ON THE PECULIARITIES OF ELECTRICAL CONDUCTIVITY IN ARC PLASMA CONTAINING STAINLESS STEEL AND TUNGSTEN

P.V. Porytskyy

Institute for Nuclear Research, Kyiv, Ukraine

E-mail: poryts@kinr.kiev.ua

The influence of stainless steel and tungsten impurities on the electrical conductivity of multicomponent arc plasma is considered in the ambient atmosphere of argon and air. The calculations are carried out on the base of Grad's method, and it is shown that a small amount of metal causes the essential changes in the values of electrical conductivity in comparison with the case of pure gaseous mixtures. It is revealed that the increasing of metal concentration leads to the decreasing of electrical conductivity under the certain conditions in arc plasmas.

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

INTRODUCTION

Arc plasma is often used in metallurgical applications such as plasma etching, spraying, cutting and welding. The presence of metallic vapors is widely observed in arc plasma. Stainless steel and tungsten is widely used in plasma devices and industrial electronic plants. Sometimes they are doped with other materials to lower the work function of the cathode material. At operation the process of erosion leads to the evaporation of the metal impurities into the discharge region that causes the change of plasma properties.

The improvement in controlling plasma processing needs for accurate numerical modeling. Transport properties are indispensable input data for the modeling. At weakly ionization the Lorentzian theory is suitable to calculate the properties of multicomponent thermal plasma [1]. But at increasing of ionization processes a number of collision processes are known to be included into consideration. Because of that it is the many processes are needed to take into account in the calculation procedure.

In this paper, the electrical conductivity for multicomponent plasma with stainless steel and tungsten impurities is calculated on the base of the Grad's method [2, 3]. It is shown that the impurities have an influence on the transport properties of thermal plasma. The influence of stainless steel and tungsten impurities on the electrical conductivity of arc plasma is considered in the ambient atmosphere of argon and air.

The increasing of metal concentration in discharge plasma are known to be lead to the corresponding increasing of electrical conductivity due to the low value of ionization potential of metal. However, for the case of tungsten and stainless steel components it is the decreasing of electrical conductivity takes place. That phenomenon caused by the shape resonance under the collision of electron with neutral atom.

1. METHOD OF CALCULATION

It should be noted that the present state of the theory of gas mixtures, as well as multicomponent plasma, is characterized by the lack of a unified approach to the description of transport processes. The reason for this is a very complex nature of dependencies of the properties of gas mixtures and plasma on the properties of pure gases and concentrations of the components.

It should be underlined that, now, the Grad's method of moments [2, 3] is an unique alternative in spite of the most developed Chapman-Enskog' method [4-8] to solve the kinetic Boltzmann equation. Both the methods are based on the formalism of Chapman-Cowling kinetic integrals

$$\Omega_{\alpha\beta}^{lr} = \left(\frac{kT}{2\pi\mu_{\alpha\beta}}\right)^{1/2} \int_0^\infty \varsigma^{2r+3} e^{-\varsigma^2} Q_{\alpha\beta}^{(l)}(\varsigma)\, d\varsigma \quad , (1)$$

where k is Boltzmann constant, T is temperature, $\mu_{\alpha\beta}$ is a reduced mass of collided species of α and β, $\varsigma = \left(\mu_{\alpha\beta}/2kT\right)^{1/2} g$, g is the relative velocity, and transport cross-section of order l is determined as

$$Q_{\alpha\beta}^{l}(g) = 2\pi \int_0^\pi \sigma_{\alpha\beta}(g,\chi)\left(1-\cos^l\chi\right)\sin\chi\, d\chi \; ,$$

where χ is scattering angle, $\sigma_{\alpha\beta}(g,\chi)$ is differential scattering cross-section.

In the 13-moments (13M) approximation of the Grad's method the translational transport coefficients are calculated as the sum of effective coefficients for each species. The effective coefficients are calculated on the base of combination of the Chapman-Cowling integrals (2.1).

