MECHANISMS OF THE CONTRACTION OF AN ARC DISCHARGE. 2. PECULIARITIES OF THE CONTRACTION OF A LOW-CURRENT ARC IN THE MIXTURE OF A NOBLE GAS WITH COPPER

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The influence of properties of the gaseous medium on the processes of contraction (self-constriction) of an arc discharge in the atmosphere of the mixture of a noble gas with copper is considered. The calculation are carried out, and it is shown that the degree of constriction of an arc discharge is determined by both the thermophysical characteristics of the gaseous medium and the effective characteristics of electron-atom collisions. We have studied the influence of both the Ramsauer effect and the shape resonance on a character of the contraction of an arc discharge. It is shown that the influence of the Ramsauer effect on the contraction of an arc may be neutralized in gaseous mixtures.

1. Introduction

The contraction (self-constriction) of an arc discharge consists in the diminution of the region occupied by the gas-discharge plasma under increasing the discharge current or the external pressure [1—7]. The contraction is usually considered as a negative phenomenon that restricts an application of arc discharges [1]. However, on the other hand, namely the contraction can be a base in certain cases in applications of arc discharges in technology [6].

It is typical that the thermal contraction takes place in the arc discharges at a high or medium pressure. That constriction of an arc is caused by the fact that the temperature at the periphery of the discharge falls and the gas density (under constant pressure) rises. Therefore, electrons at the periphery give up a larger amount of energy to neutral particles and their temperature falls, which leads, in its turn, to a decrease in the concentration of electrons because of the intensification of the recombination processes.

In the slightly ionized plasma of arc discharges, the amount of energy that is transferred to heavy particles from electrons is mostly determined by elastic collisions. It should be pointed that the cross-sections of electron-atom collisions may be frequently characterized by a nonmonotonous dependence on the electron energy. Especially, a deep minimum is observed for certain noble gases and alkaline metals (that phenomenon is called as the Ramsauer effect), which has a significant influence on the plasma properties. Therefore, the process of contraction has essentially different characters in various gaseous media.

The thermal contraction of arcs in noble gases is studied in works [3—7], but the obtained results are not extended on the practically important case of gaseous mixtures due to the fact that the properties of gaseous mixtures and those of the multicomponent plasmas of discharges in these mixtures are not additive functions relatively to the properties and concentrations of the pure components of mixtures.It should be also taken into consideration that, besides the Ramsauer effect, the resonance processes occur at the scattering of electrons by atoms. Thus, in accordance with [8], in the case of the scattering of low-energy electrons by copper atoms, the shape resonance takes place, because the quasisteady state of a negative ion is formed.

Copper is one of the widely used electrode materials and, due to that, is often a component of the gas-discharge medium. The detailed reviews of various models of electron-atom cross-sections for copper and the results of their application for the modeling of low-temperature plasmas are given, e.g., in [9,10]. It is worth noting three most significant models for the scattering of low-energy electrons by copper atoms, namely, the resonance model [8], non-resonance one [9, 10], and the model of hard spheres [11] (see. Fig. 1).

The aim of this work is to study the influence of physical characteristics of the mixture of a noble gas with copper on the contraction of an arc discharge. Taking into account the peculiarities of electron-atom cross-sections, we will carry out the detailed analysis of the processes which cause the thermal contraction under the assumption that the electron temperature and the gaseous one are different.

2. Two-temperature Thermal Plasma

The state of the plasma of arc discharges at the normal or high pressure is assumed to be that of a local thermodynamic equilibrium (LTE) [2—5]. Because of the high concentrations of atoms and electrons, the collision processes play a significant role in that plasma. On the other hand, one may expect the influence of radiation on the establishment of LTE in the plasma of copper arcs. It is typical that LTE exists in the plasma of stabilized copper arcs and in the column of free-burning copper arcs [12—14]. However, the equilibrium state is broken in the near-electrode layers of free-burning arcs due to the transfer of a resonance radiation [14].

