Flow modelling and gas heating inside a profiling channel of an electric arc plasma torch

FLOW MODELLING AND GAS HEATING INSIDE A PROFILING CHANNEL OF AN ELECTRIC ARC PLASMA TORCH

V.M. Lelevkin, E.B. Kulumbaev, V.F. Semenov, D.K. Otorbaev and D.C. Schram*

Kyrgyz-Russian Slavic University, 720000, Bishkek, Kyrgyzstan;
* Department of Physics, Eindhoven University of Technology, The Netherlands.

ABSTRACT

This paper presents a theoretical model for the numerical analysis of the acceleration and heating of a gas by an electric arc in a profiling channel with a diffusor anode. The thermal parameters and transport coefficients of helium have been determinated and the approximative expression for their calculation in a broad range of temperature (0,3-100) kK and pressures have been proposed. The calculation and investigation of the effect of the thermal non-equilibrium plasma on the characteristics of the cylindrical arc have been carried out. The results of the calculations have been compared with experimental data and calculations obtained on the basis of an equilibrium plasma model.

INTRODUCTION

The theoretical modelling of gas motion and its heating by an electrical arc torch in a channel has been done in the papers [1-3]. In [2-4] the main role of self electromagnetic forces on the formation of plasma flows from electrodes and contraction positions of the arc column has been shown. It agrees with experimental data and qualitative estimations [5]. The numerical solution of gasodynamic equations [6] made it possible to describe short electrical arcs and plasma flows in the channel with different configurations (chambers, diaphragms, etc.) [1-4].

The aim of the study is : -to carry out some numerical experiments about the gas motion and heating in the arc channel [7];

- and estimated the thermal non-equilibrium of the helium arc, and the influence of this non-equilibrium on the characteristics of the cylindrical arc.

MODELLING

In order to describe the flow characteristics and heating inside the profiling arc channel, it is assumed that the flow is axi-symmetric, radiation is emitted from the whole volume of the plasma, the plasma is stationary, quasi-neutral and in local thermodynamic equilibrium state.

The system of magnetohydrodynamic (MHD) equations is used for the modelling of plasma flows inside the arc channel :

- the continuity equation

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho \vartheta r)+\frac{\partial}{\partial z}(\rho u)=0\,,$$

- the motion equations

$$\rho\vartheta\frac{\partial\vartheta}{\partial r}+\rho u\frac{\partial\vartheta}{\partial z}=-\frac{\partial P}{\partial r}-j_z\mu H_\varphi+\frac{2}{r}\frac{\partial}{\partial r}\left(r\eta\frac{\partial\vartheta}{\partial r}\right)-\frac{2\eta\vartheta}{r^2}+\frac{\partial}{\partial z}\left[\eta\left(\frac{\partial u}{\partial r}+\frac{\partial\vartheta}{\partial z}\right)\right]-\frac{\partial}{\partial r}\left[\frac{2}{3}\eta\left(\frac{1}{r}\frac{\partial r\vartheta}{\partial r}+\frac{\partial u}{\partial z}\right)\right],$$

$$\rho\vartheta\frac{\partial u}{\partial r}+\rho u\frac{\partial u}{\partial z}=-\frac{\partial P}{\partial z}+j_r\mu H_\varphi+2\frac{\partial}{\partial z}\left(\eta\frac{\partial u}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left[r\eta\left(\frac{\partial u}{\partial r}+\frac{\partial\vartheta}{\partial z}\right)\right]-\frac{\partial}{\partial z}\left[\frac{2}{3}\eta\left(\frac{1}{r}\frac{\partial r\vartheta}{\partial r}+\frac{\partial u}{\partial z}\right)\right],$$

