ON THE CONTRACTION OF AN ARC DISCHARGE IN GASEOUS MIXTURES

P. V. Porytskyy

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

The influence of properties of a gaseous medium on the process of contraction (self-constriction) of an arc discharge in the atmosphere of the mixtures of noble gases is considered. The calculations are carried out, and it is shown that the degree of constriction of an arc discharge is determined by both the thermal characteristics of the gaseous medium and the characteristics of electron-atom collisions. It is revealed that the Ramsauer effect has an influence on a character of the contraction of an arc. Also, it is shown the possibility to neutralize this influence in gaseous mixtures.

PACS: 52.20.Fs, 52.25.Fi, 52.25.Ya, 52.27.Cm, 52.77.Fv, 52.50.Nr, 52.80.Mg

1. INTRODUCTION

Thermal contraction (self-constriction) of an arc discharge is caused by the fact that temperature at the periphery of the discharge falls and the gas density (under constant pressure) rises [1-5]. Therefore, electrons at the periphery give up a larger amount of energy to neutral particles and their temperature falls, which leads, in turn, to a decrease in the concentration of electrons because of the intensification of the recombination processes.

The contraction of an arc in one-component gas media is studied in papers [3-5]. Unfortunately, the obtained results can not be apply to the case of an arc discharge in gaseous mixtures due to the fact that the properties of the mixtures and multicomponent plasmas are known to be not additive relatively to the concentration of components [6,7].

In this paper, the real cross-section of electron-atom collisions are taken into account, and the influence of characteristics of the gaseous medium on the process of thermal contraction in the atmosphere of the various mixtures of noble gases.

It should be mentioned that the contraction is usually considered as a negative phenomenon that restricts an application of arc discharges [1]. However, on the other hand, in certain cases, namely the contraction can be a base in applications of arc discharges in technology [4].

2. MODEL OF AN ARC DISCHARGE

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

$$\frac{1}{r}\cdot\frac{d}{dr}\left\{r\left[\kappa(T)\frac{dT}{dr}+\left(\kappa_e(T_e)+\kappa_p(T_e)\right)\frac{dT_e}{dr}\right]\right\} \qquad (1)$$
$$+q(r)=0$$

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

Consider a gas at low ionization, when $kT_e \ll U_I$, where U_I is the effective energy of ionization of a gaseous medium. If LTE occurs, the number density of electrons n_e at the point of discharge is connected with the number densities of ions n_i and neutrals n_a by the well-known Saha formula

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

where m_e is electron mass, h is the Planck constant, g_i, g_a are the effective statistical weights of ion and atom, respectively.

Since LTE occurs in the plasma region, which is determined by its heat balance, the temperatures of electrons and gas are varied weakly. That fact allows to obtain an approximate solution of Eq.(1) by using the method stated in [3,5]. Accordingly to this method, we assume that the dependences of the current density, power of heat release, and corresponding quantities on the temperature in the cross-section of a discharge are given, and the coefficients in Eq.(1) are constant, and their values are set on the discharge axis. In this way we obtain the following system of equations that is described an arc discharge:

$$T_e-T=\frac{M}{3k}\left(\frac{eE}{m_e}\right)^2\frac{\left\langle u_e^2/\nu_{ea}\right\rangle}{\left\langle u_e^2\nu_{ea}^*\right\rangle}\quad, \qquad (3.1)$$

$$IE=\frac{\pi kT_e^2}{E_I}\left[16\kappa\zeta_T\left(1+\left(\frac{r_g}{R}\right)^2\right)^{-1}+5\left(\kappa_e+\kappa_p\right)\right]\quad, \qquad (3.2)$$