Consider a two-temperature model of plasma in the case where a state is described by both the certain gaseous temperature T and the electron one T_e which correspond to the Maxwellian function distributions of atoms and electrons over velocities, and let the ionization equilibrium hold relative to T_e. To obtain a relation between T and T_e, we consider the equilibrium between both electrons and the mixture of atomic gases, taking into account the action of the electric field on electrons. We assume that the gaseous medium is weakly ionized, and the frequency of electron-atom collisions ν_{ea} is larger than the effective frequency of electron-ion collisions ν_{ei}. In such a medium, the collision of electrons with neutral atoms and the electron-electron collisions play a leading role.

Under these assumptions, the kinetic equation for the distribution function of electron velocities $f_e(\overrightarrow{u_e})$ is converted into the linearized Boltzmann equation [15, 16]

$$\frac{e\overrightarrow{E}}{m_e}\frac{\partial f_e}{\partial \overrightarrow{u_e}} = I_{ee}(f_e) + I_{ea}(f_e), \tag{1}$$

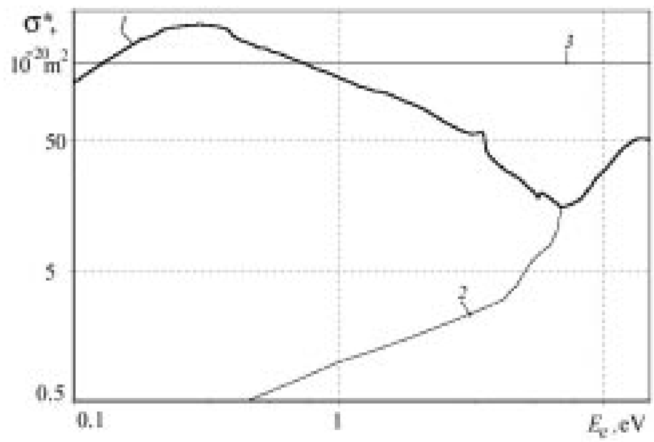

Fig. 1. Momentum-transfer cross-section for the scattering of an electron by a copper atom σ^* versus the electron energy E_e. Curve *1* follows from the resonance model [8], *2* corresponds to the non-resonance model [9,10], and *3* is a hard-sphere cross-section [11]

where $\overrightarrow{E}$ is the electric field intensity, e is the electron charge, m_e is the electron mass, $I_{ee}(f_e)$ is the operator of electron-electron collisions, and $I_{ea}(f_e)$ is the operator of electron-atom collisions.

In the case of the enough large electron densities, which are typical of arc discharges, namely $n_e \gg (m_e\sigma_{ea}/m_a\sigma_{ee})\,n_a$ (m_a is the atom mass, n_e and n_a are the densities of electrons and atoms, σ_{ea} and σ_{ea} are the characteristic cross-sections of electron-atom collisions and electron-electron ones, respectively), we have that the operator of electronic collisions $I_{ee}(f_e) = 0$.

Consider the nature of the energy transfer from electrons to atoms. Because of the large difference between the electron mass and the atom one, the velocity of an electron is larger than that of an atom. Moreover, the electron momentum direction is varied only under collisions, and the absolute magnitude of the momentum is changed only slightly. Moreover, a change in the electron energy is small, because its variation may be assumed continuous. The pointed assumptions allow us to expand the electronic distribution function into spherical harmonics and to solve the problem of electron drift in external fields [17].

In view of the linearity of the operator of electron-atom collisions relative to the electron distribution function $f_e(\overrightarrow{u_e})$, the kinetic equation (1) yields the following system of equations which establishes the connection between the spherically symmetric harmonic and non-symmetric one:

$$\frac{eE}{m_e}\frac{df_{e0}}{du_e} = -\nu_{ea}u_e f_{e1} \tag{2}$$

$$\frac{eE}{m_e}\frac{df_{e0}}{du_e} = -\nu_{ea}u_e f_{e1}. \tag{3}$$

Here, f_{e0} and f_{e1} are the spherically symmetric part of the distribution function and the non-symmetric one, respectively; $\nu_{ea} = \sum\limits_{\alpha} \nu_{e\alpha}$ is the total frequency of electron-atom collisions, $\nu_{e\alpha} = n_\alpha u_e \sigma^* (u_e)$ is the frequency of electron collisions with atomic species of the kind α, $\sigma^* (u_e)$ is the momentum-transfer cross-section of electron-atom collisions, and u_e is the electron velocity. Under the Maxwellian distribution function, Eq. (2) yields that $f_{e1} = eEf_{e0}/\nu_{ea}kT_e$. Therefore, the drift velocity of electrons equals

