up to $4 \cdot 10^8$ W/m^2 to limited area metal surfaces with good thermal conductivity. Obtaining higher fluxes apparently will require use of gaps of more temperature-stable material. The maximum flux producable into a wall of silicate material comprises $\sim 1 \cdot 10^8$ W/m^2. The results presented may be used to optimize surface thermoprocessing of various materials. The method developed for determining the profile of the thermal flux from arc to wall and the programs for processing of the experimental data can be used to study nonsteady-state thermal fields in various high-temperature apparatus.

NOTATION

U, i, voltage, current; ℓ_a, arc length; ℓ, distance between gap walls; L, distance from cathode; q, q_m, q_w, q_s, thermal flux, maximum thermal flux, thermal flux into wall and sensor; r, distance; ρ, c, λ, density, specific heat, thermal conductivity; T_w, T_s, temperatures of wall and sensor surface; v, velocity; δ, width of action zone; W, energy supplied to surface; W_e, energy supplied to arc; t_a, action time; n, time step number; Δt, time interval; τ_t, τ, gas transit time past sensor and thermal conductivity time; h, characteristic scale of temperature drop; a, thermal diffusivity; λ_g, thermal conductivity of gas; ∇u, u, velocity gradient and gas velocity at wall.

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DISTURBANCE OF LOCAL THERMAL EQUILIBRIUM IN AN ELECTRIC-ARC ARGON PLASMA

L. N. Panasenko and V. G. Sevast'yanenko

UDC 537.523.5

It is shown that allowance for the condition $T_e \neq T_h$ in determining the composition and transport properties and allowance for reabsorption of radiation permit refinement of the region of disturbance of local thermal equilibrium in electric arcs.

In calculating the characteristics of electric-arc devices, the choice of the arc model is very important. In a wide range of the parameters (current, gas flow rate, channel size) good agreement with the experimental characteristics can be obtained using an equilibrium model of an arc. At the same time, there are rather inconsistant data on the disturbance of local thermal equilibrium (LTE) in an electric-arc plasma. The disturbance of LTE in an

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk.

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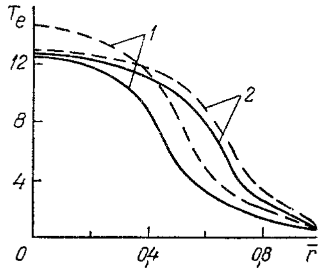


Fig. 1. Temperature distribution (10^3°K) over the channel radius (P = 0.1 MPa; I = 85 A, G = 1 g/sec, R = 0.5 cm; solid curves: with the equation of motion (3); dashed curves: $V_z = V_{z0}(1 - \bar{r}^2)$): 1) z = 0.5; 2) 1 cm.

argon plasma at atmospheric pressure for currents lower than 10 A was established experimentally in [1]. The data of [2, 3] indicate nonequilibrium in electric arcs at far higher currents. Thus, regimes with currents of 50, 100, and 200 A, channel diameters of from 0.2 to 4 cm, and gas flow rates of up to 1 g/sec were investigated in [3]. A pronounced nonequilibrium (up to 1000°K) at the axis of the arc was revealed upon a decrease in the current and the channel diameter to I/d < 100 A/cm. The distributions of temperatures T_e and T_h obtained lay below the experimental ones. Regimes with currents of 50-200 A and argon flow rates of 0.1-3.9 g/sec were investigated in [2]. It was noted that in an argon plasma a disturbance of LTE at the channel axis is observed at currents of ≈ 50 A. The discrepancy between the data of [2, 3] and the experiment of [1] is explained by the inaccuracy of the transport coefficients used. We note that reabsorption of radiation was not taken into account in these papers.

In order to refine the region of disturbance of LTE in an electric arc burning in a longitudinal argon stream and to reveal the processes promoting temperature equalization, in the present work principal attention was paid to the construction of a model, the calculation of transport coefficients under the condition $T_e \neq T_h$, and an analysis of radiation transfer in the real spectrum.

