ON THE EQUATION OF STATE AND PROPERTIES OF THE PLASMA IN UNDERWATER DISCHARGES

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It is considered the peculiarities of the equation of state of plasma in underwater discharges. The transport properties of a nonideal plasma of underwater discharges are calculated at pressure range from 1 bar up to 200 bar. The transport coefficient set based on the Grad's method is compared with the data obtained by using of the Lorentzian plasma theory at the same plasma composition. Also, the calculation data are considered to be in reference with transport coefficients obtained by using the Chapman-Enskog' method. It is pointed that the nonideality effects are needed to take into consideration under calculation of properties of underwater discharge.

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INTRODUCTION

Over the last decades a substantial growth has occurred in technological applications and researching of underwater discharges (arcs and electrical pulse discharges) [1-5]. The processes in the plasma of underwater discharges have been characterized by a variable complexity.

At the initial stage of electrical pulse discharges (EPD) small-scale irregularities of heat flow distribution were detected on a surface of channels [1, 2]. Development of such perturbations was accompanied by space modulation of an irradiation intensity, strain of a surface of channels, drop of conductance of plasma. These excitations are connected with the development of Rayleigh-Taylor instability. Thus in EPD it may be realized the two different regimes of discharges the first is characterized by developed perturbation and the second is the discharges without it.

Because of that the nonideal plasma of EPD takes place in various dense states. Also, that picture is established in underwater arc discharges. In this paper it is studied the peculiarities of the equation of state (EOS) for the plasma of underwater discharges. Also, on the base of the EOS the transport properties of the nonideal plasma are calculated in the pressure range from 1 bar up to 200 bar.

1. METHOD TO CALCULATE TRANSPORT PROPERTIES

It is considered the calculation of transport coefficients (thermal conductivity, viscosity, electrical conductivity) in dense water plasma. The most important factors determined the properties are the following: gaseous and plasma non-idealities, multicomponent contents. To include the factors into consideration the combined calculation procedure is used on the base of the Grad's method [6, 7] and Lee-More theory [8]. The non-ideality corrections are made according to [9-11].

The obtained results are compared with the previous calculations based on the Lorentzian theory (LM) [5, 12]. Also, the calculation data are considered to be in reference with transport coefficients obtained by using the Chapman-Enskog method [13,14] and reference data [15]. The algorithm of calculation consists of three stages. At the first time it is needed to obtain the multicomponent plasma composition under certain pressure and temperature. This problem leads to the system of Saha equations with lowering of ionization energies supplemented by conservation of nuclei and electric charge. The calculations are carried out, and the following 13 species have been taken into account: e^-, H_2O, H_2O^+, H_2, H_2^+, OH, OH^+, O_2, O_2^+, H, H^+, O, O^+.

Having been obtained plasma composition, the thermodynamic and transport properties of plasma can be calculated in the, so-called, zero-density model (ZM) i.e. without consideration of the nonideality effects. At next stage the nonideality corrections are included to obtain the set corresponding to the dense model (DM).

A number of the properties are very interested in the connection of intended use to simulate underwater discharges. Therefore it is focused attention upon such properties.

2. EQUATION OF STATE

The non-ideality corrections to equation of state (EOS) are made according to [9-11]. In that way the EOS has the following form

$$p + \Delta p_{Coul} = n_e kT_e + \sum_{\alpha} n_{i\alpha} kT + \sum_{\beta} n_{0\beta} kT$$
$$+ Bn_0^2 + \; I_0 + I_1 \;\; n_0^2 kT, \tag{1}$$

where $\sum_{\beta} n_{0\beta} = n_0$, $\sum_{\alpha} n_{i\alpha} = n_i$.

Here, p is pressure, T is temperature, Δp_{Coul} is the Coulomb correction to pressure, n is number density, k is the Boltzmann constant, B is the second virial coefficient, both the I_0 and I_1 are kinetic integrals. The integral I_0 corresponds to repulsive forces, and I_1 is to attractive ones. Subscripts are the following: e corresponds to electrons, i is to ions, 0 is neutrals.

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According to the Rainwater-Friend theory [9] the second virial coefficient B may be calculated in that way. For $B^* = B/\omega^3$, were ω is the distance that intermolecular potential is zero, it may be obtained that

$$B^* = B^{2M\,*} + B^{3M\,*} + B^{MD\,*}, \qquad (2)$$

where $B^{2M\,*}$ is due to the interaction between two-monomer, $B^{3M\,*}$ is the presence of effect of third particle in monomer-monomer collision, $B^{MD\,*}$ is the contribution of dimmer-monomer collision. B^* depends on intermolecular potential and temperature.