$$S=0.215q_0r_0^{\,2}\ln\left(\frac{R}{r_0}\right)\quad, \qquad (3.3)$$

$$p+\Delta p=NkT+n_ekT_e\quad, \qquad (3.4)$$

$$I=\sigma E\cdot\pi r_0^2\quad. \qquad (3.5)$$

Here e is an electron charge, M is an effective mass of atom in gaseous mixtures ($M^{-1}=\sum_\alpha x_\alpha m_{a\alpha}^{-1}$, where the subscript α indicates the type of species, $m_{a\alpha}$ is an atom mass, x_α is the molar concentration of α-species), $\nu_{ea}=\sum\limits_\alpha \nu_{e\alpha}$, $\nu^*_{ea}=\sum\limits_\alpha \left(M/m_{a\alpha}\right)\nu_{e\alpha}$, where $\nu_{e\alpha}$ is the frequency of electron-atom collisions for the α-species in mixture, u_e is the electron velocity, and the bracket $\langle\ \rangle$ denotes the averaging over the Maxwellian distribution of electron velocities; I is the arc current, R is the radius of the chamber wall, S is the heat function, $q_0=\sigma E^2$, $\zeta_T=dT/dT_e$, Δp is the diminution of pressure in plasma, and r_0 is a characteristic radius of plasma (radius of contraction), which is determined from the relation $r_0^2\approx 1.32r_g^2+r_J^2$, where r_g and r_J are determined as

$$r_g^2=\frac{16kT_e^2\kappa\zeta_T}{q_0E_I}, \qquad r_J^2=\frac{11.6kT_e^2\left(\kappa_e+\kappa_p\right)}{q_0E_I}.$$

The heat function S is determined as

$$S=\int\limits_0^{T_e}\left(\kappa_e\left(T_e'\right)+\kappa_p\left(T_e'\right)\right)dT_e'+\int\limits_0^{T}\kappa\left(T'\right)dT'.$$

For gaseous conductivity of inert gas mixtures it is used the Wassiljeva's formula with coefficients calculated by the Mason-Saxena method [6] via the conductivities of inert gases from [8]. To calculate electric conductivities of the complex arc plasma it is used the first order approximations from [7]. The k_p can be expressed via the coefficient of ambipolar diffusion [1]. Under calculations the cross-section data are used from [9]. Upon increasing the ionization degree it is essential to consider the Coulomb collisions because it should be respectively modified the above frequencies.

Also, it should be took into account the following conditions: the quasineutrality of plasma $n_e=n_i$, the electric field strength and the atmosphere pressure are constant ($E=const$, $p=const$).

The system (3) with the Saha formula (2) allows us to obtain the values of E,T_e,T,n_e,n_a,N,r_0 under the desired values of the arc current I and pressure p and vice versa.

3. 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 wall of the discharge tube. This situation corresponds to the idealization of a long arc (see [5]).

The characteristics of an arc without radiation transfer are known to describe in unified variables r/R, ER and I/R. The calculation of a reduced radius of contraction r_0/R in various regimes allows us to depict the following discharge contraction pattern (Fig.1 and Fig.2). At a relatively low current the extremely strong constriction of an arc occurs under dominating the gaseous heat conductivity. At increasing of current the electron heat conductivity is raised to a leading hand. If the electron-atom collisions are still dominated than the value of reduced radius of contraction is stabilized i.e. $r\propto R$. At the follow-up increasing of current the Coulomb collision is prevailed and the discharge field is diminished.

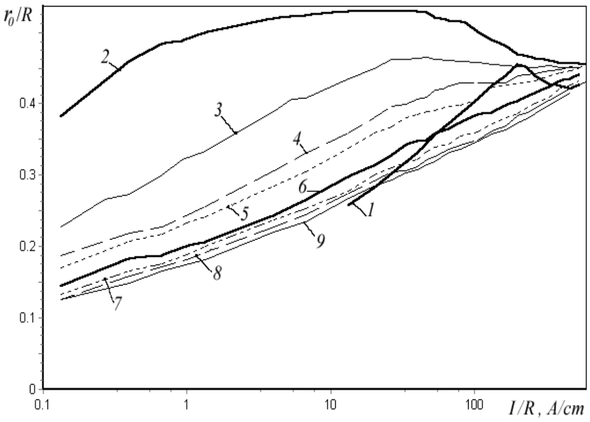

Fig.1. The calculated values of the reduced radius r_0/R of contraction via reduced current I/R (p =1 atm). Curves 1-He, 2-Ar, 3-He:Ar(10:90%), 4-He:Ar(20:80%), 5-He:Ar(30:70%), 6-He:Ar(50:50%), 7-He:Ar(70:30%), 8-He:Ar(80:20%) 9-He:Ar(90:10%)

It should be noted that Ar, Kr, and Xe belong to the gases with a remarkably expressed Ramsauer effect that causes the expansion of an arc discharge (see Fig.1 and Fig.2). But, in the gaseous mixtures this influence may be neutralized. Thus, the relatively small addition of He into Ar causes the intense constriction of a discharge region (Fig.1). Otherwise, for the mixture of gases having Ramsauer effect an additional constriction is absent (Fig.2).