The system of equations describing a partially ionized plasma in the case of $T_e \neq T_h$ is derived from the Boltzmann kinetic equations in a way similar to what is done for a fully ionized plasma [4], and it has the form

$$\frac{5}{2}kn_e\left(V_z\frac{\partial T_e}{\partial z}+V_z\frac{\partial T_e}{\partial r}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_e\frac{\partial T_e}{\partial r}\right)+\sigma E^2-\Delta\varepsilon-\nabla q_{\mathrm{cont}}, \tag{1}$$

$$\frac{5}{2}k(n_i+n_n)\left(V_z\frac{\partial T_h}{\partial z}+V_r\frac{\partial T_h}{\partial r}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_h\frac{\partial T_h}{\partial r}\right)+\Delta\varepsilon-\nabla q_r-J'\cdot\Gamma_i, \tag{2}$$

$$\rho V_z\frac{\partial V_z}{\partial z}+\rho V_r\frac{\partial V_z}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial V_z}{\partial r}\right)-\frac{\partial P}{\partial z}, \tag{3}$$

$$\frac{\partial}{\partial z}(\rho V_z)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho V_r)=0, \tag{4}$$

$$\frac{\partial}{\partial z}(n_iV_z)+\frac{1}{r}\frac{\partial}{\partial r}(rn_iV_r)=\Gamma_i, \tag{5}$$

$$\Delta\varepsilon=\frac{3m_e}{m_n}kn_e\nu_e(T_e-T_h), \tag{6}$$

$$E=\frac{I}{2\pi\int\limits_0^R\sigma r\,dr}, \tag{7}$$

$$\rho=m_en_e+m_n(n_i+n_n), \tag{8}$$

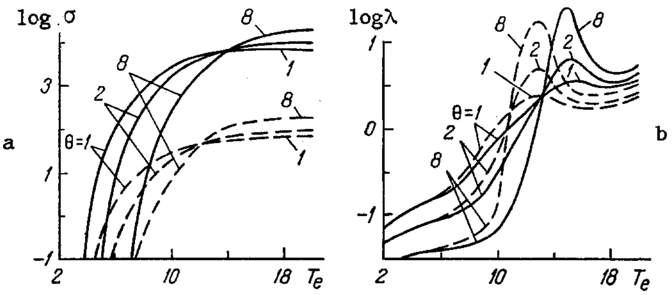


Fig. 2. electrical conductivity (a) and thermal conductivity (b) of a nonequilibrium argon plasma ($\Theta = T_e/T_h$, $[\lambda] = W/(m\cdot°K)$): solid curves) P = 0.1 MPa, $[\sigma] = \Omega^{-1}\cdot m^{-1}$; dashed curves) P = 0.01 MPa, $[\sigma] = \Omega^{-1}\cdot cm^{-1}$.

$$P = n_e kT_e + (n_i + n_n) kT_h. \tag{9}$$

This system was solved under the assumption of a parabolic profile of the velocity V_z, which corresponded to the consideration of developed flow in the channel, when $V_r = 0$. It proves possible to use such a simplification of the system (1)-(9) because in calculating the characteristics of an electric arc from an equilibrium model, the influence of radial convection on the formation of the temperature profile is felt only at a very small distance from the channel entrance. The radial velocity component very rapidly (over a distance of about one diameter) becomes far smaller than V_z. In Fig. 1 we show temperature profiles obtained in a solution of the equation of motion (3) and without it, when the parabolic velocity profile $V_z = V_{z0}(1 - \bar{r}^2)$ was adopted, while the values of V_{z0} were determined from the condition of constancy of the gas flow rate in each channel cross section. It is seen that in the cross section z = 1 cm radial convection already has practically no influence on the temperature distribution. The influence of the intrinsic magnetic field on the gas dynamics of the stream can also be neglected, since it is important if the magnetic pressure number is $R_H = V_H^2/V_z^2 > 1$, where $V_H = H\sqrt{\mu/\rho}$ is the Alfvén wave velocity. For a laminar electric arc in a channel with a current strength I < 2000 A, when the magnetic pressure is much less than atmospheric pressure, $V_H < V_z$, and hence $R_H < 1$.

