INFLUENCE OF MOLECULAR AND ELECTRONEGATIVE IMPURITIES ON THE CONTRACTION OF THE PLASMA COLUMN OF AN ARGON ARC

P. V. Porytskyy
Institute for Nuclear Research, pr. Nauky 47, Kiev 03680 , Ukraine,
fax: +380-44-2654463, e-mail: poryts@kinr.kiev.ua

The constriction of an argon arc caused by electronegative and molecular impurities is considered at atmospheric pressure. It is shown that the presence of electronegative and molecular impurities leads to an additional diminution of sizes of field occupied by discharge. The action of molecular vapors and electronegative species causes also the split of arc column in the layers, which may be characterized by the different effective temperatures. Spatial characteristics of the arc are calculated and then ones are compared with experimental data.
PACS: 52.80.-s

1. INTRODUCTION

Properties of an arc depend on the processes in arc plasma medium and on the electrodes. In particular they depend on the impurities evaporated from electrodes. In the region of arc this impurities take part in the reactions of ionization, dissociation and electron attachment, and as a result of that the complicated plasma composition occurs with positive and negative, atomic and molecular ions, atoms, molecules and radicals. In this paper the process of contraction is studied for the case of an argon arc with a small quantity of impurities.

Constriction (self-compression) of discharge takes place if the following conditions are met [1-4]: (1) bulk neutralization of the charged particles dominates their diffusion drift to walls of the discharge chamber; (2) frequency of formation of the charged particles decreases from axis to walls of the chamber. Thus, the degree of contraction of discharge depends upon non-uniformity of the temperature across its section. In particular, thermal contraction is caused by the fact that 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 neutrals particles and their temperature falls, which in turn leads to a decrease in the concentration of electrons because of intensification of the recombination processes. The presence of molecular vapors and long-life negative ions in the arc gas leads to an increase in contraction of the arc column [1,3]. In the process of welding under flux molecular and electronegative species are appeared in the arc gas due to the evaporation of flux from the surface of anode.

2. CONTRACTION OF AN ARGON ARC COLUMN BY MOLECULAR AND ELECTRONEGATIVE IMPURITIES

In electronegative gases the basic mechanism of neutralization is connected to an attachment of electrons to atoms and molecules. In this case neutralization of charged particles happens sequentially, in two stages:

$$e + Ng \longrightarrow Ng^- , \qquad (1)$$

$$Ng^- + Ng^+ \longrightarrow 2Ng , \qquad (2)$$

where the process of an attachment (1) happens usually to participation of the third particle, Ng is an electronegative particle.

At discharge in gas with the electronegative components the formed negatively ionized atoms will recombine with positively ionized atoms A^+ basic component:

$$Ng^- + A^+ \longrightarrow X + Y , \qquad (3)$$

Where, generally, X and Y - neutral particles: atoms, molecules or composite complexes.

As the processes (1) - (3) in this case take place on a background of other processes of a recombination of charged particles, the presence in discharge of electronegative impurities reduces in an additional diminution of sizes of field occupied by discharge.

In molecular gases there are essential inelastic processes: transitions between oscillatory and rotary levels of molecules, dissociation of molecules and association of atoms, chemical reactions (in a mixture of gases). The inelastic processes reduce in a modification of intrinsic energy of particles and consequently influence transposition of an energy (thermal conduction). The excited particles pass in field with smaller temperature and there transmit the intrinsic energy to a translational degree of freedom of particles, thus incrementing transposition of an energy. It reduces in magnification of a heat conductivity and, as the corollary, strengthens squeezing discharge[4].

Consider plasma of a positive column of a cylindrical electric arc, in which the local thermodynamic equilibrium is maintained, including ionization. We consider an electronic thermal conduction and inelastic losses of electrons small in comparison with Joule heat and elastic losses of electrons. Neglect a radiation transfer of an energy. The Coulomb impacts also are neglected, supposing low ionization of plasma: $kT << eU_{i;eff} = E_{i;eff}$, where k is Boltzmann constant, T is temperature, e is an elementary charge, $U_{i;eff}$ is an effective potential of ionization of gas, $E_{i;eff}$ is a relevant ionization energy. Assuming that the intensity of heat release is proportional to the local current density and the electron and gas temperatures are equal to each other, the heat transfer equation can be written as follows:

$$\frac{1}{r}\cdot\frac{d}{dr}\left(r\chi(T)\frac{dT}{dr}\right)+q(r)=0 \qquad (4)$$

Here r is a distance from an axis, $\chi(T)$ is heat conductivity, $q(r)=j(r)E$ is capacity of an energy release in a unit volume, $j(r)=\sigma E$ is a density of an electrical current, E is electric field strength, σ is conductivity of plasma. Choose boundary conditions in the following aspect: temperature on a discharge axis $T(0)=T_0$, $q(0)=q_0$ and the temperature on periphery let's assume equal to constant (zero or 300 K).

