Effect of turbulence on the parameters of the plasma flow in a high-voltage AC plasma torch

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A three-dimensional model of a dual-channel plasma torch operating on air at a flow rate of 3 g/s has been developed. A comparative analysis of laminar and turbulent formulations was conducted.

Keywords: low-temperature plasma, plasma torch, numerical simulation, turbulence, alternating current.

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Thermal plasma generators are applied in a number of demanded technologies, including production of hydrogen and syngas from hydrocarbons, waste reprocessing, destruction of toxic compounds and synthesis of ultrafine materials. Electric arc plasma torches that provide high energy intensity in a working gas can intensify chemical processes, decrease a reaction zone and reduce overall dimensions of equipment at high performance. Key fields of application include: metallurgy — plasma-arc heating for smelting and purification of metals — cutting, welding, coating; plasma-based chemistry — hydrocarbon pyrolisys, treatment of toxic and radioactive waste reprocessing. The plasma torches designed in the Institute for Electrophysics and Electric Power of the Russian Academy of Sciences have a service life of up to 2000 h, thermal efficiency of up to 95 % and low operating costs, thereby making them competitive for industrial application [1,2].

Optimization of promising designs requires studying physical-chemical processes in an arc discharge, which shall include simulation of fluid dynamics, heat exchange and electromagnetic phenomena.

Taking into account a wide range of operating parameters of the AC plasma torches within the gas dynamics field, it is required to consider both laminar and turbulent flow regimes. In plasma technologies, turbulence plays a critical role due to enhancing transfer of mass, momentum and energy. In particular, in arc DC plasma torches with a long arc column turbulent effects significantly affect stability and heat exchange.

The main complexity when calculating turbulent flows in a plasma is related to a wide range of scales of vortex structures, thereby making it almost impossible to construct a universal model of turbulence. Traditionally, the arc plasma torches are simulated using RANS-models that provide stability and acceptable computational costs [3–5].

The present study logically continues a cycle of studies by the authors, which are dedicated to simulating physical processes in the AC plasma torch. For a single-liquid approach that assumes that it is possible to describe a reacting plasma-forming gas of a complex composition within the framework of a model of single „fluid“ with physical properties depending on the temperature and pressure [6–8], the previous research stages included development and verification of numerical models of a separate plasma torch channel — in a simplified two-dimensional axisymmetric approximation [9–11] and in a three-dimensional formulation [12]. The numerical analysis included comprehensive calculation of thermophysical and electrodynamic parameters of a plasma flow.

Results of the said studies demonstrated a high degree of consistency of data obtained by the single-liquid model with calculations within the framework of a model of a chemically reacting flow, which takes into account a system of 34 reactions of formation and recombination of neutral particles [11]. The obtained results also showed good agreement with the experimental data [12]. Besides, it is confirmed that within a wide range of working gas flowrates a static pressure difference along the channel is small and significantly less than the atmospheric pressure (it does not exceed 200 Pa) [9]. This circumstance makes it possible to neglect a dependence of the plasma properties on the pressure and limit by their function on the temperature.

Previously, the studies dedicated to simulation of the processes in the AC plasma torch [9–12] considered quite small flowrates of the plasma-forming gas (up to 2 g/s). The respective Reynolds numbers calculated by the flow parameters of the „hot“ plasma-forming gas in the channels and the jet did not exceed 3000 and a laminar formulation was used for the calculations. However, even in this range for the maximum flowrates we observed formation and displacement of the vortex structures at a jet periphery outside the plasma torch channels. It should be also noted that in some designs of the plasma torches the gas is supplied into the channels via small-diameter branch pipes.

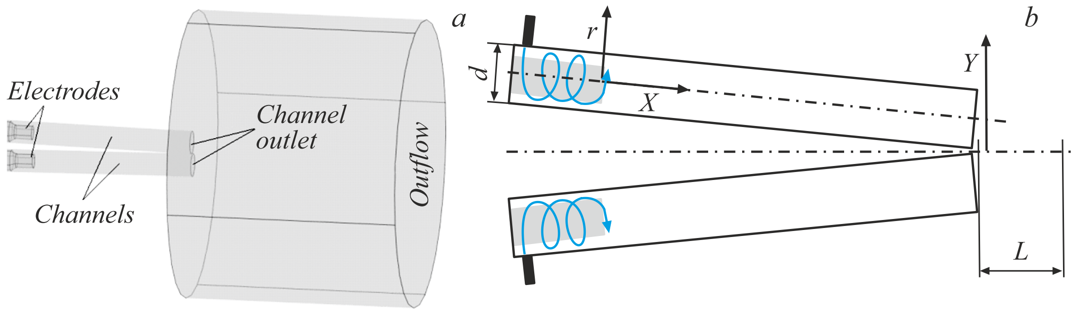

Figure 1. Setup diagram: *a* — overall view of the computational domain, *b* — axes and typical dimensions [12].