The studies of electronic transport coefficients are known to need using of higher approximations. In that way for electrical conductivity σ, can be write [3] as

$$\sigma = \frac{3}{2} n_e^2 e^2 \left(\frac{2\pi}{m_e kT}\right)^{1/2} \frac{|q'|}{|q|} \quad . \qquad (2)$$

Here m_e is the mass of electron, n_e is electronic density, the elements of determinants p^{nk} and q^{nk} are the functions of the above pointed Chapman-Cowling integrals. Script " ' " denotes the absence of elements with indexes 0 and 1 (see for details [3-8]).

Others coefficients are calculated according to the Lorentzian theory [2].

2. RESULTS AND DISCUSSION

The calculations are carried out at assumption of local thermodynamic equilibrium. The following species have been taken into account for argon-based mixtures: e^-, *Ar*, Ar^+, *Me*, Me^+, Me^{2+}, Me_2, Me_2^+ and others analogous mixtures. In turn, for air-based mixtures the following species had used that's are e^-, N_2,O_2,*NO*, *N*, *O*, N^+, O^+, NO^+, N_2^+, O_2^+, *Me*, Me^+, Me^{2+}, Me_2, Me_2^+. Where *Me* denotes the metal component.

The results of calculations for the case of nickel are shown in Figs. 1-5.

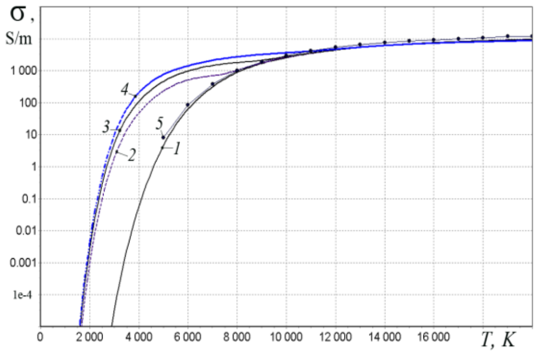

Fig. 1. Electrical conductivity of thermal plasma (p =1 atm) for pure argon and the equimolar mixtures of argon with tungsten. Curves 1 – Ar (this work calculations); 2 – Ar –W (99.9:0.1); 3 – Ar –W (95:5);

4 – Ar-W (90:10); 5 – Ar (data from [8])

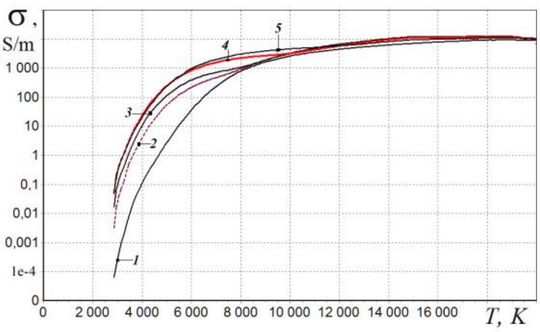

Fig. 2. Electrical conductivity of thermal plasma (p =1 atm) for pure air and the equimolar mixtures of air with tungsten. Curves 1 – pure air (this work calculations); 2 – air –W (99:1); 3 – air –W (95:5); 4 – air –W (70:30); 5 – air –W (50:50)

The obtained values are in a good agreement with the data obtained by Chapman-Enskog method (Fig. 1). The peculiarity of the Grad' method is that the values have the same dimensions at all of stages in calculation procedure due to the control of calculation procedure may be improved.

It should be noted that under scattering of electrons on argon the Ramsauer effect takes place that is determined the properties of pure argon. However this influence can be neutralized by metal additions in plasma.

Also, one can see that the appearance of tungsten impurities causes the essential changing of electrical conductivity coefficient with comparison to the case of pure argon. That is needed to take into account under studies of discharges with tungsten electrodes.

Let's increase the concentration of tungsten in mixture. One can see (Fig. 2) that in dense vapor the electrical conductivity may be drop down under the temperature growth.