3. RESULTS AND THEIR DISCUSSIONS

The results of calculations are shown in Figs. 1-6. One can see that the properties of dense water plasma have a pronounced non-monotone character with sharp pikes in certain temperature and pressure ranges. The pikes are appeared due to the dissociation, ionization and from others effects. Thus, the viscosity peaks (see Figs. 5, 6) are caused by the dissociation and the presence of minor additions of ions in gases at weakly ionization.

It should be mentioned that the plasma composition is the same as used in paper [5] that it is allowed to compare both the Grad method approach with the Lorentzian theory. The results have a similar character at normal pressure (see Figs. 1, 3, 5). On the other hand at higher pressure the essential discrepancy takes place (see Figs. 2, 4, 6). One can be deduced that the effects of nonideality have influence on the transport coefficients mainly in more dense conditions and the Lorentzian theory is suitable to calculate the transport properties of multicomponent plasma at relatively low temperature and normal pressure.

Also, one can see that the calculations of some properties are in a good agreement with the data from [13-15] at normal pressure. The results may be distinguished due to the various initial data for calculation.

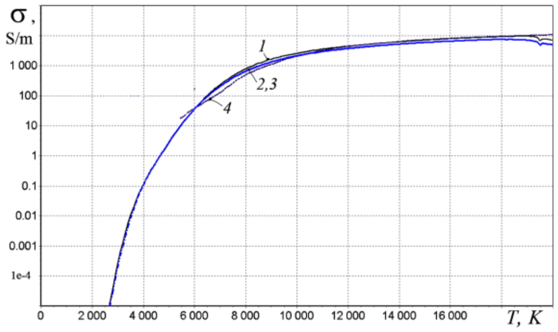

Fig. 1. Electrical conductivity of water plasma (p =1 bar). Curves 1 – Loretzian model (LM); 2 – zero-density model (ZM); 3 – dense model (DM); 4 – data from [14]

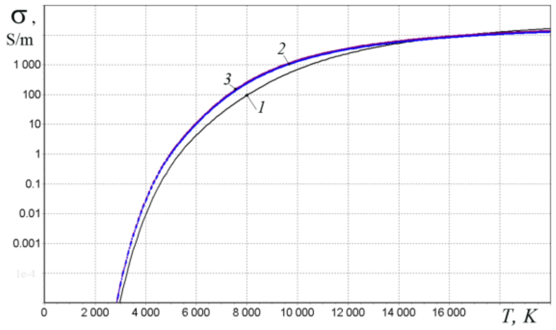

Fig. 2. Electrical conductivity of dense water plasma (p =200 bar). Curves 1 – LM; 2 – ZM; 3 – DM

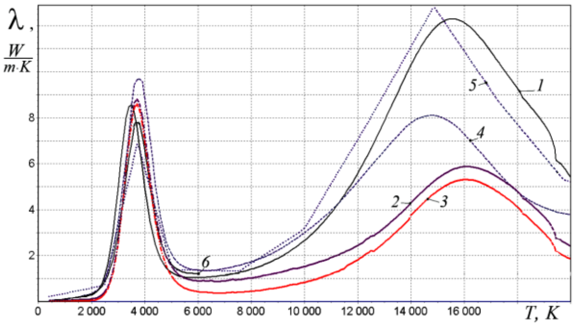

Fig. 3. Thermal conductivity of water plasma (p =1 bar). Curves 1 – LM; 2 – ZM; 3 – DM; 4 – data from [14]; 5 – [13]; 6 – [15]

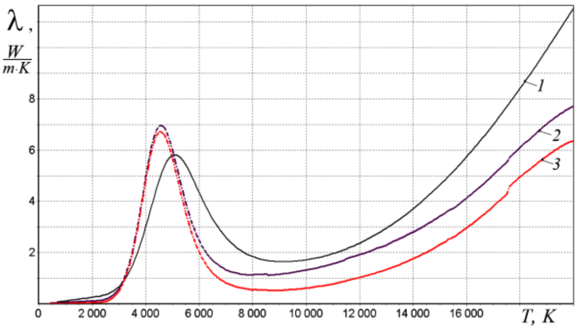

Fig. 4. Thermal conductivity of dense water plasma (p =200 bar). Curves 1 – LM; 2 – ZM; 3 – DM