$$w_e = \frac{eE}{3kT_e}\left\langle \frac{u_e^2}{\nu_{ea}} \right\rangle, \tag{4}$$

where the brackets $\langle\rangle$ denote the averaging with the distribution function of electrons over velocities, ans k is the Boltzmann constant.

To obtain the collision operator $I_{ea}(f_{e0})$ from the spherically symmetric harmonic of the electron distribution function, we use a smallness of variations of the electron energy at one collision act in comparison with the energy proper. This allows us to consider the energy variation as continuous. In this case, the operator of electron-atom collisions may be represented as the right-hand side of the Fokker—Planck equation. After a number of transformations, the balance equation for the energy transferred from the electric field to electrons and from electrons to gas atoms takes the following form:

$$eEw_e = m_e^2\left(1 - \frac{T}{T_e}\right)\left\langle \sum_\alpha \frac{u_e^2 \nu_{e\alpha}}{m_{a\alpha}} \right\rangle. \tag{5}$$

Let us to introduce the effective mass M of an atom of the gaseous mixture as $M^{-1} = \sum\limits_\alpha x_\alpha m_{a\alpha}^{-1}$, where x_α are the molar concentrations of components of the gaseous mixture. Then, in view of (5) on the basis of formula (4) for the drift velocity of electrons, we obtain

$$T_e - T = \frac{M}{3k}\left(\frac{eE}{m_e}\right)^2 \frac{\langle u_e^2/\nu_{ea}\rangle}{\langle u_e^2 \nu_{ea}^* \rangle}, \tag{6}$$

where $\nu_{ea} = \sum\limits_\alpha \nu_{e\alpha}$, $\nu_{ea}^* = \sum\limits_\alpha (M/m_{a\alpha})\, \nu_{e\alpha}$.

In the case of a one-component gas, formula (6) is converted into the well-known one for the discrepancy between the electron temperature and the gaseous one[1,16]. It should be pointed out that formula (6) may be converted into

$$T_e - T = \left(\frac{E}{N}\right)^2 g(T_e),$$

where the function $g(T_e)$ is independent of the electrical field and the gas density.

With increase in a degree of ionization $\alpha_i = \sum\limits_\alpha n_{i\alpha}/N$ (where N is the density of heavy particles, $n_{i\alpha}$ is the density of ion species of the kind α) up to $10^{-4} \div 10^{-3}$, the collisions of electrons with ions become important. To take into account the Coulomb collisions in the used formulae, we need to substitute the frequencies of electron-atom collisions by the effective collision frequencies of electrons with heavy particles (atoms and ions) $\nu_e = \nu_{ea} + \nu_{ei}$, $\nu_e^* = \nu_{ea}^* + \nu_{ei}^*$, where ν_{ei} and ν_{ei}^* are the corresponding effective frequencies of electron-ion collisions.

For a low-temperature plasma, when LTE occurs, the number density of electrons n_e at a given point of the discharge is connected with the number densities of ions n_i and neutral atoms n_a by the Saha formula [1]

$$\frac{n_e n_i}{n_a} = \frac{2g_i}{g_a}\left(\frac{2\pi m_e kT_e}{h^2}\right)^{\frac{3}{2}} \exp\left(-\frac{E_I}{kT_e}\right), \tag{7}$$

where h is the Planck constant, g_i and g_a are the statistical weights of an ion and an atom, respectively, and E_I is the effective ionization energy.

The information about the dependence between the electron and gaseous temperatures and on the densities of charged particles allows us to calculate the transport coefficients in the plasma of an arc discharge. Then, let us go on to the consideration of the model of an arc discharge.