- the energy equation

$$\rho\vartheta C_P\frac{\partial T}{\partial r}+\rho u C_P\frac{\partial T}{\partial z}=j_rE_r+j_zE_z-\psi+\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\vartheta\frac{\partial P}{\partial r}+u\frac{\partial P}{\partial z}+2\eta\left[\left(\frac{\partial\vartheta}{\partial r}\right)^2+\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\vartheta}{r}\right)^2+\frac{1}{2}\left(\frac{\partial u}{\partial r}+\frac{\partial\vartheta}{\partial z}\right)^2\right]-\frac{2}{3}\eta\left(\frac{1}{r}\frac{\partial r\vartheta}{\partial r}+\frac{\partial u}{\partial z}\right)^2,$$

- Maxwell's equation

$$\frac{\partial E_r}{\partial z}-\frac{\partial E_z}{\partial r}=0,\qquad \frac{1}{r}\frac{\partial}{\partial r}(rH_\varphi)=j_z,\qquad \frac{\partial H_\varphi}{\partial z}=-j_r,$$

- Ohm's law

$$j_r=\sigma(E_r-u\mu H_\varphi);\qquad j_z=\sigma(E_z+\vartheta\mu H_\varphi),$$

- the integral relations for the arc current conservation and the gas flow rate conservation

$$I=2\pi\int_0^R j_z r\,dr,\qquad G=2\pi\int_0^R \rho u r\,dr\ ,$$

where r,z are the cylindrical coordinates, ϑ,u the velocity components, ρ the density, σ the electric conductivity, λ the thermal conductivity, ψ the radiation ability, η the viscosity, C_P the specific heat, P the pressure, E,H the electric and magnetic field strengths.

The boundary conditions are defined on the whole range of the calculated space which includes solid occupied areas (the cathode is tungsten, the anode is copper, channel walls are from the dielectric material with copper electrophysical properties) and plasma. The velocity is equal to zero at the external space boundary which coincides with non-penetrable unmovable solid surfaces. The density in the circular area of the inlet section is calculated from the state equation at the fixed temperature T_R and the pressure which is determined by the linear extrapolation from the calculated space upflow; the pressure 10 mbar is assumed downflow behind the outlet section. Symmetry conditions are taken at the axis. The heat transfer with real properties of a solid is taken into account at boundaries of the solid surface.

Transport coefficients of the helium plasma are calculated based on the ideas on the mean free path of the particles and with taking into account dependencies of the transport coefficients on temperature and pressure. The transport coefficients are approximated by expressions which have satisfactory agreement with the results of calculations [8-9].

The chemical composition of the plasma (n_j, $j=a,i,2i,e$) is determined by solving the joint system of Saha equation, equation of state, Dalton's law and condition of quasi-neutrality.

Electric conductivity

$$\sigma = \frac{n_e e^2}{m_e \nu_e} K_\sigma ,$$

Thermal conductivity and viscosity

$$\lambda = \lambda_e + \lambda_h + \lambda_{1r} + \lambda_{12} + \lambda_t , \qquad \eta = \eta_h + \eta_t ,$$

where the thermal conductivity for the electrons

$$\lambda_e = \frac{n_e k^2 T_e}{m_e \nu_{e_{..}}} K_\lambda ,$$

the reactive conductivity

$$\lambda_{1r} = \frac{2 n_e n_a D_{amb} U_1^2}{k T_e^2 \left[\left(1 + \frac{T_e}{T} \right) n_e + 2 n_a \right]}, \qquad \lambda_{2r} = \frac{2 (n_e - n_i) U_2^2 D_{amb}}{k T_e^2 \left[\left(2 - \frac{n_i}{n_e} \right) + \frac{n_e}{n_i} \left(1 + \frac{2 T_e}{T} \right) \right]},$$

the thermal conductivity and heavy particle viscosity

$$\lambda_h = \frac{75}{32} \sqrt{2} \frac{k^2 T}{m_a} \sum_j \frac{n_j}{\nu_j}, \qquad \eta_h = \frac{20\sqrt{2}}{9\pi} kT \sum_j \frac{\eta_j}{\nu_j}, \qquad j \equiv a, i, 2i,$$

the turbulent components λ_t, η_t are taken into account in the diffusor channel and are determined by expressions of Prandtl model

$$\lambda_t = \eta_t \frac{C_P}{Pr_t}, \qquad Pr_t = 1, \qquad \eta_t = \rho (\alpha l_n)^2 \frac{\partial \vartheta_\tau}{\partial n} .$$

where $\alpha = 0.41$, l_n is a distance in the direction normal to the wall profiles, ϑ_τ is a component of the velocity vector parallel to the wall.