The following comment must be made about the allowance for radiation. A calculation of the characteristics of an electric arc from an equilibrium model with allowance for radiation transfer in the real spectrum showed that reabsorbed radiation is an additional source of gas heating [5]. To allow for heating of the gas (heavy particles) due to reabsorption of radiation in a two-temperature model, we must separate the radiation emitted by free electrons from the radiation of atoms and ions. The electron gas emits bremsstrahlung in free–free transitions. This radiation yields a continuous spectrum, which was taken into account in Eq. (1). The reabsorbed lines, emitted in bound–bound transitions in atoms and ions, as well as the photoionization continuum were taken into account in Eq. (2). Such a "separate" allowance for radiation enables us to describe the additional heating of heavy particles due to the absorption of radiant energy.

The continuum emission ∇q_{cont} was calculated from the Kramers equations, while the radiation power in the equation of energy transfer for the heavy particles was defined as

$$\nabla q_r = \nabla q_\Sigma - \nabla q_{cont}, \tag{10}$$

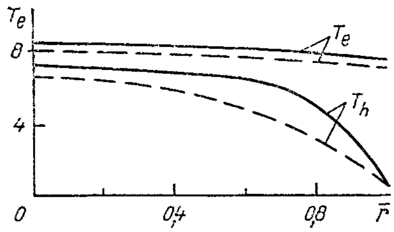
where q_Σ is the integral radiation flux over the entire spectrum and volume; the method of partial characteristics [6] was used to find it.

As the boundary conditions required to solve Eqs. (1)-(2) we assigned at the channel entrance (z = 0) the profiles

$$T_e = T_e^0(1 - \bar{r}^2) + T_e^W;\ T_h = T_h^0(1 - \bar{r}^2) + T^W, \tag{11}$$

at the axis (r = 0)

$$\frac{\partial T_e}{\partial r} = \frac{\partial T_h}{\partial r} = 0; \tag{12}$$



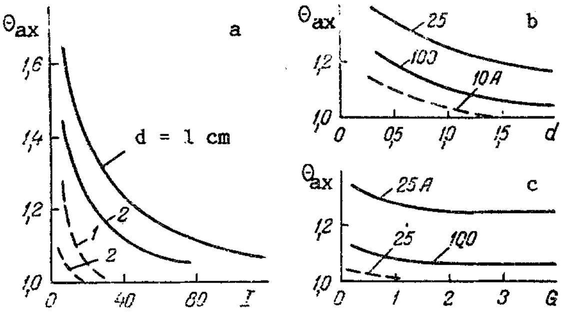


Fig. 3 Fig. 4

Fig. 3. Temperature fields (10^3°K) in a plasmatron channel (P = 0.1 MPa, I = 5 A, G = 1 g/sec, R = 0.5 cm): dashed curves) z = 1; solid curves) 10 cm.

Fig. 4. Dependence of the degree of nonequilibrium at the axis of the arc on the current strength (a), the channel diameter (b), and the gas flow rate (c): solid curves) P = 0.01; dashed curves) P = 0.1 MPa. d, cm; G, g/sec; I, A.

at the wall (r = R)

$$T_h = T^{\mathrm{w}};\ \lambda_e \frac{\partial T_e}{\partial r} = 0. \tag{13}$$

The boundary condition for T_e at r = R was chosen on the basis of an analysis of the calculations of [7], where temperature profiles of an electron gas with $\partial T_e/\partial r|_{r\,=\,R} = 0$ were obtained. For different variants of the calculation in [7] it was noted that T_e tended toward the value of 9000°K. On this basis we chose the constant T_e^{w} in the condition (11).

