MECHANISMS OF THE CONTRACTION OF AN ARC DISCHARGE 3. PECULIARITIES OF THE THERMAL CONTRACTION OF AN ARC IN A MOLECULAR GAS

P.V. PORYTSKYY

Institute for Nuclear Research, Nat. Acad. of Sci. of Ukraine
(47, Nauky Prosp., Kyiv 03680, Ukraine; e-mail: poryts@kinr.kiev.ua)

UDC 533.952:537.523.5

We consider the influence of properties of a gaseous medium on the processes of contraction (self-constriction) of an arc discharge in the atmosphere of hydrogen, the mixture of hydrogen and copper, and water vapor. The calculations show 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–neutral particle and ion–atom collisions. The similarity of the contraction of an arc in both the hydrogen and water vapor media is shown.

1. Introduction

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 external pressure [1–9]. The contraction is usually considered as a negative phenomenon that restricts an application of arc discharges [1]. On the other hand, just the contraction can be, in certain cases, a base in applications of arc discharges in technology [6].

Arc discharges at a high or middle pressure are characterized by the thermal contraction. It is caused by the fact that the temperature at the periphery of a discharge falls, and the gas density (at a constant pressure) rises. Therefore, electrons at the periphery give up a larger amount of energy to neutral particles, whose temperature falls. This leads, in turn, to a decrease in the concentration of electrons because of the intensification of the recombination processes. The character of the energy interchange between particles strongly depends on their type. Therefore, the processes of contraction are essentially different in different gaseous media.

The thermal contraction of arcs was studied in works [3–9], but the obtained results cannot be extended to the practically important case of molecular gases and mixtures containing them due to the fact that the properties of molecular gases, gaseous mixtures, and multicomponent plasmas of discharges in these mixtures are strongly different from those in the case of atomic gases. It should be mentioned that the last decade is characterized by the enhanced interest in the use of water vapor along with hydrogen in the electric arc apparatus, which expands the field of applications of thermal plasma [10].

The aim of this work is to study the influence of physical characteristics of a molecular gas (water vapor or hydrogen) and a mixture of a molecular gas with a metal (copper) on the contraction of an arc discharge. The peculiarities of electron–atom and ion–atom cross-sections are taken into account. To reach the pointed aim, we will consider the idealized model of a long arc where the heat released in a discharge is carried out onto the walls of a discharge chamber [7].

2. Properties of the Thermal Plasma of a Molecular Gas

It is generally agreed that the plasma of an arc discharge at the normal or high pressure is in a state of local thermodynamic equilibrium (LTE) [2–5]. Because of the high concentrations of neutral atoms and electrons, the collision processes play a more significant role in that

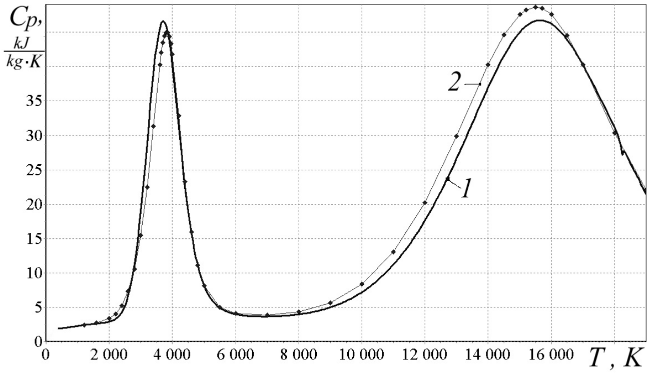

Fig. 1. Specific heat capacity at a constant pressure of the thermal plasma of water vapor ($T_e = T$, pressure $p = 1$ bar). Curve *1* shows the result of calculations (this work); *2* gives the data from [14]

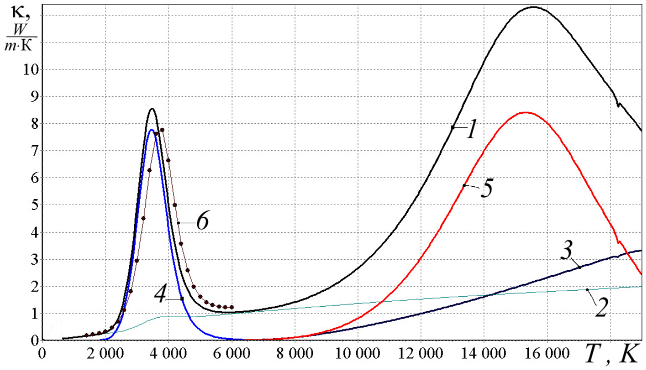

Fig. 2. Heat conductivity of the thermal plasma of water vapor ($T_e = T$, $p = 1$ bar). Curve *1* is the total heat conductivity κ, *2* is the gas heat conductivity κ_g, *3* is the electron heat conductivity κ_e, *4* is the heat conductivity due to dissociation κ_{rd}, *5* is the heat conductivity due to ionization κ_{ri}, and *6* gives the data from [15]

plasma in comparison with diffusive and radiative processes.