The kinetic corrections of K_σ, K_λ for the data [8-9] are determined as a function of collision frequency ratio $\gamma = \frac{\nu_{ei}}{\nu_{ea}}$

$$K_\sigma = 1.0 + 0.25 \cdot arctg(0.5\gamma), \qquad K_\lambda = 2.1 + 0.8 \cdot exp(-0.002\gamma).$$

The frequency of collisions between the particles are

$$\nu_j = \sum_k \sqrt{\frac{8kT_j}{\pi m_j}} n_K Q_{jk} , \quad j=e,i,2i,a.$$

The interaction cross-sections of the charged particles are

$$Q_{jk} = \pi b_j^2 \ln \frac{2 r_D}{b_j}, \qquad b_j = \frac{e z_j e z_k}{6 \pi \varepsilon_0 k T_j}, \qquad r_D = \left[\frac{e^2}{\varepsilon_0 k} \sum \frac{n_j z_j^2}{T_j} \right]^{-1/2},$$

where $z_{j,k}=1$ for the electrons and ions, $z_{j,k}=2$ for the two-multiplicity ionization of the atoms.

The interaction cross-sections of the atoms with electrons and with heavy particles are

$$Q_{ea} = \left(6.25 + 0,.5 \cdot 10^{-4} T_e - 10^{-7} \cdot T_e^{3/2}\right) \cdot 10^{-20}, \quad Q_{ia} = \left(16.2 - 1.02 \cdot ln(\vartheta_a)\right)^2 \cdot 10^{-20},$$

$$Q_{aa} = \left[5.376 + \frac{24.6}{\sqrt{T}} - \frac{1.2 \cdot 10^5}{T^2} - 0.339 ln\, T\right]^2 \cdot 10^{-20}, \; Q_{kj} = Q_{jk}.$$

Radiation ability is approximated by the expression

$$\psi = 1.2 \cdot 10^{-40} (T_e)^{1/2} \cdot n_e \cdot exp\left(-\frac{\Delta U_1}{kT_e}\right)\left[n_i \cdot exp\left(\frac{\varepsilon_a}{kT_e}\right) + 4n_{2i}\, exp\left(\frac{\varepsilon_i}{kT_e}\right)\right], \text{ W/m}^3$$

where ε_a=3.6 eV and ε_i=10.3 eV are the values of atom and ion energy.

The coefficients of ambipolar diffusion

$$D_{amb} = \frac{3}{8}\left(\frac{\pi kT}{m_a}\right)^{1/2} \cdot \frac{\left(1 + \frac{T_e}{T}\right)}{Q_{ia} \sum_j n_j}.$$

Thermal capacity of plasma

$$C_P = \sum_j \frac{\partial h_j}{\partial T_j}, \; j{=}e,r,i,,a,$$

where

$$h_e = \frac{1}{\rho}\frac{5}{2} kT_e n_e, \quad h_r = \frac{1}{\rho}\left[n_i (U_1 - \Delta U_1) + n_{2i}(U_1 - \Delta U_1 + U_2 - \Delta U_2)\right],$$

$$h_i = \frac{1}{\rho}\left[\frac{5}{2} kT(n_i + n_{2i}) + kT_e^2 n_i \frac{\partial}{\partial T_e} ln \Sigma_i\right], \quad h_a = \frac{1}{\rho}\left[\frac{5}{2} kTn_a + kT_e^2 n_a \frac{\partial}{\partial T_e} ln \Sigma_a\right].$$

