. The electric discharge is initiated in the initially quiescent air at normal conditions between two tungsten electrodes 0.1 mm thick and 37 mm long. The electrodes are installed in the central part of the discharge chamber with
Figure 1. Scheme of the experimental setup (from the left-hand side) and the appearance of the electrodes (from the right-hand side): 1—electrodes; 2—aerodynamic chamber; 3—permanent magnets; 4—receiver; 5—high-speed photoregistrator; 6—optical mirror; 7—computer; 8—oscilloscope; 9—flowmeter; 10—compressor; 11—circuit for measuring $I_{arc}$ and $U_{arc}$.

a cross-section of $20 \times 60 \text{ mm}^2$, open at both ends. The distance between electrodes is 10 mm. Using a system of permanent magnets (NdFeB38 $100 \times 100 \times 40 \text{ mm}^3$ with a magnet core), a constant uniform transverse magnetic field of 0.33 T normal to the electrodes plane is created. Power is supplied to the discharge in the mode of current source, a current pulse being a half sine wave with an amplitude of 30 A at a pulse length of 548 µs. To facilitate the breakdown, a pair of sharpeners is present on the electrodes. The discharge was visualized using a high-speed video camera with an exposure of the order of 1 µs.

The basic characteristics used to compare the calculation with the experiment were the arc sweep velocity (hot point velocity in numerical results), determined from the displacement along the electrodes of the central part of the discharge, and also the diameter of the luminous channel. The method of high-speed photographic registration made it possible to trace in detail the dynamics of the electric discharge under these conditions (figure 2).

As a result of the experiment, we can conclude that there is a significant three-dimensional discharge structure in this electrode configuration. The form of the discharge is a classic cord spanning the gap between electrodes. In all experiments, the velocity of anode spot exceeded the velocity of the cathode one. The central part of the arc channel in the growing part of the pulse retains its linear form. On the descending part of the pulse, a complex deformation of the arc channel is observed. The reason for this can be caused by the instability of the channel in this mode and requires a more detailed study. The maximum arc velocity at a given condition was found to be less than 125 m/s. During the evolution of channel, an increase in the primary size of the arc was observed with the subsequent channel diameter stabilization.

The waveforms of the current and voltage are shown in figure 3. It can be noted that there are no steps in the voltage trace, typical for shunting a part of the channel. In general, we can say that in the first half of the pulse (up to 300 µs), the central part of the arc channel can be regarded as a linear channel perpendicular to the electrodes and to the magnetic field. Consequently, the characteristics of the arc in this section can be used for comparison with the two-dimensional numerical modeling.

3. Numerical calculation

Numerical investigation of the channel motion in an external magnetic field was carried out in a two-dimensional magnetoplasmadynamic (MHD) approximation. A schematic diagram of the
Figure 2. Photographs of arc motion along the electrodes: left—31 800 fps; right—18 500 fps.

The numerical calculation is shown in figure 4. The motion of the arc is simulated in the X–Y plane; the magnetic field is directed along the Y axis, and is considered everywhere homogeneous and equal to 0.33 T.

For a detailed study of individual processes and obtaining the maximum available space-time resolution, a simplified two-dimensional cross-sectional model of the arc channel was considered. Within the framework of this model, the equations of gas dynamics and heat transfer were jointly solved. The heat release and the volume forces in the equations were calculated at each step as explicit temperature functions.

Mathematical modeling of the process was carried out in the commercial software package Comsol Multiphysics 5.3 and the numerical code PLASMAERO. The latter was previously designed in JIHT RAS for the problems of magneto gas dynamics and chemically reacting flows. The general model is based on the self-consistent solution of the Navies–Stokes equations, low-frequency electrodynamic equations and physical-chemical kinetics [1, 3]. For the problem considered in this paper, the PLASMAERO configuration was used describing the two-dimensional flow of the ionized air in the external electric and magnetic fields [1, 3]. In both cases air characteristics as a function of local temperature were estimated in accordance to [4]. Hall effect was not considered, i.e. local current density was proportional to the external electric field: \( j = \sigma E \), the latter considered constant across the calculation domain. In the case of the Comsol package, the solution of the equations of gas dynamics and thermal conductivity was realized by means of the Nonisothermal Flow module, which combines the gas-dynamic module Laminar Flow and heat transfer module Heat Transfer.

The calculation area in both cases was a rectangle with dimensions of 60 × 10 mm². A uniform rectangular grid with 0.1 mm step was used. As initial conditions in the primary
Figure 3. Current and voltage waveforms during discharge movement.