The large values of the flowrate result in high values of the Reynolds numbers (above 10 000) in an area of inlet branch pipes and a turbulent nature of the flow in the initial section of the plasma torch, which precedes a section containing electrodes [13]. Thus, the large gas flowrates generally require consideration of different flow regimes.

The present investigation is based on the problem formulation [12], the geometric parameters and the laminar flow model, which were previously provided. It is assumed in the present study to extend the problem formulation by studying the effects of turbulence simulated within the framework of the RANS-approach. The present study provides results of simulation using the Realizable k–ε-model, which overcomes limitations of a standard version of the k–ε-model and is better suitable for the flows with strong vortices, breakaway and anisotropy, as well as compares them with a laminar model. This modification was designed for calculations within the wide range of the Reynolds numbers and demonstrates higher accuracy when simulating complex turbulent flows [14,15].

The mathematical model [6,9] presupposes a joint solution of the system of equations of continuity (1), motion (2), energy taking into account losses for radiation in an approximation of an optically transparent plasma [16] (3), an equation for turbulence kinetic energy k (4), an equation for turbulence kinetic energy's dissipation ε (5) and an equation for an electric field potential (6):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{1}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \nabla \cdot \tau, \tag{2}$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p(\mathbf{u} \cdot \nabla T) = \nabla \cdot (\lambda \nabla T) - \tau : \nabla \mathbf{u} + \sigma E^2 - Q_{rad}, \tag{3}$$

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho k \mathbf{u}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + P_k - \rho\varepsilon, \tag{4}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla \cdot (\rho\varepsilon\mathbf{u}) = \nabla \cdot \left[\left(\mu + \mu_t/\sigma_\varepsilon\right)\nabla\varepsilon\right] + C_1\rho\frac{\varepsilon}{k}P_k - C_2\rho\frac{\varepsilon^2}{k}, \tag{5}$$

$$-\nabla \cdot \left(\frac{\partial \varepsilon_0 \varepsilon \nabla V}{\partial t} + \sigma \nabla V\right) = 0, \tag{6}$$

where t is time, [s]; ρ is a medium density, [kg/m^3]; $\mathbf{u}$ is a flow velocity, [m/s]; p is a pressure, [Pa]; T is a temperature, [K]; V is an electric field potential, [V]; C_p is heat capacity at the constant pressure, [J/(kg·K)]; μ is dynamic viscosity, [Pa·s]; λ is thermal conductivity, [W/(m·K)]; σ is specific conductivity, [S/m]; ε is relative permittivity of the medium; Q_{rad} is specific power of losses for radiation, [W/m^3]; τ is a tensor of viscous stresses; $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$ is turbulence viscosity; $P_k = \mu_t S_{ij} S_{ij}$ is production of turbulence kinetic energy; $S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$ is a strain tensor; C_1 and C_2 are constants. The system of equations (1)–(6) is closed by a generalized Clapeyron equation written via a molar mass of a mixture [8].

The model presupposes presence of local chemical and thermodynamic equilibrium. The heat capacity, thermal conductivity coefficient, molar mass and gas electrical conductivity are temperature functions and take into account effects of variation of the mixture parameters when chemical reactions proceed [6–8]. Traditional assumptions also include negligence of the influence of magnetic fields for the considered range of plasma torch currents. The model does not take into account processes of cooling of the electrodes and the walls (the surface temperature is 300 K), electrode erosion and an Archimedes force. Thus, the problem formulation generally corresponds to the study [9]. The considered problem geometry is shown in Fig. 1 and corresponds to the study [12].