The composition and transport coefficients of a two-temperature argon plasma required to solve the stated problem were preliminarily calculated for pressures of 0.01 and 0.1 MPa [8]. In calculating the composition we used the formula

$$n_e\left(\frac{n_i}{n_n}\right)^{1/\theta} = \frac{2Z_i(T_e)}{Z_n(T_e)}\left(\frac{2\pi m_e k T_e}{h^2}\right)^{3/2}\exp\left(-\frac{J-\Delta J}{kT_e}\right), \tag{14}$$

obtained independently in [9, 10]. It should be noted that this formula does not have a rigorous foundation, since thermodynamic methods were applied to a system with partial equilibrium in its derivation. The possibility of using this model is based on a comparison of the calculation results and experimental data. Such a comparison was made in [11], where good agreement was obtained between the experimental transport coefficients and those calculated using Eq. (14). The experimental characteristics of an electric arc and those calculated using the methods of [9, 10, 11] were compared in [12]. The composition and transport properties determined in [8] were also compared with experimental data available in the literature and with the data of [7, 11]. An analysis of this comparison allows us to conclude that the model equation (14) is suitable for determining the composition of a two-temperature plasma, at least in that region of the parameters for which the test was made.

In calculating the electrical conductivity we took into account the difference in the cross sections of electron collisions with atoms and with ions and the influence of electron–electron interactions. The latter correction was borrowed from the results of a solution of the Boltzmann kinetic equation. In calculating the coefficient of thermal conductivity we took into account electronic heat conduction, the heat conduction of heavy particles, ambipolar diffusion, thermal diffusion, the electrothermal effect, and the thermal conductivity λ_R connected with the transport of ionization energy. The influence of the separation of temperatures was felt mainly through the heat capacity of bound states and the composition of the plasma. It is interesting to note that a region of temperature T_e exists where the thermal conductivity of an argon plasma grows sharply with an increase in the degree of nonequilibrium, whereas the electrical conductivity increases slightly (Fig. 2). Such properties of an argon plasma promote the equalization of temperatures in an electric arc at the high current strengths for which axial temperatures $T_e \geq 13{,}000$°K are characteristic. If a departure from LTE develops in this region, for example, then the transport of energy and charge promotes the liquidation of this departure: The electron gas obtains from the electric field an amount of energy somewhat less than in the equilibrium case ($E \propto 1/\sigma$, and hence $\sigma E^2 \propto 1/\sigma$ decreases with an increase in Θ), and at the same time, the increasing thermal conductivity assures the faster transfer of this energy to the plasma. If the characteristics of an arc are calculated from a two-temperature model but with equilibrium transport coefficients, this effect of temperature equalization due to transport phenomena is not taken into account. In the calculations of [2, 3] this is one of the reasons for the narrowing of the region of existence of LTE in comparison with experiments [1]. The neglect of gas heating in the absorption of radiation was another such reason.

The system of equations (1)-(9) was solved, using the assumptions given above and the boundary conditions (11)-(13), by the stream-sweep method with iterations with respect to nonlinearity. We obtained distributions of the temperatures T_e and T_h, the velocity, the electric field strength, and the heat fluxes to the channel wall at pressures of 0.01 and 0.1 MPa for currents of from 5 to 160 A, gas flow rates of 0.5-5 g/sec, and channel radii of 0.5 and 1 cm.

It should be mentioned that the iteration process converges far faster for P = 0.01 MPa than for P = 0.1 MPa. The influence of the initial profiles was felt only at very small distances from the channel entrance, where the calculation was made with a step $\Delta z = 10^{-5}$. With greater distance from the entrance, the step was varied as a function of the number of iterations required to achieve a given calculation accuracy. The method of lower relaxation was used to improve the convergence.

For P = 0.1 MPa a pronounced temperature difference in the axial region was obtained for currents less than 10 A (Fig. 3), which agrees with the conclusions of [1]. In contrast to the calculations of [2, 3], at higher currents the temperatures T_e and T_h were the same over almost the entire cross section of the arc except for the wall region. In calculations with equilibrium transport coefficients and with emission in the approximation of volumetric de-excitation, we obtain nonequilibrium over the entire channel cross section even for a current of 160 A.