$$\Delta U_z = \frac{(z+1)e^2}{8\pi\varepsilon_0 r_D}, \quad z = 1,2$$

Density of the plasma

$$\rho = \sum_j n_j m_j \approx m_a (n_a + n_i + n_{2i}).$$

The solution method. The solution of the differential equation system is made by a grid-discretization method in physical variables. The calculated space is partitioned by a rectangular non-uniform grid. The equation discretization is carried out by a checking (testing) space method. The field of pressure is computed on the basis of the SIMPLE procedure [6]. The equations are in a "compressed" form, which takes into account the density correction as function of pressure. The solution of discretized equations is made by an iterative method which uses runs in radial direction. In the whole computed space, the universal calculation method is used.

RESULTS AND DISCUSSION

Initial data are the following: the volume gas flow rate is 1000 cm^3/s, the arc current is 100 A and 500 A, behind the outlet section pressure is 10 mbar. The computational scheme of the arc is shown in Fig. 1.

It follows from the calculated results (Figs. 1-2) that in the initial section of the cylindrical part, the intensive arc core heats and accelerates the cold gas. The main role in plasma-acceleration is reserved for electromagnetic forces, which suck the cold surrounding gas into the arc column like a pump, heat it and pump it over in the axial direction. The expension of the arc column from the cathode surface results in decreasing current density, electromagnetic field strength, pressure and temperature of plasma in axis region. Non-monotonous character of changes is mostly revealed with current acceleration.

Towards to the diffusor part of the anode, the plasma flow characteristics begin to change qualitatively: the arc cross section is narrowed, the radial components of electric current density and field strength, and pressure increase. In the diffusor part of the channel, the acceleration of the plasma flow by electromagnetic forces again can be observed. Velocity at arc axis is increased from the cathode. Near anode it exceeds the sound velocity. This agrees with hydrodynamical ideas about one-dimensional gas flow out from channel with constant section and with a contrapressure less than critical.

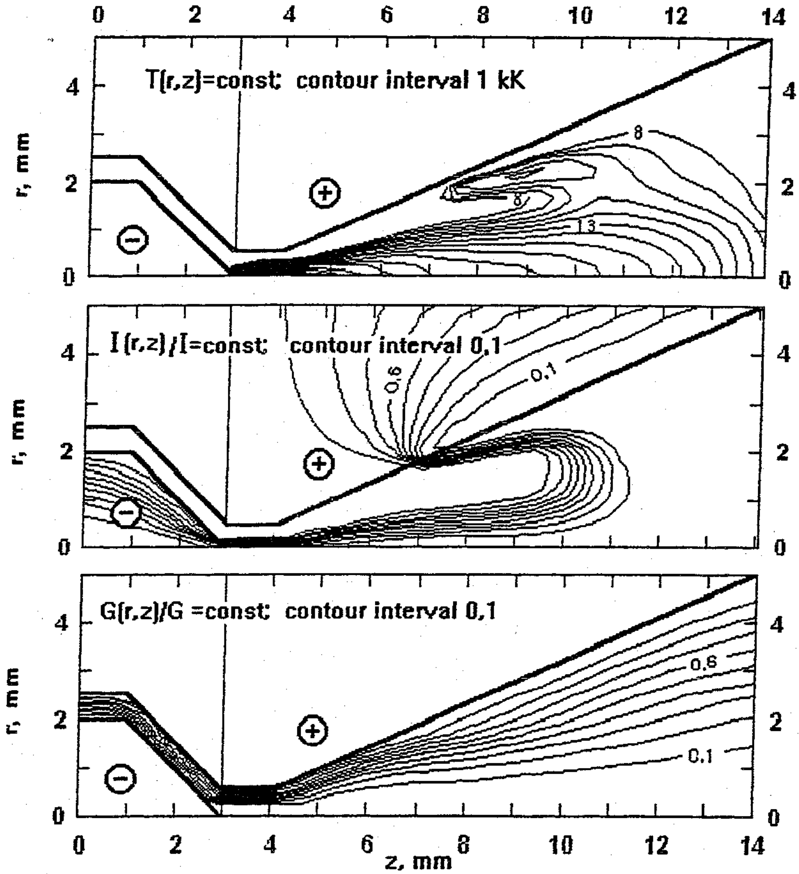

Fig. 1. Isotherm field, electric current lines and gas flow lines for I=1,00 A.

