High voltage AC plasma torch: dynamics of plasma-forming gas

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A mathematical model of the multiphysical processes occurring in an alternating current plasma torch has been developed. A numerical study of the dynamics of plasma-forming gas (air) for a single-phase plasma torch developed at the IEE RAS operating at atmospheric pressure has been carried out. The calculation results are compared with experimental data. The proposed model and computational algorithm can be used to estimate gas parameters in plasma torch channels and the reactor area when developing modern technologies for the synthesis/destruction of materials.

Keywords: AC plasma torch, computer modeling, plasma gas dynamics, heat transfer processes.

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High-voltage AC arc plasma torches designed at the Institute for Electrophysics and Electric Power of the Russian Academy of Sciences (IEE RAS) for operation on air and neutral gases have a number of advantages over traditional DC plasma torches, which include a long service life of continuous operation and high thermal efficiency [1]. IEE RAS offers a number of low-temperature plasma generation facilities: single-phase plasma torches (with a power of 5−15 kW), three-phase plasma torches with rod electrodes (30−75 kW), and high-power three-phase plasma torches with hollow electrodes (150−500 kW).

Current plasma-chemical applications involve the use of such devices for hydrogen production, synthesis of new materials, enhancement of the efficiency of hydrocarbon fuel utilization, and waste recycling. The development of these technologies requires a reliable tool for determining the gas-dynamic parameters of plasma-forming gas in the „working“ volume, which includes, in the general case, both the internal channels of a plasma torch and the region of plasma jet expansion in a reactor. In the past decade, computer modeling based on mathematical models of multiphysical processes has emerged as such a tool. Although considerable progress was achieved in the development of models and computational scenarios for commercial packages [2–4], the main barrier to their widespread use is the lack of reliable verification.

The present study has three objectives: (1) further development of the approach proposed in [4] for calculating multiphysical processes in a real plasma torch; (2) numerical examination of the dynamics of plasma-forming gas and determination of characteristic values of the parameters critical for the processes of synthesis/destruction of materials; (3) comparison of the obtained data with the results of a specially designed experiment.

A single-phase AC plasma torch with two cylindrical channels with diameter $d = 32$ mm operating at atmospheric pressure is considered (Fig. 1). The plasma-forming gas is air. The inlet sections of channels feature openings for tangential gas supply at a given flow rate G ($G/2$ per channel) and rod electrodes. An arc is ignited between the electrodes, covering both the channels and the area beyond them. The amplitude values of arc current fall within the range of 5−20 A. Current frequency $f = 50$ Hz. Weakly ionized plasma outflows into the open space, heating the surrounding gas.

The model of plasma-forming gas dynamics relies on simultaneous solution of the Navier−Stokes equations for a compressible heat-conducting gas and the equation for the current potential. This model was described in detail in [4].

The key distinguishing feature of our study is the completely three-dimensional formulation of the problem, which provides an opportunity to examine a non-coaxial arrangement of channels and simulate tangential supply of plasma-forming gas. In addition, radiation losses are taken into account in the energy balance equation. The computational scenario is implemented in the Comsol Multiphysics commercial package.

The non-steady character of current change translates into (1) an oscillatory nature of variation of the parameters of plasma-forming gas; (2) temporal variation of the spatial distributions of parameters (Fig. 2). At the same time, the parameter distributions are steady-state in nature and depend only on the voltage phase.