Write down the coefficient of thermal conductivity in the following form [2]:

$$\chi=\chi_{elst}+\chi_{int} , \qquad (5)$$

Where χ_{elst} is related to the energy transfer by the translation degree of freedom is assumed to be equal to the coefficient of thermal conductivity of argon , $\chi_{Ar}(T)$, obeying the following dependence [2]:

$$\chi_{Ar}(T)=\chi_*\left(\frac{T}{T_*}\right)^{0.68} , \qquad (6)$$

where $\chi_*=4.2\cdot10^{-2}$ W/m·K, $T_*=1000$ K.

And χ_{int} is caused by the energy transfer at the internal degree of freedom and can be written as follows[4]:

$$\chi_{\text{int}}=\chi_{ros}+\chi_b \qquad , \qquad (7)$$

where χ_{ros} is associated with processes occurring at the rotation and oscillation degrees of freedom, and χ_b is caused by the processes of splitting of particles.

Supposing that density of particles of an impurity of molecular gas in an argon n_f is insignificant in comparison with a density of working gas n, therefore we can neglect χ_{ros} because that $(\chi_{ros}/\chi_{elst})\propto(n_f/n)$. The processes of dissociation of molecules and subsequent ionization of atoms even at small concentration of an impurity can cause a fundamental increase essentially increase in a heat conductivity. This is related to the fact that, during splitting, a particle transfers the energy which is much in excess of the thermal energy of the particles. In turn, the value of χ_b can be written as the sum of dissociation (index *d*) and ionization (index *i*) contributions:

$$\chi_b=\chi_d+\chi_i \qquad . \qquad (8)$$

Limit our consideration to a case of relatively low temperatures, when energy of dissociation $E_D>>kT$ and ionization $E_i>>kT$. Then for a case of a dissociation of the diatomic perfect gas the value χ_d can approximately be calculated from the formula [5]:

$$\chi_d\approx\frac{D_f p_f}{T}\cdot\frac{\alpha_d(1-\alpha_d)}{(2-\alpha_d)}\cdot\left(\frac{E_D}{kT}\right)^2 , \qquad (9)$$

where D_f is diffusivity of an impurity in working gas, p_f is pressure of dissociating gas (molecular impurity), $\alpha_d=\frac{n_{f;a}}{n_M+n_{f;a}}$ is degree of dissociation, n_M is density of molecules, $n_{f;a}$ is density of d atoms.

Similarly, the contribution of ionization to a thermal conduction can be calculated as

$$\chi_i\approx\frac{D_{amb}p_g}{T}\cdot\frac{\alpha_i(1-\alpha_i)}{(2-\alpha_i)}\cdot\left(\frac{E_i}{kT}\right)^2 , \qquad (10)$$

where D_{amb} is the coefficient of an ambipolar diffusion, p_g is the pressure of gas, α_i is the degree of ionization.

We can obtain an analytical solution of equation (4). As in this equation the strongest dependence upon r is of an exponential character , to solve it, we will assume all the coefficients of derivatives to be constant and equal to those at the discharge axis.

Having been reduced equation (4), we obtain the solution for temperature field and then for the current density in the form [3]:

$$j(r)=j_0\varpi(r)F(r) \quad , \qquad (11)$$

where $j_0=j(0)$, $F(r)=\frac{1}{\left(1+(r/r_0)^2\right)^2}$,

$$r_0^2=\frac{16\chi_0 kT_0^2}{q_0E_{i;eff}}, \ \chi_0=\chi(0),$$

$E_{i,eff}$ is the an effective energy of ionization of arc gas, and the function $\varpi(r)$ is associated with the distribution of negative ions in the discharge.

The Fig.1 shows the results of calculation from formula (11) and corresponding experimental data for the typical regime of welding of titanium under flux NaF . We can see a good agreement of both the calculated and experimental data. The similar results also are obtained for other typical conditions of welding arcs.