A similar picture takes place in the case of the mixture of components of stainless steel in mixture (Figs. 3-5).

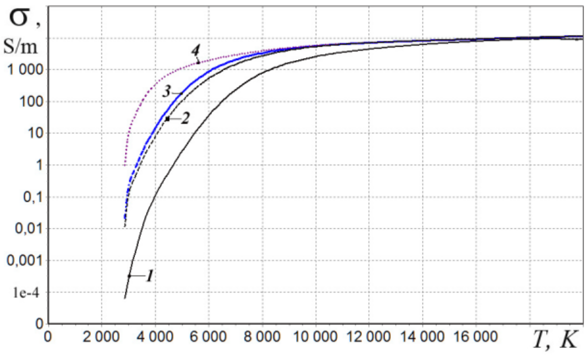

Fig. 3. Electrical conductivity of thermal plasma (p =1 atm) for pure air and the equimolar mixtures of air with iron. Curves 1 – air (this work calculations); 2 – air –Fe (99.9:0.1); 3 – air –Fe (95:5); 4 – air-Fe (90:10)

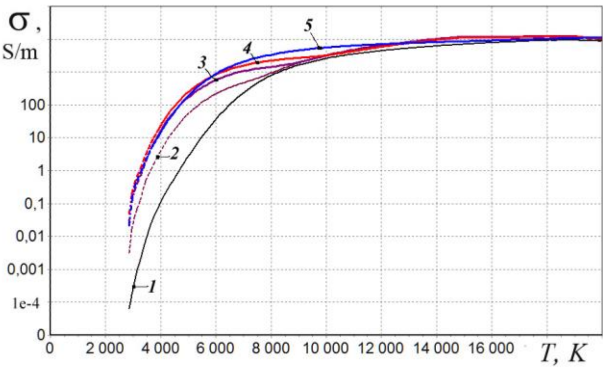

Fig. 4. Electrical conductivity of thermal plasma (p =1 atm) for pure air and the equimolar mixtures of air with iron. Curves 1 – air (this work calculations); 2 – air-Fe (99:1); 3 – air -Fe (90:10); 4 – air-Fe (70:30); 5 – air-Fe (50-50)

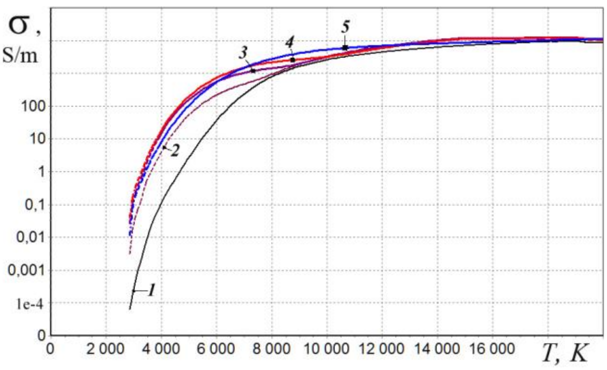

Fig. 5. Electrical conductivity of thermal plasma (p =1 atm) for pure air and the equimolar mixtures of air with stainless steel. Curves 1-air (this work calculations); 2- air-Fe-Mo (99.9:0.5:0.5); 3- air-Fe-Mo (95:2.5:2.5); 4-air-Fe-Mo (90:5:5); 5- air-Fe-Mo (70-20-10)

The increasing of metal concentration in discharge plasma are known to be lead to the corresponding increasing of electrical conductivity due to the low value of ionization potential of metal. However, for the case of tungsten and stainless steel components it is the decreasing of electrical conductivity takes place. This phenomenon caused by the shape resonance under the collision of electron with neutral atom. It should be pointed that the observed decreasing of electrical conductivity takes place in the mixtures of metal with ambient gas only. In pure metal vapors that effect has not realized.

Thus, it is needed the three following conditions to appear the decreasing of electrical conductivity in arc plasmas. They are the high concentration of metal, the ambient gas, and the presence of a shape resonance for electron-atom collisions.