3. Model of an Arc Discharge

Consider the plasma of the column of a cylindrical arc discharge, in which a local thermodynamic equilibrium is maintained. Assuming that the heat release is proportional to a local current density and ignoring the radiation transfer, the heat transfer equation (the Elenbaas-Heller equation [3,18] can be written as

$$\frac{1}{r}\frac{d}{dr}\left\{ r\left[\kappa(T)\frac{dT}{dr} + (\kappa_e(T_e) + \kappa_p(T_e))\frac{dT_e}{dr}\right]\right\} +$$

$$+q(r) = 0. \tag{8}$$

Here, r is the distance from the discharge axis, $\kappa(T)$, $\kappa_e(T_e)$, and $\kappa_p(T_e)$ are the coefficients of gaseous, electron, and heat conductivities due to the ionization-recombination process, respectively; $q(r) = j(r)E$ is the heat release power per unit volume; $j(r) = \sigma E$ is the electric current density, and σ is the electric conductivity of the plasma.

Since LTE occurs in the plasma region, which determines its heat balance, the temperatures of electrons and gas are varied slightly. That fact allows us to obtain an approximate solution of Eq. (8) by using the method stated in [3—7]. Accordingly to this method, we assume that the dependences of the current density, heat release power, and corresponding quantities on the temperature in the cross-section of the discharge are given. The coefficients in Eq. (8) are assumed to be constant and equal to their values on the discharge axis. In this way, we can transform Eq. (8) to the form of an ordinary differential equation. An analytic solution of this equation gives the distributions of temperatures, current density, and others values over the discharge cross-section.

The analytic solution of Eq. (8) is important despite its approximate nature, because it allows us to analyze the influence of various physical mechanisms on the distributions of temperatures and others values over the cross-section of the discharge. By applying the above-mentioned method and using the formulae which are adduced in the previous section, we can obtain the following system of algebraic equations to calculate the parameters of an arc discharge:

$$T_e - T = \left(\frac{E}{N}\right)^2 g\left(T_e\right), \tag{9}$$

$$IE = \frac{\pi k T_e^2}{E_I}\left[16\kappa\zeta_T\left(\frac{1}{1+\left(r_g/R\right)^2}\right) + 5\left(\kappa_e+\kappa_p\right)\right], \tag{10}$$

$$S = 0.215\, q_0\, r_0^2 \ln\left(\frac{R}{r_0}\right), \tag{11}$$

$$p + \Delta p = NkT + n_e k T_e, \tag{12}$$

$$I = \sigma E \pi r_0^2. \tag{13}$$

Here, I is the arc current, R is the radius of the discharge chamber wall, S is the thermal function (the function of thermal potential), $q_0 = \sigma E^2$, $\zeta_T = dT/dT_e$, Δp is the Coulomb correction to the pressure, and r_0 is the characteristic radius of the plasma (the contraction radius), $r_0^2 \approx 1.32 r_g^2 + r_J^2$, where r_g and r_J are the characteristic radii of contraction in the case where the gaseous heat conductivity or the electron one dominates, respectively, in the heat transfer. These radii are calculated on the basis of the following relations [7]:

$$r_g^2 = \frac{16 k T_e^2 \kappa \zeta_T}{q_0 E_I},$$

$$r_J^2 = \frac{11.6 k T_e^2\left(\kappa_e+\kappa_p\right)}{q_0 E_I}.$$

In the limit case where the gas heat conductivity dominates, the profiles of temperature, current density, and heat power release are determined over the discharge cross-section by an inverse parabolic function (see, e.g., [7]). At the radius r_g, the mentioned values are decreased about 15 times in comparison with those on the discharge axis. When the electron conductivity dominates, the profiles are determined by the Bessel function, and the values are decreased about 20 times at the radius r_J.

The following additional conditions should be taken into account: the electric field strength and the pressure are constant (E = const, and p = const) over the discharge cross-section. Also we mention that, in system (9)—(13), the temperatures and other values are stated on the discharge axis.