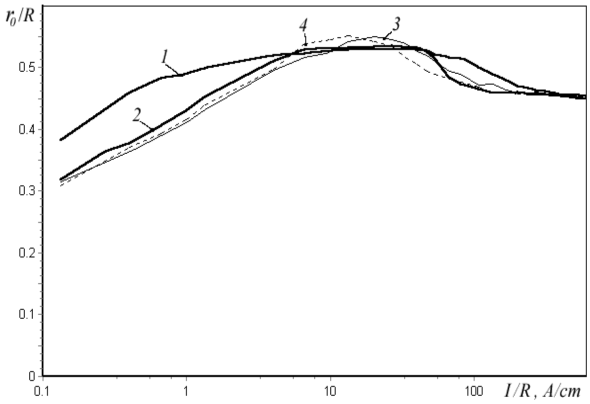

Fig.2. The calculated values of the reduced radius r_0/R of contraction via reduced current I/R (p =1 atm). Curves 1-Ar, 2-Xe, 3-Ar:Xe(10:90%), 4-Ar:Xe(20:80%)

4. CONCLUSION

The degree of thermal contraction of an arc discharge is determined by the heat transfer characteristics of the gaseous mixture and by the characteristics of electron-atom collisions.

The contraction of a discharge in a certain mixture is more pronounced in the case where the gaseous thermal conductivity dominates in the heat transfer processes.

The presence of the Ramsauer effect for a gas medium where an arc is burning has an essential influence on the process of contraction, which is revealed in a decrease in the constriction of an arc discharge in the corresponded temperature range. But, in the gaseous mixtures this influence may be neutralized by choosing a suitable composition of mixture.

REFERENCES

[1] A.V. Yeletsky, L.A. Palkina, B.M. Smirnov. *Transfer phenomena in the slightly ionized plasma.* Moscow: “Atomizdat”, 1975 (In Russian).

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

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

[4] B.E. Paton, V.N. Zamkov, V.P. Prilutsky, and P.V. Porytskyy. Contraction of the welding arc caused by the flux in tungsten-electrode-argon arc welding // *The Paton Welding Journal.* 2000, No.1(562), pp.5-11.

[5] P.V. Porytskyy. Mechanisms of the contraction of an arc discharge I. Peculiarities of thermal contraction // *Ukrainian J. Phys. (49).* 2004, pp.883-889.

[6] R.C. Reid, J.M. Prausnitz, T.K. Sherwood. *The properties of gases and liquids*. NY: McGraw-Hill. 1973.

[7] V.M. Zhdanov. *Transport Phenomena in Multi-component Plasma.* Moscow: “Energoatomizdat”, 1982 (In Russian).

[8] V.G. Fastovskii, A.E. Rovinskii, Yu.V. Petrovskii, *Inert Gases*. Moscow: “Atomizdat”, 1972 (In Russian).

[9] L.G.H. Huxley, R.W. Crompton. *The diffusion and drift of electrons in gases.* NY: Wiley, 1974.

О ТЕПЛОВОЙ КОНТРАКЦИИ ДУГОВОГО РАЗРЯДА В ГАЗОВЫХ СМЕСЯХ

П. В. Порицкий

Рассмотрено влияние характеристик газовой среды на процесс контракции (сжатия) дугового разряда в смесях инертных газов. Проведены расчеты и показано, что степень сжатия дугового разряда определяется теплофизическими характеристиками газовой среды и характеристиками столкновений электронов с атомами и ионами. Выявлено влияние эффекта Рамзауэра на характер контракции дугового разряда, а также показана возможность нейтрализации этого эффекта соответствующим подбором состава смеси.

ПРО ТЕПЛОВУ КОНТРАКЦІЮ ДУГОВОГО РОЗРЯДУ В ГАЗОВИХ СУМІШАХ

П. В. Порицький

Розглянуто вплив характеристик газового середовища на процес контракції (стягування) дугового розряду в сумішах інертних газів. Проведені розрахунки і показано, що ступінь стягування дугового розряду визначається теплофізичними характеристиками газового середовища і характеристиками зіткнень електронів з атомами та іонами. Висвітлено вплив ефекту Рамзауера на характер контракції дугового розряду, а також показана можливість нейтралізації цього ефекту відповідним підбором складу суміші.