The tangential gas supply and the process of heat release into the flow shape a complex flow pattern in the plasma torch channels and outside them. The tangential velocity in channels reaches its maximum within the initial section and decreases downstream. The velocity distribution on the flow axis for $G = 1$ g/s is shown in Fig. 2 (the distance is measured from the end of the electrode along the axis; the channel outlet coordinate is $x/d \cong 6.9$). The longitudinal velocity increases along the channel to 5.5 m/s at the outlet

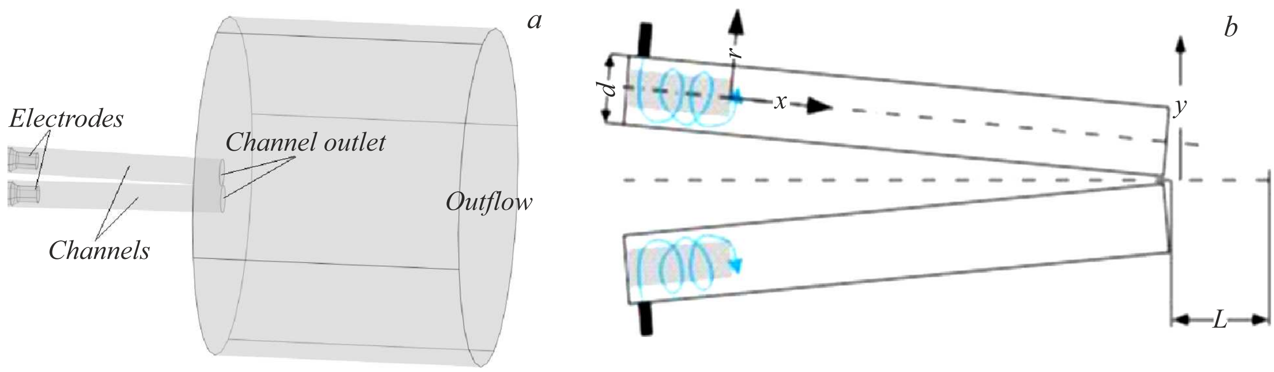

Figure 1. Diagram of the setup. *a* — Overall view of the computational domain; *b* — channel geometry.

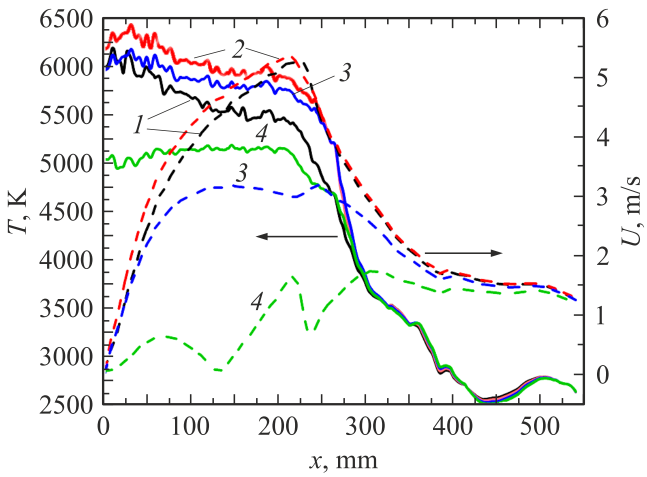

Figure 2. Distributions of velocity (dashed curves) and temperature (solid curves) of plasma-forming gas along the channel axis (coordinate x; $x = 0$ corresponds to the end of the electrode) at different moments in time: *1* — $1/(8f)$, *2* — $1/(4f)$, *3* — $3/(8f)$, *4* — $1/(2f)$.

(for the moment of time corresponding to the maximum arc current ($t = 1/(4f)$). In the open space, the velocity decreases to a certain level and remains virtually constant in time afterward.

At all points in time, the temperature varies only slightly along the length of the channel (Fig. 2). The maximum temperature (approximately 6000 K) corresponds to the maximum arc current. The minimum temperature (5000 K) corresponds to the minimum current (moment of time $t = 1/(2f)$). The temperature of plasma-forming gas drops sharply outside the channels.

Jets flow out of the plasma torch channels at an angle to each other. A single plasma torch is formed at a certain distance. This effect is illustrated in Fig. 3, *a*, where the distribution of transverse temperatures at different distances L from the plane indicated in Fig. 1, *b* is shown. The approximate distance at which a jet is characterized by a „common" temperature profile with a single maximum is $L/d = 2.3$.