A zero-potential condition is pre-defined at one electrode, while a current condition is pre-defined at another one by the following dependence (7):

$$\int \mathbf{j} \cdot \mathbf{n} \cdot dS = I_{rms} \cdot \sin(2\pi \cdot f \cdot t), \tag{7}$$

where $\mathbf{j}$ is a current density, [A/m^2]; $\mathbf{n}$ is a normal vector; S is a surface area, [m2]; I_{rms} is an effective current

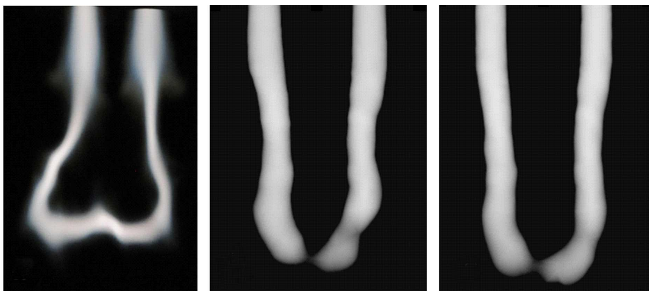

Figure 2. Arc comparison: *a* — the experiment photo, *b* — the laminar model, *c* — the turbulent model.

value (6 A), [A]; f is a current frequency (50 Hz). Initial conditions and boundary conditions for the other surfaces correspond to the study [9,12].

Fig. 2 compares three images of the electric arc (at the temperature above 5000 K), which are obtained experimentally (Fig. 2, *a*) and computationally (Fig. 2, *b*, *c*).

In practice, the plasma torch is arranged in a horizontal position and the flow goes upward (the left part of the arc). The arc has a bright glow that is more intense in the central part and gradually evanescent towards the periphery. An arc shape is slightly widened at its base and narrows with a distance from the electrode. Luminosity is the greatest in the arc center and decreases towards the periphery. It is related to a temperature gradient: the high temperature in the arc core causes intense light emission. Slight oscillations of the arc shape are visible, thereby indicating its instability under effect of external factors (turbulence, the Archimedes force). The simulated arcs are more sharply outlined and symmetrical. They have clear boundaries between the core and a surrounding gas. It should be noted that calculations both in the laminar and turbulent formulation result in a qualitatively correct arc shape. The result of calculations based on the different models turn out to be similar. The calculation models predict a higher voltage peak during arc reignition relative to the experiment (Fig. 3). This divergence is related to the fact that the calculation does not include copper atoms in a flow field (a result of electrode erosion). Addition of copper increases conductivity of the medium can result in reduction of the reignition voltage. The experiment also exhibits an additional voltage peak before the main one and it is not reproduced in the calculations.

Fig. 4 shows distribution of the temperature and the velocity modulus of the plasma-forming gas along the axis of the plasma torch channel, which are average over five periods. The graph shows data for the two regimes: the zero current („min“) and the amplitude current value („max“). The temperature in the channel varies from 4500 to 6500 K in both the models. A nature of behavior of the temperature is identical for all the cases with a deviation by 100–200 K. At the current zero moment, the maximum temperature is recorded at the electrode in both the cases. It is related to the fact that at this moment in the area of the electrode butt-end a Joule heating energy is zero and a stagnant zone is formed in this area. At the moment of a current maximum value, the maximum temperature is shifted from the electrode by 25 mm. The turbulent model predicts smaller values of the temperature due to more intense mixing of the flows.

It is shown by the simulation results that the distribution of the velocity modulus insignificantly depends on selection of the flow model. For the laminar and the turbulent model, the flow is characterized by a smooth increase of the velocity from 0 m/s at the electrode butt-end to 11 m/s at the channel outlet. At the zero current, the laminar model exhibits a wave-like change of the velocity with an increase to 2 m/s due to pulsed energy input, subsequent reduction to below 0.5 m/s and the repeated increase to 2 m/s. The turbulent model is characterized by sharper initial perturbation with the increase of the velocity to 3 m/s, after which the variation nature is similar to the laminar case. In the maximum current regime, there is a significant increase of the velocity modulus at the distance of 40 mm from the electrode. The laminar model demonstrates smooth distribution of the velocity along the channel. The turbulent model is characterized by a velocity surge that follows a profile of the laminar flow at the zero current and, then, by a sharp increase at the distance of 50 mm.