It is worth to note that the radiation can influence 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 [11,12]. However, the equilibrium state is broken in the near-electrode layers of free-burning arcs due to the transfer of a resonant radiation [11].

We mention a two-temperature model of plasma in the case where a state is described by both the certain gas temperature T and the electron one T_e, and the ionization equilibrium relative to T_e holds.

For low-temperature plasma, when LTE occurs, the number density of electrons n_e at the point of discharge is connected with the number densities of ions and that of neutral particles by the Saha's formula. For the plasma of a molecular gas, the mass action law related to the reactive processes should be taken into account.

We note that the plasma of a molecular gas is characterized by the processes of dissociation of molecules and association of atoms which do not exist in a pure atomic gas. In addition, a molecular gas has the additional (vibrational and rotational) degrees of freedom as distinct from an atomic gas. Therefore, the properties of a molecular gas are essentially different from those of an atomic gas.

In the case where the difference between the electron temperature and the gas one in plasma is caused by the electric field, the relationship between the temperatures can be calculated for multicomponent plasmas by formulae from [8, 9]. This relationship and the data on the plasma composition allow one to calculate the thermodynamic and transport properties of thermal plasma.

Consider the peculiarities of thermodynamic and transport properties of thermal plasma for the case of the thermal plasma of water vapor. In calculations, we applied the method given in [8, 9, 13] which was used earlier for the plasma of atomic gases. The results are shown in Figs. 1 and 2. We can see that the temperature dependences of heat capacity and heat conductivity have characteristic maxima corresponding to the processes of dissociation and ionization (in the case of atomic gases, the first “dissociative” maximum is absent). This result is in a good agreement with the data from [14, 15].

In the studies of arc discharges, it is important to consider the peculiarities of the temperature dependence of the heat conductivity of plasma, κ, and its components: the heat conductivity of a gas κ_g, the electron one κ_e, the heat conductivity due to dissociation κ_{rd}, and the heat conductivity due to ionization κ_{ri} (Fig. 2). Due to the dissociation and the transfer by rotational and vibrational degrees of freedom, the gas component of the heat conductivity of a molecular gas exceeds significantly the corresponding value for an atomic gas.

We also indicate that the first (dissociative) maximum for water vapor has shape of a single peak although the dissociation of a water molecule occurs in several ways. Such a pattern of the process is generally characteristic of two-atomic molecular gases, in particular of hydrogen. For water vapor, the absolute values of these maxima are mainly determined by the mobility of hydrogen atoms and ions as the lightest particles in a mixture. From that, it can be deduced that the properties of the thermal plasma of water vapor and hydrogen should be similar. As a consequence, we may expect that the arc discharges in these media are also similar.

3. Model of 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 intensity is proportional to a local current density and ignoring the radiation transfer, the heat transfer equation (the Elenbaas–Heller equation [3–5, 16, 17]) can be written as

$$\frac{1}{r}\frac{d}{dr}\left\{r\left[\left(\kappa_g\left(T\right)+\kappa_{rd}\left(T\right)\right)\frac{dT}{dr}+\right.\right.$$
$$\left.\left.+\left(\kappa_e\left(T_e\right)+\kappa_{ri}\left(T_e\right)\right)\frac{dT_e}{dr}\right]\right\}+q\left(r\right)=0. \quad (1)$$

Here, r is the distance from the discharge axis, $q\left(r\right)=j\left(r\right)E$ is the power of heat release per unit volume; $j\left(r\right)=\sigma E$ is the electric current density, and σ is the electric conductivity of plasma.

Because a region occupied by plasma is characterized by LTE, which determines the heat balance, the temperatures of electrons and a gas vary slightly. That fact allows us to obtain an approximate solution of Eq. (1) by using the method in [3–7]. According 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. The coefficients in Eq. (1) are assumed to be constant, and their values are set on the discharge axis. In this way, we can transform Eq. (1) to the form of an ordinary differential equation. The analytical solution of this equation gives the distributions of temperatures, current density, and other quantities over the discharge cross-section.