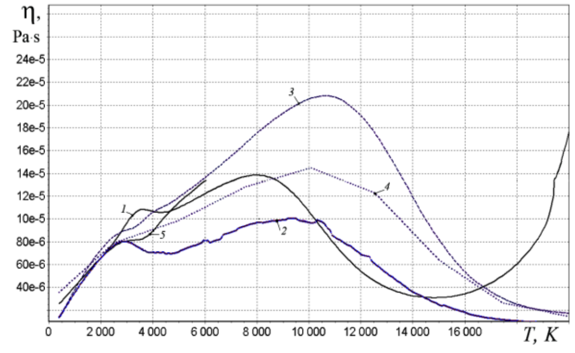

Fig. 5. Viscosity of water plasma. (p =1 bar). Curves 1 – LM; 2 – DM; 3 – data from [14]; 4 – [13]; 5 – [15]

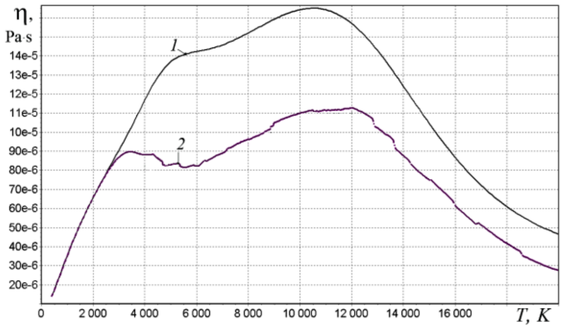

Fig. 6. Viscosity of dense water plasma. (p =200 bar). Curves 1 – LM; 2 – DM

CONCLUSIONS

The properties of dense water plasma of underwater discharges are essentially depended on both the temperature and pressure conditions. The properties have a pronounced non-monotone character with sharp pikes in certain temperature ranges.

It is needed to include into the consideration the non-ideality corrections to both the equation of state and transport coefficients.

The calculations are carried out on the base of the Grad's method including the nonideality effects. At atmospheric pressure the results are in a good agreement with the previous calculations and data calculated on the base of Chapman-Enskog' method. On the other hand it should be pointed that the nonideality effects are needed to take into consideration under calculation of properties of underwater discharge at high pressure.

The obtained results confirm the conclusion of paper [12] that the Lorentzian theory is suitable to calculate the transport properties of multicomponent plasma at relatively low temperature and normal pressure. Also, it should be born in mind that Lorentzian plasma model on the one hand takes into account the kinetic effects and on the other hand is characterized by relative simplicity, which allows its use for direct computation of the properties of plasma in the simulation of arc and pulse underwater discharges at normal pressure.

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ОБ УРАВНЕНИИ СОСТОЯНИЯ И СВОЙСТВАХ ПЛАЗМЫ В ПОДВОДНЫХ РАЗРЯДАХ

П.В. Порицкий, П.Д. Старчик

Рассмотрены особенности уравнения состояния для плазмы подводных разрядов. Проведены расчёты транспортных свойств неидеальной плазмы подводных разрядов в диапазоне давлений 1…200 бар. Транспортные коэффициенты, которые рассчитывались на основе метода Грэда, сравниваются с результатами, полученными исходя из лоренцевой теории при одинаковом составе плазмы. Также результаты вычислений сравниваются с данными, полученными методом Чепмена-Энскога. Подчёркивается необходимость принятия во внимание эффектов неидеальности при расчёте свойств подводных разрядов.

ПРО РІВНЯННЯ СТАНУ ТА ВЛАСТИВОСТІ ПЛАЗМИ В ПІДВОДНИХ РОЗРЯДАХ

П.В. Порицький, П.Д. Старчик

Розглянуто особливості рівняння стану для плазми підводних розрядів. Проведені розрахунки транспортних властивостей неідеальної плазми підводних розрядів у воді в діапазоні тисків 1…200 бар. Транспортні коефіцієнти, що були розраховані на основі методу Ґреда, порівняно із результатами, які ґрунтувалися на лоренцевій теорії за однакового складу плазми. Також результати обчислень порівнювалися із даними, що отримано за допомогою метода Чепмена-Енскоґа. Наголошено на необхідність взяти до уваги ефекти неідеальності плазми для розрахунку властивостей плазми підводних розрядів.