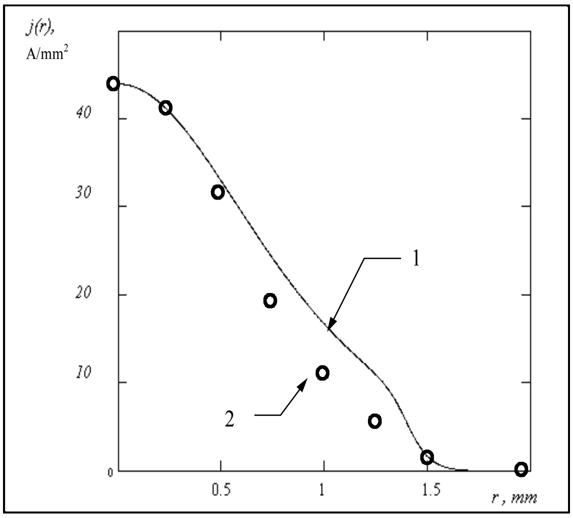

Fig.1. Current density distribution in the condition corresponding to the the welding under flux NaF [3]. Curve 1 is the calculation, and 2 is the experimental data. Arc current I=100 A, and $q_0 \approx 2\cdot10^{10}$ *W/m*^{3}

3. NUMERICAL SIMULATION

The numerical calculations of the properties of that plasmas are carried out and the temperature field in the arc is studied for the various regimes of the discharge. We study processes corresponding to the case of welding of titanium over flux [3] with such impurities as halide salts (*CsF, NaF, KF*). In this connection the equation of heat transfer (4) with nonlinear coefficients has been solved by numerical methods. For the approximation of eq. (4) the divergent form of standard difference approximation of second kind has been used for the equation of heat conductivity [5].

The coefficients in equation (12) has been chosen in the form of tabular functions of temperature, at that the values of that coefficients had been calculated before starting of numerical simulation at the stage of initialization of the task.

The electrical conductivity of plasma has been calculated from Frost's formula [6] with having been used the well known data of cross-section [7].

The numerical solution of the difference approximation equation has been found by an optimized sequential algorithm of upper relaxation, and at that when a number of knot is more than 1000 it has been done by an implicit method of minimal discrepancy [5]. The total arc current had been supported constant (*I*=100 A), and a radial distribution of the current density has been recalculated at every iteration accordingly to electrical conductivity.

The calculations of the properties of argon plasma with impurities are carried out and the temperature field in the arc is studied for the various regimes of the discharge. From the results of simulations (Fig.2) we can see that plasma column splits in a number of layers, which may be characterized by the different effective temperatures. The molecular impurities are localized to the periphery of discharge. The analogous results we obtain for the electronegative species. We can see that plasma column splits in a number of layers.

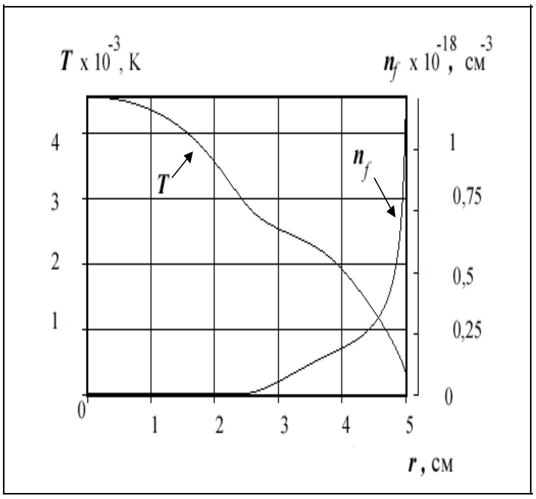

Fig2. The calculated distributions of the temperature T *and concentration of impurity* n_f *(NaF) in arc column. Arc current I=100 A*

4. CONCLUSION

The presence in discharge of electronegative and molecular impurities leads to an additional diminution of sizes of field occupied by discharge. The action of molecular vapors and electronegative species causes also the split of arc column in the layers which may be characterized by the different effective temperatures.

REFERENCES

[1] A V Yeletsky, A T Rakhimov , "Instabilities in the gas discharge plasma", Chemistry of Plasma, Vol.4, pp.123-167, 1977. (In Russian).

[2] B M Smirnov , "Contraction of the high-pressure positive arc column", High Temp. Phys. (Teplofizika vys. Temp.), Vol.35, pp.14-18, 1997.

[3] B E Paton, V N Zamkov, V P Prilutsky, and P V Porytsky, The Paton Welding Journal No.1(562),pp.5-11,2000.

[4] A V Yeletsky, L A Palkina, B M Smirnov, "Transfer phenomena in the slightly ionized plasma", Moscow, Atomizdat, 1975.

[5] Samarskii A.A. Theory of difference approximation (Moscow, Nauka), 1989 (In Russian).

[6] Mitchner M., Kruger C.H. Partially ionized gases (NY, Wiley) 1973.

[7] Huxley L.G.H., Crompton R.W. The diffusion and drift of electrons in gases (NY,Wiley) 1974.