In the diffusor channel, the increased pressure region disappears, temperature of plasma and jet intensity decreases. Inside this region behind the cylindrical anode, a cut is observed, the current stream lines are distorted and then are closed on the diffusor of the anode. That causes the electromagnetic interaction of antiparallel currents. The position of binding of the arc to the anode with a variation in the current from 100 A up to 500 A has not practically changed. Main part of the gas flows along the surface of the diffusor.

Effects of the thermal non-equilibrium. To evaluate the helium arc plasma non-equilibrium, we supposed that the plasma consists of two types of particles, namely electrons and heavy particles (atoms, ions). The LTE state is therefore established independently in electronic gas and in the gas of heavy particles with characteristic temperatures of T_e and $T \equiv T_i \approx T_a \approx T_{2i}$ (partially non-equilibrium model of plasma, PLTE [3]). The conditions of ionization equilibrium are fulfiled. Variations of the plasma parameters in the axial direction are small compared with radial ones (model of the cylindrical arc [2]).

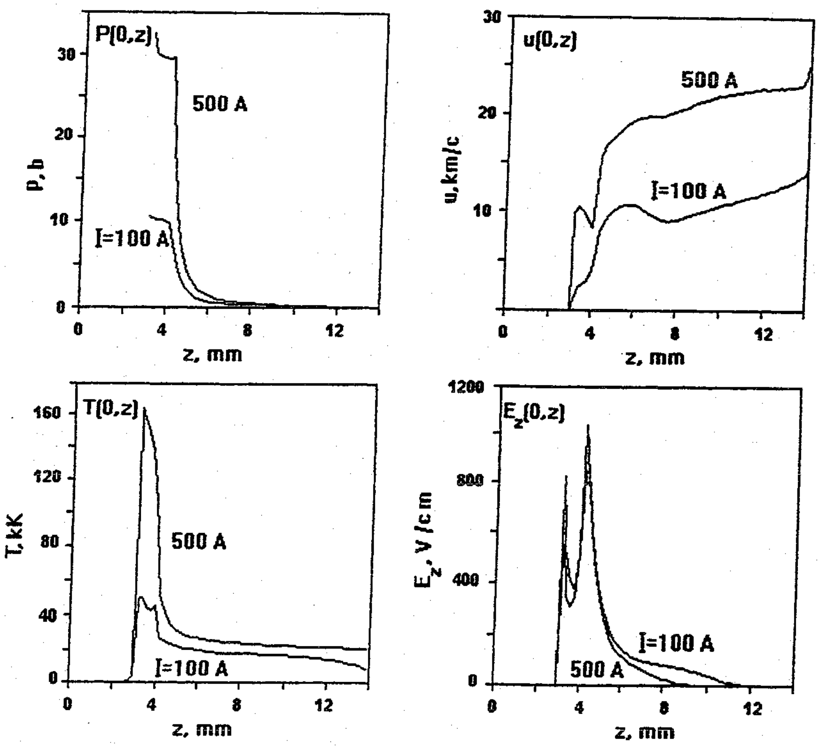

Fig. 2. Pressure, velocity, temperature and electric field strength versus arc axis.