The thermal function S is defined in the following way:

$$S = \int_0^{T_e}\left(\kappa_e(T_e{}') + \kappa_p(T_e{}')\right) dT_e{}' + \int_0^{T} \kappa(T')\, dT'. \tag{14}$$

It should be noted that the current state of the theory of gaseous mixtures and that of multicomponent plasmas is characterized by the absence of a uniform approach to describe the transport processes due to the very complicated dependences between the properties of gaseous mixtures and plasmas and the properties of pure gases and their concentrations in mixtures. The detailed analysis of this situation can be found in [19—23]. In this paper, to calculate the transport coefficients of gaseous mixtures and multicomponent plasmas, we choose the methods and formulae from [19—21].

A peculiarity of the heat conductivity of a gaseous mixture is its non-additivity relative to the conductivities of mixture components. To calculate the gaseous heat conductivity of two gases, the well-known Wassiljeva's formula is used with the coefficients which are calculated according to the approximate Mason-Saxena's method [19,20].

The heat conductivity of gases is known to be practically independent of the pressure (except for the case of a low pressure), and the coefficient of heat conductivity of noble gases is approximately described by formula [24]

$$\kappa = \kappa_{273}\left(T/T_{273}\right)^{\gamma}, \tag{15}$$

where $T_{273} = 273.16$K, $\kappa_{273} = \kappa(T_{273})$, $0.7 < \gamma < 0.95$.

The heat conductivity of an atomic copper gas will be calculated in the following way. In according to the first approximation of the Chapman-Enskog's method [15],

$$\kappa = \frac{25}{32}\frac{(\pi m_a kT)^{1/2}}{\pi s^2 \Omega^{(2,2)*}}\frac{3k}{2m_a}, \tag{16}$$

where $\Omega^{(2,2)*}$ is the reduced Chapman–Cowling integral, s is the radius of a hard sphere (for copper, it is recommmended to take $s = 1.400$ Å[10]). Having assumed the Lennard—Jones (LJ) model potetial for the interatomic interaction, it is easy to calculate the mentioned integral according to approximation [25] that is cited in [20] as well. Using the Brokaw method [20] to calculate the LJ-potential parameters for copper, we obtain the following values: $\sigma_{LJ} = 2.240$ Å, $\varepsilon/k = 3343$ K.

Then, the calculated data are approximated by a dependence of the type (15). This calculation has no large error, because the precision of calculations of heat conductivity with the use of formula (16) is known to be enough [20]. In this way, we obtain $\kappa_{273} \approx 8.68$ mW/(m·K) and $\gamma \approx 0.876$ for an atomic copper gas. That is, the curve of gaseous heat conductivity for copper lies between both those of argon and krypton.

The electrical conductivity of the plasma and the coefficients of electron heat conductivity and heat conductivity due to the processes of ionization-recombination are calculated in the same way as in [7]. The momentum-transfer cross-sections are selected according to the tabulated data [26, Chapter 14]. The ambipolar diffusion coefficient D_{amb} needed in calculations was calculated in the multicomponent plasma as [21]

$$D_{\text{amb}} = \sum_i \frac{n_i}{n_e} D_i \left(1 + \frac{T_e}{T}\right), \tag{17}$$

where the sum is taken over the all types of ions, D_i are the diffusion coefficients of species of the kind i which are defined as $D_i = 1/\sum\limits_l \frac{x_l}{D_{il}}$, where x_l is the molar part of species of the kind l, and the reciprocal diffusion coefficient of an ion D_{il} in the mixture component of kind of l is calculated, in its turn, via formula [27]

$$D_{il} N = d_{i0}\sqrt{\frac{T}{T_{i0}}}, \tag{18}$$

where d_{i0} is a constant for the given type of ions and the ambient gase, and $T_{i0} = 1000$ K . In the calculations, the experimental data on ion diffusion [27,28] are used. If the data were absent, the coefficient was calculated via the cross-section of the polarization capture of an ion by an atom [29] using the data given in [30].