The analytical solution of Eq. (1) is of importance despite its approximate nature, because it allows us to analyze the effect of various physical mechanisms on the distributions of the temperature and other quantities over the discharge cross-section. By applying the above-mentioned method and by using the formulae given in the previous section, we obtain the following system of algebraic equations for the parameters of an arc discharge:

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

$$IE=\frac{\pi kT_e^2}{E_I}\times$$
$$\times\left[16\left(\kappa_g+\kappa_{rd}\right)\zeta_T\left(\frac{1}{1+(r_g/R)^2}\right)+5\left(\kappa_e+\kappa_{ri}\right)\right], \quad (3)$$

$$S=0.215q_0r_0^2\ln\left(\frac{R}{r_0}\right), \quad (4)$$

$$p+\Delta p=NkT+n_ekT_e, \quad (5)$$

$$I=\sigma E\pi r_0^2. \quad (6)$$

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

$$r_g^2=\frac{16kT_e^2\left(\kappa_g+\kappa_{rd}\right)\zeta_T}{q_0E_I},\quad r_J^2=\frac{11.6kT_e^2\left(\kappa_e+\kappa_{ri}\right)}{q_0E_I}.$$

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 [7]). At the distance equal to the radius r_g, the mentioned quantities are decreased by 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 quantities are decreased by about 20 times at the radius r_J.

The additional conditions for the presented system of equations are the following: the quasineutrality of plasma and the constancy of the electric field strength and the pressure (E =const and p =const) over the cross-section of a discharge. It should be also mentioned that the temperatures and other quantities in system (2)–(6) are set on the discharge axis.

The thermal function is defined as follows:

$$S=\int\limits_0^{T_e}\left(\kappa_e\left(T_e'\right)+\kappa_{ri}\left(T_e'\right)\right)dT_e'+$$
$$+\int\limits_0^{T}\left(\kappa_g\left(T'\right)+\kappa_{rd}\left(T'\right)\right)dT'. \quad (7)$$

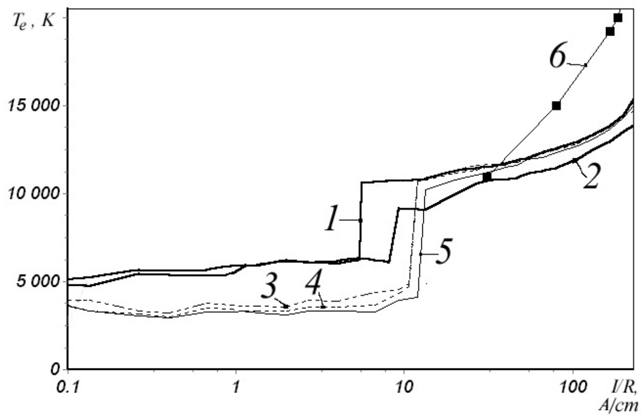

Fig. 3. Temperature T_e on the axis of an arc discharge vs the reduced current I/R (p = 1 atm). Curve *1* – H_2, *2* – H_2O, *3* – H_2:Cu (equimolar mixture 99:1 mol. %), *4* – H_2:Cu (95:5 mol. %), *5* – H_2:Cu (90:10 mol. %), and *6* gives the experimental data on H_2 [16]

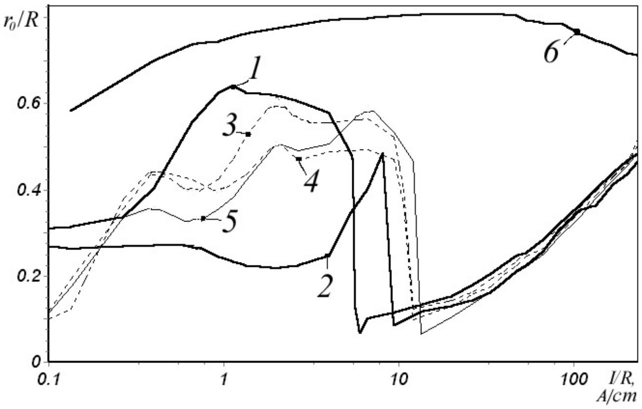

Fig. 4. Reduced radius of contraction of an arc r_0/R vs the reduced current I/R (p = 1 atm). Curve *1* – H_2, *2* – H_2O, *3* – H_2:Cu (equimolar mixture 99:1 mol. %), *4* – H_2:Cu (95:5 mol. %), *5* – H_2:Cu (90:10 mol. %), and *6* – Ar

System (2)–(6) should be supplemented by the Saha's equation for every component of the mixture and the relation of the mass action law for components of a molecular gas.

Given the temperature and the composition of plasma, we calculated the transport coefficients, by following works [7–9, 13].