One of the main objectives of this study was to verify the reliability of the computational model by comparison with experimental data on the temperature distribution in a jet in the immediate vicinity of the channel outlet. Experimental data (Fig. 3, *b*) for several points in space and different moments in time were obtained using an optical system that was fitted with a Shamrock DV420-FK spectrograph. An automated algorithm was used to determine the plasma temperature. This algorithm estimated the intensity ratio of lines 510.554, 515.324, 521.82, 570.024, and 578.213 nm of copper, which is present in the jet volume in a low concentration (due to erosion of the electrode material) that is insufficient to determine the temperature at $r > 9$ mm (Fig. 3, *b*). The figure shows the radial temperature distribution at distance $x/d \cong 7.8$ along the jet axis (outside the channel) for the moments of time corresponding to the maximum and minimum of the jet current. It can be seen that the transverse temperature distributions agree fairly closely with each other. The existing differences are attributable to the simplified formulation of the problem and the specifics and errors of the measurement method and data processing.

A mathematical model and a computational algorithm for the Comsol Multiphysics package were developed for calculating the spatial non-steady flow of plasma-forming gas in an AC plasma torch with rod electrodes. As far as we know, the flow for a real configuration of a single-phase plasma torch has been calculated in the considered formulation for the first time. The features of the resulting flow were analyzed. The model and the computational algorithm were validated by comparison with experimental data obtained for the design under consideration. The model provides an opportunity to predict the temperature distribution in plasma torch channels and in the reactor area, simplifying the development of advanced techniques for synthesis/destruction of materials and application of coatings.

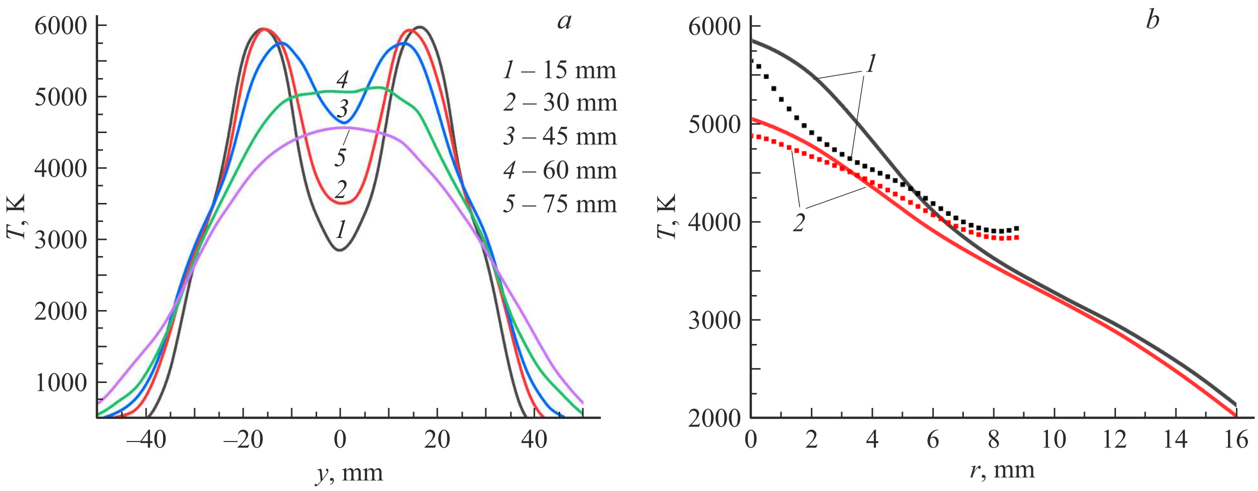

Figure 3. Transverse temperature distributions. *a* — At different distances *L* from the plane indicated in Fig. 1, *b*. *b* — At distance $x/d \cong 7.8$ and different moments in time: *1* — $1/(4f)$ (maximum current); *2* — $1/(2f)$ (zero current). Dots — experimental data.

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Conflict of interest

The authors declare that they have no conflict of interest.

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