A non-stationary model of the AC plasma torch

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Abstract. Modelling of a single-phase two-channel AC plasma torch with a calculated power of 1.1 kW at a current value of 6 A is presented in the paper. A model of the plasma torch operation on argon at a flow rate of 0.69 g/s is considered. A 35-millisecond operation of the plasma torch has been simulated. The obtained temperature distributions and arc voltage drops allow us to evaluate the simulation results at a qualitative level.

1. Introduction

Properties of electric arcs of the plasma torches are not fully investigated and at the moment there are many unresolved issues. The characteristics of electric arcs are important for a wide range of tasks: film deposition [1], waste disposal [2]. Study of these physicochemical processes and their characteristics are topical and urgent for further efficient improvement and practical application of the studied plasma torches, as their efficiency, reliability, stability, long lifetime and control over of these processes issue the engineering and practical challenges [3]. A large volume of studies of AC plasma torch was carried out at the Institute for Electrophysics and Electric Power of the Russian Academy of Sciences [4,5]. Such devices can be powered from hybrid power sources [6], which will lead to high stability of the autonomous operation of plasma chemical facility. Studies of the AC plasma torch as a part of the plasma chemical reactor for the waste destruction for the Mars mission were conducted in Kennedy Space Center NASA [4]. A comprehensive study of the operation of the three-phase low voltage AC plasma torches with the use of mathematical modelling was held in MINES ParisTech [5]. However, in terms of the complexity of the study of plasma torches in the laboratory environment, mathematical modelling presents a powerful tool in the hands of the researchers. Most of the papers on simulation of plasma torches are devoted to DC devices [6,7] and devices operating at high frequency [8]. In some papers, researchers consider models with turbulence [9, 10], taking into account the erosion of electrodes [11], and non-equilibrium models [12]. This work continues the cycle of works [13,14] on modelling the AC high voltage arc.
2. Single-phase high voltage AC plasma torch
The object of study in this work is an AC high-voltage plasma torch with the gaseous-vortex stabilization of the arc. A single-phase AC high-voltage plasma (Figure 1) torch can operate in different plasma media, such as air or argon [15]. The power of the plasma torch can reach 10 kW. The housing is made of stainless steel and equipped with a water cooling jacket. There are the converging cylindrical channels in it. Replaceable electrodes are made of a special alloy of iron and copper. An arc discharge is initiated when the operating voltage is applied to the electrodes in the areas of the minimum gap between them and the channel walls. The formed electric arcs are blown out by the flow of plasma-forming gas to the ends of the electrodes, stabilized and closed at the outlet of the channels. Figure 2 shows a typical oscillogram of voltage and current for this type of plasma torch [16].

![Figure 1. High-voltage AC plasma torch with rod electrodes: 1-housing, 2-electrode, 3-channels.](image1.jpg)

![Figure 2. Oscillogram of current and voltage at air flow 1.26 g/s.](image2.jpg)

3. Model of the AC plasma torch
The simulation is performed in the Comsol program. The model is time-dependent, it is modelled for 0.12 seconds with a 50-microsecond step. The following modules were taken to simulate the arc combustion process: CFD (Laminar flow), Heat transfer in fluids, AC/DC (Electrical Circuit, Electrical current, Magnetic Fields) and Multiphysics (Lorentz force, Equilibrium discharge). Equations 1 and 2 describe the motion of the incompressible fluid taking Lorentz force into account.
The heat problem is described by the energy balance equation (3). The electromagnetic field is calculated using the set of Maxwell’s equations and Ohm’s law (4-7).

\[\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = \nabla [\rho (\nabla P + \mu (\nabla u + (\nabla u)^T)) + \frac{Re (J \times B)}{2}] \]

(1)

\[\rho \nabla (u) = 0 \]

(2)

\[\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla (-k \nabla T) = \frac{\partial}{\partial t} \left( \frac{5k_b T}{2q} \right) \cdot (\nabla T \cdot J) + E \cdot J + Q_{rad} \]

(3)

\[\nabla \times H = J \]

(4)

\[\nabla \times A = B \]

(5)

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

(6)

\[E = -\nabla V \]

(7)

The following simplifications and assumptions are made in this model:
1. The gas is incompressible.
2. The gas flow is laminar and time-dependent.
3. Inductive currents are neglected.
4. Gravitational effects and radiation are not taken into account.
5. Plasma is considered as a single continuous fluid (nitrogen) and at Local Thermodynamic Equilibrium (LTE).
6. The near-cathode and near-anode processes are neglected.
7. The pressure and viscous dissipation force are neglected.