To system (9)—(13), it is necessary to add the Saha equations (7) for each component of the mixture. It should be mentioned that, when the degree of ionization of each component is small, the plasma composition can be calculated by introducing the effective energy of ionization of the gas mixture in the following way:

$$E_I = -kT_e \ln\left[\frac{1}{(g_i/g_a)_{\text{eff}}}\sum_\alpha x_\alpha \frac{g_{i\alpha}}{g_{a\alpha}} \exp\left(-\frac{E_{I,\alpha}}{kT_e}\right)\right], \tag{19}$$

where $(g_i/g_a)_{\text{eff}} = \sum\limits_j (g_{i\alpha}/g_{a\alpha})x_\alpha$ is the effective ratio of statistical weights; $E_{I,\alpha}$ is the ionization energy of the component, and x_α is the molar part of a species of the kind α. If E_I is defined in the above manner, then this energy in the limit case of a small content of impurities coincides with the ionization energy of a pure gas.

It should be pointed out that the increase in the concentration of charged particles leads to the amplification of effects due to the non-ideality of a low-temperature plasma. Namely, both the pressure and the ionization energy in the plasma decrease. These effects are calculated by using the well-known Griem correction [31].

Thus, the system of equations (9)—(13) together with the Saha equation (7) for each component in the mixture allow us to obtain the arc parameters E, T_e, T, n_e, n_a, N, and r_0 for the given values of the arc current I, pressure p, and wall radius R. Vice versa, if the parameters are given, then the values of I/R and p can be calculated.

4. Results and Discussion

The above-presented model of an arc discharge describes the discharge where the released heat is transferred by means of conductivity into the walls of the discharge tube which are maintained at a fixed temperature. This situation corresponds to the idealization of a long arc (see [7,32]).

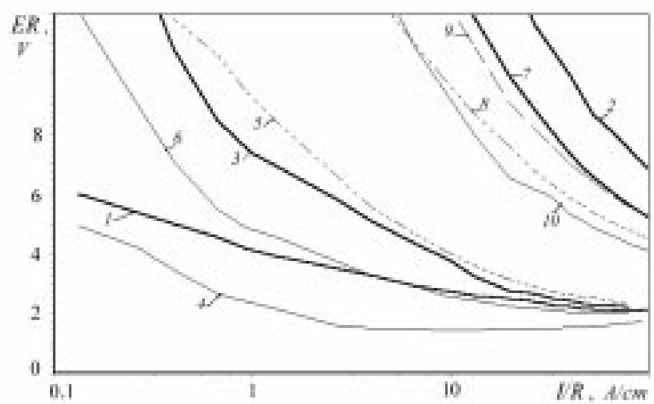

Fig. 2. Calculated volt-ampere ($E - I$) characteristics of arc discharges at atmospheric pressure. Curve *1* corresponds to the discharge in Ar, *2* — He, *3, 4, 5* — Ar:Cu (90 : 10 vol.%), *6* — Ar:Cu (97 : 3 vol.%), *7, 8* — He:Cu (90 : 10 vol.%), *9* — He:Cu (97 : 3 vol.%), *10* — Ar:He (50 : 50 vol.%). The curves for mixtures containing copper are calculated with the use of the resonance model except for curves *4,8* (the non-resonance model) and *5* (the model of hard spheres)

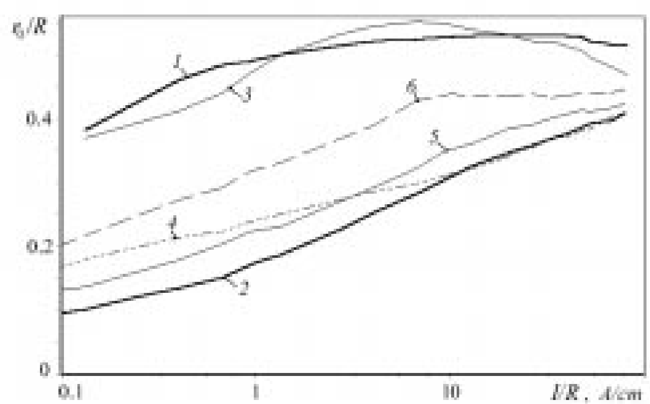

Fig. 3. Reduced contraction radius of an arc r_0/R vs the reduced current I/R ($p = 1 atm$). Curve *1* — Ar, *2,3,4* — Ar:Cu (90 : 10 vol.%), *5* — Ar:Cu (97 : 3 vol.%), *6* — Ar:Cu (99 : 1 vol.%). The curves for mixtures containing copper are calculated with the use of the resonance model except for curves *3* (the non-resonance model) and *4* (the model of hard spheres)