For a given gas flow rate, an increase in the channel radius led to equalization of the temperatures, even at those currents for which a departure from LTE was observed over the entire cross section of the arc for smaller radii. This can be explained by the strengthening of the role of reabsorbed radiation in the gas heating, since the optical depth of the emitting layer increases. Moreover, the specific gas flow rate decreases in this case, which leads to a decrease in electron temperature (the pinching of the arc decreases). The conditions for the establishment of LTE are created as a result of the action of these factors.

An increase in the gas flow rate caused an expansion of the zone of nonequilibrium along the length of the arc. The point is that the region of nonequilibrium is distributed not only over the radius of the arc but also along the length of the channel. Regimes exist in which nonequilibrium was observed in the initial cross sections of the arc, while starting with a certain cross section, the temperatures became practically equal to one another. The length of the region where $T_e \neq T_h$ depended strongly on the gas flow rate. Thus, at a pressure P = 0.01 MPa, a current of 100 A, and a channel radius of 1 cm, an increase in the gas flow rate from 1 to 3 g/sec caused expansion of the nonequilibrium region along the channel length from 20 to 50 cm. In those regimes where the nonequilibrium region extended over the entire channel, an increase in the gas flow rate led to higher temperatures because of the greater pinching of the arc.

The influence of the current strength, the channel diameter, and the gas flow rate on the temperature ratio at pressures of 0.01 and 0.1 MPa is given in Fig. 4. In the rarefied plasma at a pressure of 0.01 MPa, the energy exchange between the electron gas and the heavy particles took place less intensely. The radiation power was considerably lower than at atmospheric pressure. Therefore, at P = 0.01 MPa, nonequilibrium was found in all the calculation variants.

Thus, calculations of the characteristics of electric arcs made by a two-temperature model revealed the role of the nonequilibrium properties of the transfer and reabsorption of radiation in the process of establishment of a single temperature in the system, and they showed that the characteristics of an argon electric-arc plasma at P = 0.1 MPa can be calculated from the LTE model if the currents are higher than 10 A. At a pressure of 0.01 MPa the two-temperature model of the plasma must be used for such calculations, regardless of the current strength, at least in the investigated range of arc parameters.

NOTATION

I, current strength; P, pressure; G, gas flow rate; R and L, radius and length of the channel; V_z and V_r, axial and radial velocity components; E, electric field strength; T_e and T_h, temperatures of electrons and heavy particles; $\Theta = T_e/T_h$, degree of nonequilibrium; n_e, n_i, and n_n, numbers of electrons, ions, and atoms per unit volume; $J' = J - \Delta J$, effective ionization potential; ΔJ, lowering of ionization potential in the plasma; Γ_i, change in the number of ions per unit volume; ρ, gas density; σ, coefficient of electrical conductivity; λ_e and λ_h, coefficients of thermal conductivity of electrons and heavy particles; k, Boltzmann number; ν, collision frequency; m_e and m_n, masses of an electron and an atom; r and z, radial and axial coordinates; $Z_i(T_e)$ and $Z_n(T_e)$, statistical sums over states of electronic excitation of ions and atoms.

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STRUCTURE OF THE FIELD OF REFLECTED RADIATION FOR RADIATIVE HEAT EXCHANGE IN SYSTEMS WITH SPECULAR SURFACES

A. V. Arendarchuk

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Problems of the calculation of radiative heat exchange in systems with specular surfaces of arbitrary shape are considered.

In the design of modern electrothermal apparatus with specular surfaces (reflectors, mirrors) of complicated three-dimensional shapes one needs a highly informative method of calculating the distribution (field) of radiant flux in the radiation source—mirror—receiver system. Such a calculation allows one to estimate the effectiveness both of the chosen system as a whole and of its individual components [1].

Two main approaches to the solution of problems of the reflection of radiant flux in thermal apparatus are known. The first is to investigate the transfer of a portion (beam) of the self-emission of the source in the process of its successive reflections in the system; the second is to investigate the incident and effective fluxes of each surface of the system by setting up integral (or zonal) equations for them.

For systems with specular surfaces it is more appropriate to use the first approach in practical applications. This is explained by the correspondence of the calculation algorithm to the physical representation of the process of energy transfer in such systems:

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