CONCLUSIONS

Thus, a small amount of tungsten or stainless impurities causes the essential changes in the value of electrical conductivity coefficient of arc plasma in comparison with the case of pure argon or air.

The calculations of electrical conductivity on the base of Grad's method have a good agreement with the recent calculations based on Chapman-Enskog method.

The influence of the Ramsauer effect on the transport coefficients can be neutralized by metal additions in plasma.

Also, it is shown that in the case of plasma mixture containing stainless steel and tungsten the electrical conductivity may be drop down in dense metal vapors. In other words, that is the increasing of metal concentration leads to the decreasing of electrical conductivity under the certain conditions in arc plasmas. This effect takes place in the multicomponent plasma mixtures only.

REFERENCES

1. P. Porytsky, I. Krivtsun, V. Demchenko, U. Reisgen, O. Mokrov, A. Zabirov. On the application of the theory of Lorentzian plasma to calculation of transport properties of multicomponent arc plasmas // *European Phys. Journ. D*. 2010, v. 57, № 1, p. 77-85.
2. H. Grad. On the kinetic theory of rarefied gases // *Comm. Pure and Appl. Math*. 1949, v. 2, p. 331-407.
3. V.M. Zhdanov. *Transport Processes in Multicomponent Plasma*. NY: "Taylor&Francis", 2002.
4. S. Chapman, T.G. Cowling. *The mathematical Theory of Nonuniform Gases* / 3rd Ed. Cambridge: "Cambbrige University Press", 1970.
5. J.H. Ferziger, H.G. Kaper. *Mathematical theory of transport processes in gases*. Amsterdam: "North-Holland", 1972.
6. R.S. Devoto. Transport properties of Ionized Monatomic Gases // *Phys. Fluids*. 1966, v. 9, № 6, p. 1230-1240.
7. R.S. Devoto. Simplified Expressions for the Transport Properties of Ionized Monatomic Gases // *Phys. Fluids*. 1967, v. 10, № 10, p. 2105-2112.
8. R.S. Devoto. Transport coefficients of ionized argon // *Phys. Fluids*. 1973, v. 16, № 5, p. 2105-2112.

Article received 12.09.2018

ОБ ОСОБЕННОСТЯХ ЭЛЕКТРИЧЕСКОЙ ПРОВОДИМОСТИ В ДУГОВОЙ ПЛАЗМЕ, СОДЕРЖАЩЕЙ НЕРЖАВЕЮЩУЮ СТАЛЬ И ВОЛЬФРАМ

П.В. Порицкий

Рассмотрено влияние примесей нержавеющей стали и вольфрама на электрическую проводимость многокомпонентной электродуговой плазмы в атмосфере смесей аргона и воздуха. Проведенные расчеты основывались на методе моментов Грэда. Показано, что незначительное количество примесей металла может существенно изменить величину коэффициента электрической проводимости в сравнении со случаем чистого аргона или воздуха. Выявлена возможность уменьшения электрической проводимости вследствие увеличения концентрации вольфрама или нержавеющей стали в плазменной смеси.

ПРО ОСОБЛИВОСТІ ЕЛЕКТРИЧНОЇ ПРОВІДНОСТІ В ДУГОВІЙ ПЛАЗМІ, ЩО МІСТИТЬ НЕРЖАВІЮЧУ СТАЛЬ ТА ВОЛЬФРАМ

П.В. Порицький

Розглянуто вплив домішок нержавіючої сталі та вольфраму на електричну провідність багатокомпонентної електродугової плазми в атмосфері сумішей аргону та повітря. Проведені розрахунки ґрунтувалися на методі моментів Ґреда. Показано, що невелика кількість металевих домішок може суттєво змінити величину коефіцієнта електричної провідності порівняно із випадком чистого аргону або повітря. Виявлена можливість зменшення електричної провідності внаслідок збільшення концентрації вольфраму або нержавіючої сталі в плазмовій суміші.