It should be underlined that an arc without radiation heat transfer is described by unified curves in the coordinates r/R, ER, and I/R [15]. In Fig. 2, the calculated volt-ampere characteristics are presented in the coordinates $ER - I/R$. The results of calculations of both the contraction radius and the heat release power are presented in Figs. 3—5.

The obtained results allow us to draw the following pattern of the contraction of an arc discharge in gaseous mixtures. In a particular gaseous mixture, the strongest contraction is reached under conditions when the heat transfer is due to the gaseous heat conductivity (Figs. 3, 5). This situation corresponds to the regimes of discharge characterized by relatively low temperatures and low reduced currents I/R. With increase in the current and temperature, the plasma region of the discharge is expanded. Moreover, in the case of a gas where the Ramsauer effect occurs, this expansion is more intense than that for the gas without such an effect. With a further increase in the current, the discharge turns into the regime where the electron heat conductivity dominates, and the contraction radius is

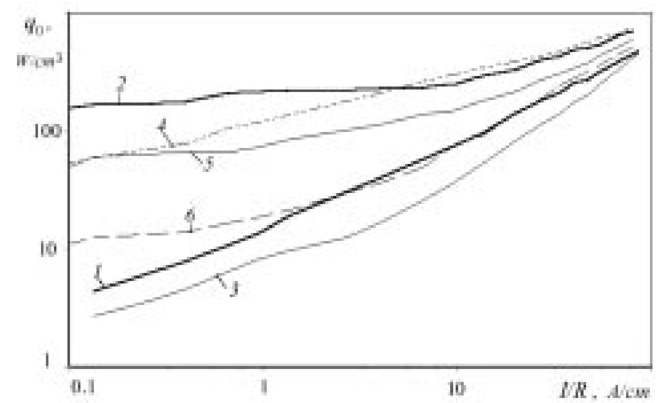

Fig. 4. Heat release power q_0 vs the reduced current I/R ($p = 1$ atm). The designations are the same as in Fig. 3

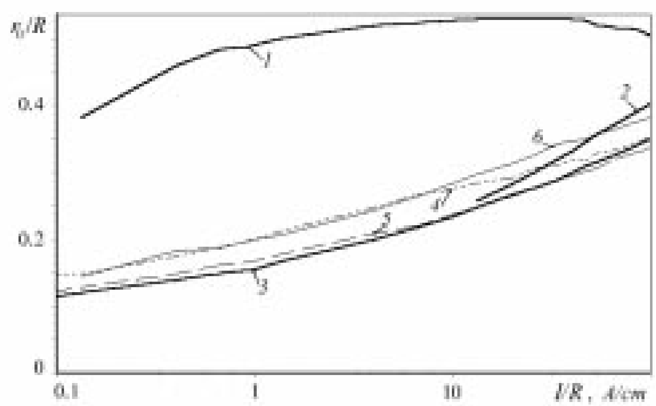

Fig. 5. Reduced contraction radius of an arc r_0/R vs the reduced current I/R ($p = 1$ atm). Curve *1* — Ar, *2* — He, *3,4* — He:Cu (90 : 10 vol.%), *5* — He:Cu (97 : 3 vol.%), *6* — He:Ar (50 : 50 vol.%). The curves for mixtures containing copper are calculated with the use of the resonance model except for curves *4* (the non-resonance model)

stabilized. Moreover, the electrons transfer the energy mainly in the collisions with neutral atoms. In this case, $r_0/R \approx$ const and, hence, $r_0 \propto R$, which is the result given in [33]. The subsequent increase in the current causes the growth of the electron temperature, and a degree of ionization of the gaseous medium is increased. The influence of electron-ion collisions is intensified because the sizes of the discharge region are diminished in the case of a stabilized arc.