It should be noted that the increase of the concentration of charged particles leads to the amplification of the effects caused by the nonideality of a low-temperature plasma: namely, both the pressure and the ionization energy in plasma decrease. These effects are calculated accordingly to the well-known Griem's correction [18].

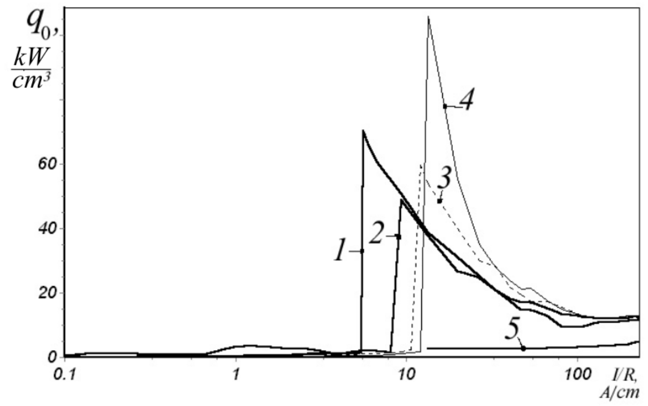

Fig. 5. Power of heat release q_0 vs the reduced current I/R (p = 1 atm). Curve *1* – H_2, *2* – H_2O, *3* – H_2:Cu (95:5 mol. %), *4* – H_2:Cu (90:10 mol. %), and *5* – He

Thus, the system of equations (2)–(6) together with the Saha's equations for every component in the mixture and the mass action law allow us to obtain the parameters of an arc E, T_e, T, n_e, n_a, N, and r_0 at 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 such a discharge where the released heat is transferred by means of heat conductivity into the walls of a discharge tube which are maintained at a fixed temperature. This situation corresponds to the idealization of a long arc (see [7, 19]).

It should be emphasized that an arc without radiation transfer is described by the unified curves in the reduced coordinates r/R , ER, and I/R [17]. The results of calculations of both the radius of contraction and the power of heat release are presented in Figs. 3–5.

The obtained results allow us to draw the following pattern of the contraction of an arc discharge in a molecular gas and gaseous mixtures. At the modes of a discharge characterized by relatively low electron temperatures and low reduced currents I/R, the contraction is reached under conditions when the heat transfer is due to the gas heat conductivity (Figs. 3 and 4).

With increase in the current and temperature, the plasma region of a discharge is expanded. This situation corresponds to the discharge in a weakly dissociated molecular gas that looks like the discharge in an atomic gas.

At the further increase in the current, the discharge enters into the mode where the dissociation of molecules and the association of atoms affect the heat transfer, which leads to a rather strong contraction of an arc. The constriction of the discharge causes an increase in the energy release power in plasma. This, in its turn, causes the intensification of dissociation and ionization. As a consequence of these processes, the full dissociation of molecules takes place, and the degree of ionization grows up. The discharge at a certain critical current reaches the mode with a dense plasma and a high power density (Figs. 3–5). The abrupt transition to a discharge in the mixture of atomic gases takes place, and the influence of dissociation on the heat transfer slumps. For hydrogen and water vapor, the critical currents correspond to the values $(I/R)_{\mathrm{cr}} \approx 7$ and 8.1 A/cm, respectively.

However, the mode with dense plasma at the subsequent increase in the current cannot be supported due to the fact that the heat conductivity of a mixture of atomic gases is much smaller than that of a molecular gas under its dissociation. The transfer of a larger amount of heat from the discharge requires that the discharge be expanded and the temperature grow up. This, in its turn, increases the electron and ionization components of the heat conductivity (Fig. 4). We note that the electron component of the transport coefficients is determined mainly by the characteristics of electron–atom and electron–molecule collisions, whereas the ionization component is associated with ion–atom collisions. In our case, just hydrogen gives the greatest contribution to the transport properties due to a high mobility of hydrogen atoms and ions as the lightest particles.

The expansion of a discharge causes the some diminution of the power density in plasma with increase in the current. However, it should be considered that, with increase in the temperature of plasma, the influence of the radiative transfer is amplified, which changes the discharge characteristics. For this reason, we meet the difference between the results of calculations and experimental data at high currents (Fig. 3). Generally, we may expect the instability of low-current arcs in hydrogen and water vapor.

Thus, we can distinguish three distinctive modes of arc discharges in molecular gases: 1) an arc in a molecular gas without dissociation; 2) an arc in a molecular gas under dissociation; and 3) an arc in an atomic mixture (the mixture of dissociation products). The later mode is characterized by a high power density in plasma in comparison with arcs in atomic gases (Fig. 5).