Figure 4. Schematic diagram of numerical simulation: (a) X–Y–Z space; (b) X–Y plane.

discharge region, a hot spot with a temperature of 9000 K and a size of 0.25 mm$^2$ was set. The pressure at all points of the computational domain was constant and equal to 1 atm; the initial flow velocity at the calculation was 0. On the left border of the region, a normal flow rate of 0 was set and a constant temperature of 273–300 K. To analyze the effect of the sidewalls of the chamber, two boundary conditions were alternatively considered: an open boundary and a symmetry condition. The magnetic field induced by the discharge current was estimated to be on the order of 3.5% of the external field, therefore it was neglected in Lorentz force term.
Figure 5. The result of the simulation—distributions of temperatures and velocity fields at a time point of 300 µs, red circle is the experimentally observed arc diameter of 1 mm: (a, b) Comsol Multiphysics; (c, d) PLASMAERO; (a, c) the open boundary condition; (b, d) the symmetry condition.
Figure 6. Comparison of numerical and experimental data: (a) the maximum gas velocity; (b) the position and velocity of the hot spot.

The determination of the source terms at each step of the calculation was carried out as follows. In the whole region where the discharge was present, the electric conductivity \( \sigma(T) \) was integrated. The value of the electric field strength was assumed constant across the domain and equal to

\[
E = \frac{I(t)}{\int \sigma(T) dS},
\]

where \( I(t) \) was the current pulse used in the experiment (see figure 3). The heat source and the Lorentz force in the discharge were calculated according to

\[
W = E\sigma(T)^2,
\]

\[
F_x = \sigma(T)EB.
\]

The structure of the flow observed in the experiment is shown in figure 5. The flowfield in the vicinity of the channel is determined by the combined influence of the Lorentz force and the thermal expansion of new gas portions in the discharge. Both in the flow field and temperature distribution, a frontal region of heat release with a maximum temperature and a pair of wake vortices following the discharge as it moves across the magnetic field, are clearly distinguished. It should be noted that, outside the described structure, the gas remains generally cold.

Despite the general qualitative agreement, the obtained patterns of temperature distribution and velocity field in different programs differ significantly (figure 6). According to the calculation in PLASMAERO, the discharge core is a small region (of the order of 1 mm) with the highest temperature (maximum value about 13 000 K); outside of this region the temperature drops sharply. Wake vortices are stretched along the sweep direction, forming two stationary “tails” with a temperature of the order of 6000 K. The size of the core approximates the experimental arc diameter (see figure 5). The boundary conditions in the first half of the pulse do not greatly affect the result. Differences appear when the current decreases in the second half of the pulse. The calculations using the symmetry condition on the sidewall shows the most close correspondance to the experimental position (and velocity) of the hot spot. Apparently, the walls of the experimental chamber, located at a distance of about 2 cm from the electrode, have some effect on the parameters of the discharge motion.

The size of the arc channel, which is calculated in the Comsol Multiphysics, is 1.5 times greater than the experimentally measured diameter (see figure 5). The length of the hot wake is
smaller; however, the temperature in the wake vortices is only slightly different from the leading core temperature. As a consequence of the larger size of the channel, the energy deposition in such an arc is less concentrated. The result of increasing the diameter of the arc channel is a decrease in the maximum gas velocity and the speed of its motion across the magnetic field (see figure 6). As in the case of the PLASMAERO code, the symmetry condition on the wall boundary gives a more plausible result, although even using it the sweep velocity differs from the experimental data by the factor of two. Still, the three-dimensional effects, obviously present in the experiment, can have a comparable effect on the discharge motion characteristics. Taking into account the general simplicity of the model used one should state a good correspondence of the obtained numerical results with the experiment, at least for the parameters used in this paper.

4. Conclusion
A numerical and experimental study of the arc channel motion at a fixed conditions (sinuous current pulse 30 A, magnetic field of 0.33 T at normal conditions is carried out. The numerical results obtained within the framework of the MHD approximation within Comsol Multiphysics 5.3 and PLASMAERO packages are compared with the experimental data on the arc channel sweep velocity. It is shown that the flow structure in the vicinity of the arc in a magnetic field is a pair of vortices whose dynamics determine the phase velocity of the arc channel motion (the arc sweep velocity). The calculated parameters of arc motion (speed, diameter, peak temperature) are determined to a significant degree by the conductivity model, and also by the method used to integrate the equations of gas dynamics. It is shown that the proximity of the walls of the aerodynamic chamber has some effect on the dynamics of the discharge; still this point requires a more detailed investigation. To provide a feasible reason for the discrepancies between the two packages one should have more details on the numerical procedures used in the commercial one.

References
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