3.1. Geometry, initial and boundary conditions

The estimated area (Figure 3) presented two channels 210 mm in height and 20 mm in diameter. The height of the electrode was 94 mm, the diameter of the wide part was 17.5 mm and of the narrow part was 12 mm. The outer volume was a 100 mm cylinder with a 140 mm diameter.

**Figure 3.** The geometry of the model.

Geometrically at the initial moment, an arc with the temperature of 8000 K was set. The gas was supplied tangentially to the electrodes. Its were investigated 4 models with a gas flow rate of 0.12 g/s, 0.38 g/s, 0.55 g/s and 0.69 g/s. The simulation time was 0.03 seconds for the first three models, for the latter it was set to 0.035 seconds. The results of the last step were the initial conditions for the subsequent model. This was done to bring the initial conditions closer to the real picture. In addition, to improving the convergence, the gas flow was fed smoothly by setting the Ramp function. It rose from zero to nominal in 0.2 ms for each of the flows. Based on experimental measurements of the light diameter of the arc for this type of plasma torch there were set the cathode/anode spots 2 mm in
diameter with a boiling point of copper 2800 K at the ends of the electrode. The temperature of 1000 K was set at the rest end surface of the plasma torch. Under the assumption that the gas was supplied with a temperature of 300 K and it cooled the walls and electrodes, the same temperature was set on them, too. At the boundaries of the output cylinder, the conditions Outlet pressure 0 atm and Outflow were set. A circuit with a current source with the effective value of 6 A was created in the Electrical Circuit module, and Terminal boundary condition was set at the first electrode and Ground boundary condition was set at the second one.

4. Results and Discussion
The main characteristics of the plasma torch, which can be obtained using the presented model, are the temperature field at the output, the velocity profile and the magnitude of the arc voltage drop. The characteristics of a plasma torch operating on argon with a flow rate of 0.69 g/s were obtained. Figure 4 gives the temperature fields in the electric discharge channels at the points of time that correspond to zero and maximum values of the current (the arc current waveform is shown in Figure 5). Formation of a near-wall layer of the cold gas and its retention during the operation is noticed in the presented temperature fields that are specific for this plasma torch. For this mode, the gas flow the arc closing occurs near the nozzle exit of channels.

Figure 4. Temperature distribution at different points of time.

It is worth noting that a significant amount of experimental studies were conducted previously for this type of plasma torches at the IEE RAS plasma torches test bench [17,18], but the studies were conducted not for argon (mainly for air). Nevertheless, the results obtained earlier allow us to assess the adequacy of the presented model at the qualitative level. When conducting the experiments at different flow rates, it can be observed that the area of the arc closing may be further or nearer to the exit of channels.
In Figure 4 one can see the break of the arc, but with the improvement of the grid this area will be more apparent and the break can be observed on the oscillogram in Figure 5 too. In Figure 7 it is clear that the pulsating nature of the temperatures specific for this plasma torch operating from the AC network at a 50 Hz frequency. Considerable temperature fluctuations are also noted near the electrode, this fact may be associated with the cooling and compression of the arc in the near-electrode area. Further, along the axis, the gas is warmed up and the temperature fluctuations decrease. With the cooling of the arc in the near-electrode area and the approaching of the current to zero, the voltage increases abruptly and the arc is re-ignited (Figure 4, Figure 5).

Figure 5. Oscillogram of voltage and current.

Figure 6. Temperature distribution along z-axis at points at distances from the nozzle exit section of the plasma torch.

Figure 7. Temperature distribution along z-axis at points at distances from the electrode face.
From Figure 6 it is seen that at a distance of 25 mm, the pulsating nature of the flow fades and at large distances, the flow is similar to the flows of DC plasma torch. The temperature curves after the point of 25 mm tend to asymptotic temperatures near 3500–4000 K. This can be defined as a transition from the initial conditions to the convergence to the operating mode. However, to speak about forcing into the regime, it is necessary to conduct a long-term study. This will allow to talk about the average mass and time-average output temperatures. The estimated power of the plasma torch was 1136 W.

5. Conclusion
This model is the first step in the study of plasma torches of this type operating on argon. The model adequately describes the change in the parameters in the discharge channels of the plasma torch, allows to analyze the electrical, thermal and gas-dynamic parameters of the plasma torch at any point in the region and at the selected time. The disadvantages of the model conditioned by the assumptions and approximations include the constant temperature on the walls and electrodes. It is also necessary to expand the design area and adapt the mesh for this calculation. The results are useful for analysis of the electrode erosion, selection of the mode of operation of the plasma torch, design of a more efficient input of plasma-forming media into the channels as applied to plasma chemistry, as well as to find out the reasons of the plasma torch failure at the boundary conditions. However, to speak about the applicability of these results, it is necessary to verify the model and make adjustments taking into account the experimental data.

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