It follows from the calculated results (in Fig. 3-5, points correspond to experimental data [10-14]) that the difference between the temperature of electrons and heavy particles is significant near the cold walls of the channel $\Delta T = T_e - T \approx 8$ kK. With decreasing of the electric current I<200 A, R=5 mm, P=1 bar, the difference between temperature is observed throughout the channel cross-section. The same tendency is observed when the channel radius is increased. Calculation according to the equilibrium plasma model overestimates the temperature at the arc axis and underestimates it at the periphery relative to the temperature of electrons and experimental data (Fig. 3). Decreasing the dimensions of the current-conductive channel in the equilibrium model results in an overestimation of the electric field strength in comparison with the results obtained from the two-temperature model. This is especially significant when decreasing the radius channel and arc current. If arc current is increased, the region of conductivity practically fills the channel. This results in a decrease of difference between the electric field strength in comparison with LTE, PLTE models and the measured values. The profile of equilibrium temperature near the walls of the channel differs slightly from the temperature of heavy particles. This can lead to a satisfactory agreement of dynamical characteristics of the flow obtained in LTE and PLTE models.

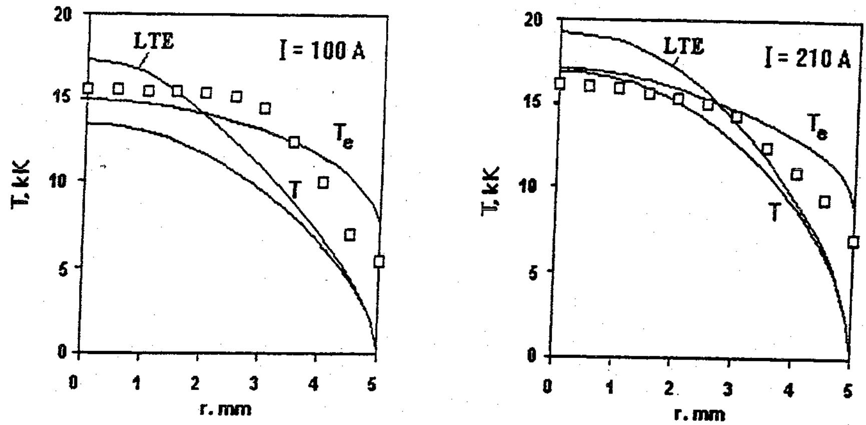

Fig. 3. Radial distribution of temperature in helium for various arc currents (pressure 1b).

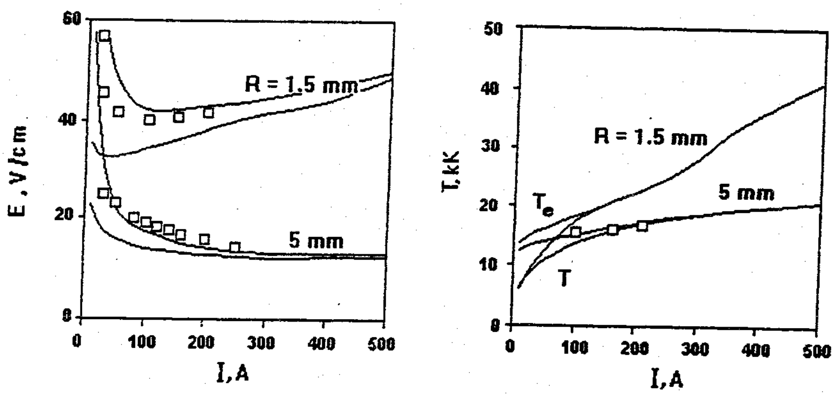

Fig. 4. Evolution of electric field strength and axial temperature with arc current (pressure 1b).