It should be mentioned that the arc discharges in hydrogen and water vapor are similar to each other, and the metal (copper) impurities do not strongly change the parameter of a discharge (Figs. 3–5). This is related to the fact that the transport coefficients are mainly determined by the transport characteristics of hydrogenic particles (atoms and ions) which are the lightest and have highest mobility.

5. Conclusion

The detailed analysis is carried out to study the processes which cause the thermal contraction of an arc discharge in the idealized model of a long arc.

It is revealed that the constriction of an arc discharge is determined by both the thermophysical characteristics of the gaseous medium and the effective electrophysical characteristics.

It should be pointed that there are three distinctive modes of an arc discharge in molecular gases: 1) an arc in a molecular gas without dissociation; 2) an arc in a molecular gas under dissociation; 3) an arc in an atomic mixture (the mixture of dissociation products). The last mode is characterized a high power density in plasma in comparison with that in an arc in an atomic gas.

An arc in a molecular gas under dissociation is characterized by a high degree of discharge constriction.

Arc discharges in hydrogen and water vapor are similar to each other. The admixture of a metal (copper) does not change significantly characteristics of a discharge in hydrogen, because the transport properties of the thermal plasmas of hydrogen and water vapor are mostly determined by those of hydrogen atoms and ions.

1. A.V. Eletskii, L.A. Palkina, and B.M. Smirnov, *Transport Phenomena in Low-Ionized Plasma* (Atomizdat, Moscow, 1975) (in Russian).
2. A.V. Eletskii and A.T. Rakhimov, Khim. Plasmy **4**, 123 (1977).
3. A.V. Eletskii and B.M. Smirnov, Phys. Uspekhi **39**, 1137 (1996).
4. B.M. Smirnov, Teplofiz. Vys. Temper. **35**, 14 (1997).
5. B.M. Smirnov and M.B. Smirnov, Phys. Scripta **56**, 302 (1997).
6. B.E. Paton, V.N. Zamkov, V.P. Prilutskyy, and P.V. Porytskyy, Paton Weld. J. **1**, 5 (2000).
7. P.V. Porytskyy, Ukr. Fiz. Zh. **49**, 883 (2004).
8. P.V. Porytskyy, Ukr. Fiz. Zh. **50**, 930 (2005).

9. P.V. Poritskyy, High Temper. **44**, 328 (2006).

10. M.F. Zhukov, I.M. Zasypkin, A.N. Timoshevskii *et al.*, *Electric Arc Generators of Thermal Plasma* (Nauka, Novosibirsk, 1999) (in Russian).

11. I.L. Babich, A.N. Veklich, and V.A. Zhovtyansky, Ukr. Fiz. Zh. **44**, 963 (1999).

12. H. Ouajji, B. Cheminat, and P. Andanson, J. Phys. D: Appl. Phys. **19**, 1903 (1986).

13. P.V. Porytskyy, in *Proceed. of the 13th Int. Congress on Plasma Physics (ICPP 2006)* (BITP, Kyiv, 2006), p. D033.

14. O. Coufal, J. Phys. D: Appl. Phys. **40**, 3371 (2007).

15. N.B. Vargaftik, *Handbook on Thermophysical Properties of Gases and Liquids* (Nauka, Moscow, 1972) (in Russian).

16. E.I. Asinovskii, A.V. Kirillin, and V.L. Nizovskii, *Stabilized Electric Arcs and Their Applicaion in Thermophysical Experiment* (Nauka, Moscow, 1992) (in Russian).

17. G.A. Desyatkov and V.S. Engelsht, *Theory of a Cylindical Arc Discharge* (Ilim, Frunze, 1985) (in Russian).

18. H.R. Griem, Phys. Rev. **128**, 997 (1962).

19. V.A. Zhovtyansky and V.M. Patriyuk, Ukr. Fiz. Zh. **45**, 1059 (2000).

Received 25.03.08

МЕХАНІЗМИ КОНТРАКЦІЇ ДУГОВОГО РОЗРЯДУ
3. ОСОБЛИВОСТІ ТЕПЛОВОЇ КОНТРАКЦІЇ ДУГИ В МОЛЕКУЛЯРНОМУ ГАЗІ

П.В. Порицький

Резюме

Розглянуто вплив характеристик газового середовища на процес теплової контракції (стягування) дугового розряду у водні, суміші водню з міддю, водяній парі. Проведено розрахунки і показано, що ступінь стягування дугового розряду в молекулярному газі визначається теплофізичними характеристиками газової суміші, характеристиками зіткнень електронів з нейтральними частинками та зіткнень іонів з атомами. Показана подібність характеру контракції дугового розряду у водні та водяній парі.