It should be born in mind that, in the case of an arc where the electron-ion collisions dominate, one needs generally to consider the influence of radiative processes on both the heat transfer and the ionization processes in a plasma. The influence of radiation may essentially change the pattern of curves in Figs. 3—5.

It should be also pointed out that the influence of the Ramsauer effect may be neutralized in gaseous mixtures. Thus, if argon is mixed with copper or helium which has not the above effect, then the contraction of an arc is increased (Figs. 3, 5). Moreover, with the use of the resonance model, it is obtained that the existence of the shape resonance for atoms which are included in the gaseous medium leads to the intensification of the constriction of an arc at low currents. This causes, in its turn, the growth of the energy heat release in a discharge (Figs. 3—5).

Thus, the arc discharge in a gaseous mixture containing copper (while the shape resonance occurs) is characterized by the strong contraction at low currents. In this case, a decrease in the reduced current I/R is not accompanied by the corresponding decrease in the power of heat release in the plasma q_0 that remains approximately constant (Fig. 4).

Thereupon, we indicate the fact that the problem of the choice of a model of the cross-section for copper is remained still unsolved. The experimental investigations of such a cross-section were carried out only for energies larger than 6 eV. Moreover, these results were critically recalculated (see [9, 34]). It should be mentioned that, if we take the non-resonance model, then the cross-section for electron collisions with a copper atom is similar to the corresponding cross-section for zinc [35] that has no stable negative ion. The shape resonance is known to be typical of atoms or molecules having a high electron affinity (for copper, it has a comparatively large value of 1.235 eV), for example, SF_6 [36]. In addition, the thermodynamical characteristics of copper (the temperatures and specific heats of boiling and melting) have essential difference from those of zinc. This is an evidence for the adequacy of the resonance model for a copper atom.

In the case of a free-burning arc, the radius R should be considered as the glow-discharge radius (see [7]). Since the latter is known to be proportional to the arc current, we may conclude that, for a free-burning arc in the gaseous mixture containing copper, the enchanced contraction is manifested at low currents stronger than that for a stabilized arc. We also mention that the enchanced constriction and the next leap expansion with increase in the current are experimentally observed for a free-burning arc in copper vapors [32, Fig. 3].

5. Conclusion

The contraction of an arc discharge in gaseous mixtures essentially depends on the kinds of mixture components and their concentrations in the mixture. The variation of these concentrations has a strong influence on the total heat transfer characteristics of the mixture and the characteristics of electron-atom collisions that determine the electrophysical parameters of an arc. The constriction of an arc discharge in the selected gaseous mixture is more pronounced in the case where the gaseous thermal conductivity dominates in the heat transfer processes.

The influence of the Ramsauer effect on the contraction of an arc is revealed in the decrease in the degree of constriction. But, in the gaseous mixtures, this influence can be neutralized. The presence of a shape resonance for the scattering of electrons on gas atoms causes the intensification of the contraction. Thus, an arc discharge in a mixture may be more constricted than that burning in pure gases.

Under the presence of a shape resonance for a copper atom, the strong arc constriction at low currents is typical of the arc burning in the gaseous mixtures containing copper.

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МЕХАНІЗМИ КОНТРАКЦІЇ ДУГОВОГО РОЗРЯДУ 2. ОСОБЛИВОСТІ КОНТРАКЦІЇ ДУГИ МАЛОГО СТРУМУ В СУМІШІ ІНЕРТНОГО ГАЗУ З МІДДЮ

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Р е з ю м е

Розглянуто вплив характеристик газового середовища на процес теплової контракції (стягування) дугового розряду в суміші інертного газу з міддю. Проведено розрахунки і показано, що ступінь стягування дугового розряду визначається теплофізичними характеристиками газової суміші та характеристиками електрон-атомних зіткнень. Досліджено взаємний вплив ефектів Рамзауера та резонансу форми на характер контракції дугового розряду. Показана можливість нейтралізації впливу ефекту Рамзауера на контракцію дуги в газовій суміші.