When decreasing pressure and current, non-equilibrium is observed in all channel cross sections. Practically homogenous temperature distributions are formated (Fig. 5). An increase of thermal non-equilibrium of plasmas at lower pressure is stipulated by an increase of electron concentration and frequency of their collisions with heavy particles. As a result the electrons can not transfer all the energy obtained from the field to a gas and remain the "hot". That is why with decrease of a pressure (at I=const) the degree of plasma non-equilibrium increases mainly due to decrease of the heavy particles temperature at almost constant electron temperature. For example, for variation pressure from 1 to 0.1 bar (I-100 A, R=5 mm) on the axis the electron temperature decreases by 1 kK, heavy particle temperatures decreases on 6,4 kK, and near to the walls the temperature difference increase from 5,2 kK to 11,3 kK. Therefore in the diffusor part of the channel (region of lower pressure) the non-equilibrium become more important and correct modeling of such plasma is only possible on the basis of non-equilibrium models.

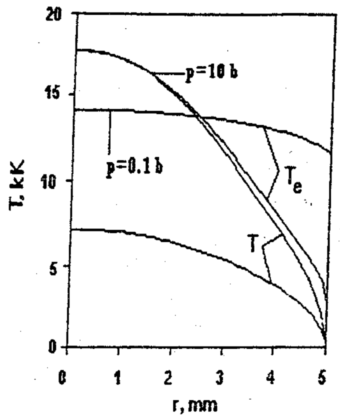

Fig. 5. Radial distribution of the temperatures of a pressure of 10 b and 0.1 b (I=100 A).

For the qualitative estimation of plasma non-isothermicity on the arc axis, the condition $\frac{I\,.\,P}{R}$ <50 *(A.bar/mm)* can be used. If *IP/R* increases, the boundary of the isothermic region is shifted towards the walls of the channel. It this case the temperature difference decreases near the axis while increasing near the walls (for *P=const*). With increase of pressure (*I/R=const*) plasma tends to the equilibrium state: near of axis T tends to T_e, near of wall T_e tends to T. The radiation losses in the energy balance are also low (1-2%).

Acknowledgements. This work was partially supported under grant No. 94-2922 of INTAS, and partially supported under grant HTECH.LG 951514 of NATO.

REFERENCES

1. Hsu K.A., Etemadi K., Pfender E. // J. Phys. 1983. - V. 54, N 3. - P. 1293 - 1301.
2. Theory of an Electric arc Column // V.S.Engelsht et. al. Novosibirsk, Nauka: SO AS USSR, 1990- 376 p.- (Low-Temperature Plasma, Vol. 1).
3. Lelevkin V.M., Otorbaev D.K., Schram D.C. Physics of Non-Equilibrium Plasmas Elsevier: Amsterdam - 1992. 418 p.
4. High-Current Arc Discharge in Magnetic Fields. Novosibirsk: Nauka SO 1992.- 276 p. (Low-Temperature Plasma, Vol. 7).
5. Filkenburg W. and Maecker H. Elektrische Bogen und Thermische Plasmen , Springer-Verlag, Berlin, 1956.
6. Patankar S. Numerical Heat Transfer and Fluid Flow. Hemisphere Publishing corporation, New York, 1980.
7. Pockl M., Stori H., Aumayr F. // J. Appl. Phys., 1995. Vol. 77, No. 7 P. 3575-3577.
8. Devoto R.S., Li C.P. // J. Plasma Phys. 1968. - Vol. 2, Part 1. P. 17-32.
9. Lick W.J., Emmons H.W. Transport Properties of Helium from 200 to 50000 K. Cambridge, Mass: Harvard University Press.- 1965. 106 p.
10. Kruger C.H. // Phys. of Fluids.- 1970.- Vol. 13, No. 7, P. 1737-1746.
11. Uhlenbusch J., Fischer E. Hackmann J. // Z. Physik.- 1970. -Vol. 238.- S.404-420.
12. Emmons H. W. The Arc Measurement of High Temperature Gas Transport Properties.- Harvard Univ. Eng. Sci. Lab. T.R. -1965.- P. 23.
13. Mckee H.B., Dean R.C., Pytte A // IEEE Trans. -NS-11.- 1964.- P.66-91.
14. Lukens L.A., Incropera F.P. // Int. Journal of Heat and Mass Transfer.- 1972.- Vol. 15, No. 5.- P. 935-952.