Operation of the AC plasma torch is characterized by presence of turbulent and laminar flow portions. It is shown by the performed study that inclusion of the RANS-model of turbulence insignificantly affects the results as compared to the laminar formulation. Further plans include calculations based on a more reasonable LES-approach and, possibly, a DNS-approach. The obtained results show that the calculation shall include the process of electrode erosion accompanied by ejection of copper atoms into the flow and

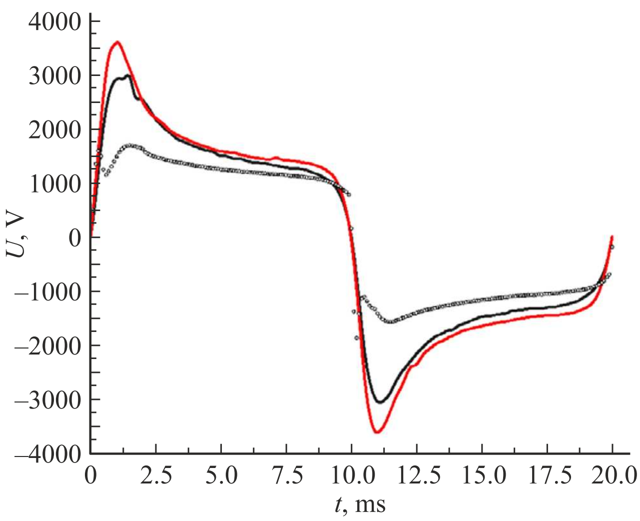

Figure 3. Comparison of the voltage drop across the arc. The red line — the turbulent model, the black line — the laminar model, the dots — the experiment.

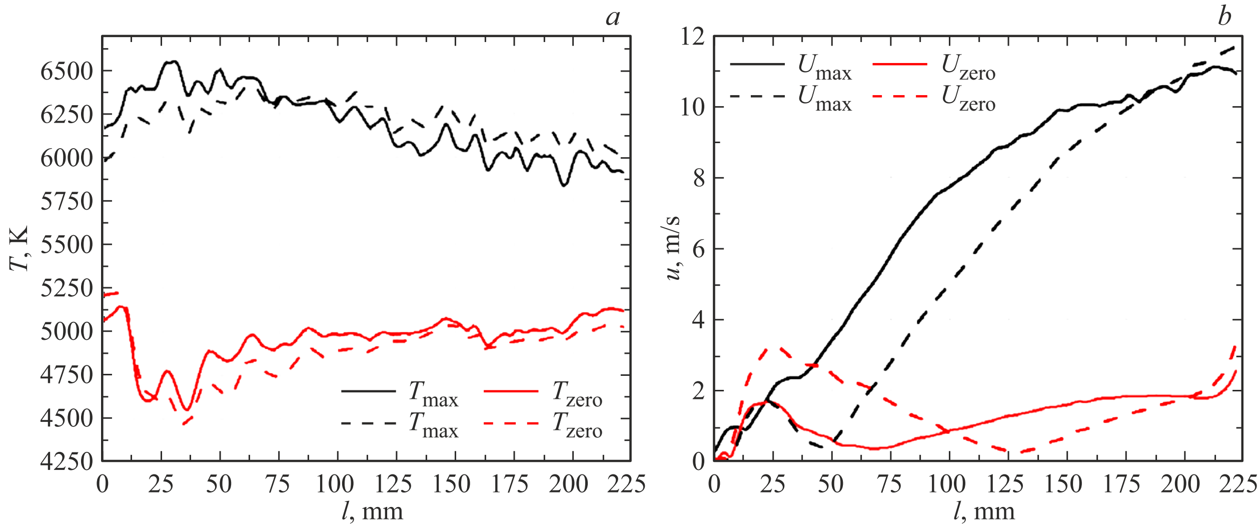

Figure 4. Distribution of the temperature (*a*) and the velocity modulus (*b*) along the channel axis. The laminar model — the solid line, the turbulent model — the dashed line (where $l = 0$ is an electrode butt end and $l = 210$ mm is a channel outlet).

reduction of electric resistance of the medium, as well as heat exchange with the walls of the plasma torch channels. It is planned to increase the qualitative and quantitative agreement with the experimental data on thermophysical parameters of the plasma-forming gas in the jet outside the plasma torch channels by including the influence of the gravitational force on dynamics of mixing of cold and hot flow areas into the calculation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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