Time dependent 2-dimensional model of an alternating current arc

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Abstract. Two computed models of an ac arc are considered in the paper. The burning of the arc in air is simulated between two electrodes, one of which is blown with gas. The simulation is performed using COMSOL Multiphysics software product. An incompressible flow is considered with default settings, when the density is constant and temperature-independent and the density is temperature-dependent. An analysis of the distribution of velocities, temperature on the axis, and the voltage drop across the arc is made.

1. Introduction

Simulation of plasma processes is a complex multiphysical problem including the description of hydrodynamics, heat exchange, chemistry and electromagnetism. At the same time the simulation of plasma processes is a powerful tool for designing and analyzing the devices using plasma. Nowadays, there is a variety of plasma arc models in various devices: DC [1], RF [2], AC [3] plasma torches and electrical apparatus [4].

The paper is dedicated to simulation of an ac arc burning in air. In the work we simulate an ac arc burning between two cylindrical electrodes, one of them is blown by air. This paper follows work [5]. Modeling of large 3D time models is a complex task requiring significant computing resources. Modeling of a compressible and turbulent flow is a time-consuming process involving a great quantity of steps with very small intervals [6]. Therefore, one of the standard approaches is the use of mathematical models with certain assumptions that allow correct description of physical processes. A lite 2D axisymmetric model is considered. The simulation enables us to describe the physical processes of real devices with specific accuracy only. Every subsequent model is improved for more exact description of the physical entity. In this particular case the gas density – temperature dependence has been added.
2. Model of an AC arc

The numerical model describes the burning of an AC arc in air between two electrodes. The task is non-stationary, the calculated time is 0.1 s with a 0.5 μs step. To simplify the numerical simulation, a two-dimensional axisymmetric problem is chosen. The simulation is carried out using Comsol Multiphysics software product.

2.1. Geometry and boundary conditions of the calculation model

The geometry and scheme are shown in Fig. 1. The model includes two electrodes 25 mm in length and 20 mm in diameter. The red line OO’ is an axis of symmetry. In 'Heat transfer in fluids' module, the 'Initial value' for the ABIJ (yellow area) is set at 3000 K and 300 K for the rest area. This means that at time t = 0, an arc 4 mm in diameter burns at temperature of 3000 K. Boundary condition for temperature is set for AB and IJ, which are cathode/anode spots is 2100 K, at boundaries BC and IH the temperature is 1000 K, at CD and HG is 300 K. For fluid at the ED edge the inlet boundary condition (normal inflow velocity) is specified. For better convergence of the hydrodynamic problem, the ramp function is used, the gas flow rate increases from zero to nominal (20 m/s) in 40 μs. Air is fed at 300 K. For the flow equations are no slip on the walls ABCD and JIHG. Pressure equals to 101325 Pa at the outlet (EFG) and temperature gradient in the normal direction is zero. Boundary condition terminal on electrode ABCD is specified in `Electric Current` module. A terminal type current has been chosen, for which a 50 Hz and 50 A sine-wave current has been set. 'Ground' condition has been chosen on JIHG electrode. Two conditions have been chosen in Multiphysics module:

1) Equilibrium discharge heat source, where the sources are set through the module coupling 'Heat transfer in fluids and Electric Current: Joule Heating, Enthalpy transport and Volumetric net radiation loss

2) Lorentz Force

2.2. Assumption and simplification

At gas velocities below 20 m/s, it is obvious that the Mach number is less than 0.3 and the gas is incompressible. The Reynolds number does not exceed 2000 and the regime is laminar. Since the model is two-dimensional and axisymmetric, gravity and buoyancy force are not allowed for. The plasma is considered in the condition of thermodynamic equilibrium and as a homogenous liquid (nitrogen, argon, etc.). The near-cathode and near-anode processes are neglected because of high voltage. The pressure and viscous dissipation force are neglected.

2.3 Set of equations

To simulate the arc burning process it is necessary to apply the following modules: CFD (Laminar flow), Heat transfer in fluids, AC/DC (Electrical current, Magnetic Fields) and Multiphysics (Lorentz force, Equilibrium discharge). Using these modules, the model is described by 11 equations, including the equation of motion (1), in which the Lorentz force (10) is taken into account and supplemented by the continuity equation (2), and the energy balance equation (3,11). The electromagnetic field is calculated using the set of Maxwell’s equations and Ohm’s law (4-9). Equation № 1 in Comsol describes the flow of an incompressible flow fluid. With the default settings for an incompressible flow, Comsol calculates the density in the hydrodynamic problem by Tref. Reference temperature is the global quantity used to evaluate the density of the fluid when the Incompressible flow is selected.
Two models were calculated: the first with the density dependence on temperature, specifying the dependence, the second using the default settings with $T_{\text{ref}} = 300$ K.

\[
\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = \nabla [-\rho I + \mu (\nabla u + (\nabla u)^T)] + F \tag{1}
\]

\[
\rho \nabla (u) = 0 \tag{2}
\]

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla (-k \nabla T) = Q \tag{3}
\]

\[
\nabla \cdot J = Q_j \tag{4}
\]

\[
J = \sigma E + \frac{\partial D}{\partial t} + J_e \tag{5}
\]

\[
E = -\nabla V \tag{6}
\]

\[
\nabla \times H = J \tag{7}
\]

\[
\nabla \times A = B \tag{8}
\]

\[
E = \frac{\partial A}{\partial t} \tag{9}
\]

\[
F = \frac{\text{Re}(J \times B)}{2
\}

\[
Q = \frac{\partial}{\partial T} \left( \frac{5 k_B T^3}{2 q} \right) \cdot (\nabla T \cdot j) + E \cdot J + Q_{\text{rad}} \tag{11}
\]

Where $T$ is the temperature; $\rho$ is the fluid density; $C_p$ is the specific heat capacity; $u$ is the velocity field; $k$ is the thermal conductivity; $Q$ is the heat source; $Q_{\text{rad}}$ is the volumetric net radiation loss, $J$ is the current density; $\sigma$ is the electric conductivity; $\varepsilon$ is the electric permittivity; $E$ is the electric field intensity; $V$ is the potential difference; $A$ is the vector potential of magnetic field; $H$ is the magnetic field intensity; $B$ is the magnetic flux density, $I$ is the identity tensor; $F$ represents the body forces, including the Lorentz force; $\mu$ is the dynamic viscosity; $p$ is the pressure.

3. Results

The calculation was carried out on one node "Polytechnic - RSK Tornado" (Intel Xeon E5 2697 v3, DDR4 64 Gb). It took 5 hours, 42 minutes, 44 seconds to calculate the model with the constant density and 4 hours, 48 minutes, 46 seconds with the variable density. As a result, the temperature, velocity, and electric field distributions were obtained. Figures 2-5 and Fig.7 show the temperature distribution and velocity components along the $z$ axis on the symmetry axis for the maximum, minimum and zero values of voltage drop on the arc (Fig.7). The temperature in the arc is on the average in the range from 6500 to 9500 K. It can be seen from Fig.7 that at the initial moment of time the voltage drop reaches 5 kV in both cases, for the next peak the voltage drop reaches 1 kV and 2 kV for the constant density and for the variable density respectively. The consequences of these phenomena are presented in Fig. 2 and Fig. 4. There is the arc break, for the repeated ignition increases the voltage. The mode is set within 0.25 s. In the steady-state regime, the peaks of the arc re-ignition for the cases with the variable density of 0.55 kV and for the constant density of 1.25 kV differ. This is due to the fact that at the constant density, the gas layers are mixed better and near the blown electrode the arc is continuously cut off and re-ignited (Fig.6). This can be traced by the temperature distribution on the axis. At the blown electrode, the reverse flow region is formed, for the case with the variable density the length of the region is 70 mm and the average speed is about 12 m/s, for the constant density the speed is 18 m/s and the length is 30 mm.
Fig. 2 Temperature distribution $V=0$ (constant density (left), variable density (right))

Fig. 3 Velocity distribution $V=0$ (constant density (left), variable density (right))

Fig. 4 Temperature distribution at minimum ($\square$) and maximum ($\Delta$) voltage peak (constant density (left), variable density (right))

Fig. 5 Velocity distribution at minimum ($\square$) and maximum ($\Delta$) voltage peak (constant density (left), variable density (right))
4. Conclusion
The temperature dependence of the density has been added to the model. From the results obtained, it can be concluded that for the given parameters the steady state regime of the arc is set within 0.025 seconds. To obtain the required calculation data and save computing resources, the simulation time can be reduced from 0.1 s to 0.055 s. This model allows us to estimate the return flow, obtain the temperature distribution and voltage drop. Analysis of the obtained data is very important in the design and study of plasma devices and processes.

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