UNIVERSITY OF NIŠ
The scientific journal **"FACTA UNIVERSITATIS"**
Series: **"Physics, Chemistry and Technology"** Vol.1, N^o 2, 1995. 114-126
Editor of Series: Predrag Dimitrijević
Address: Trg bratstva i jedinstva 2 YU-18000 Niš
Tel: +381 18 23953 Fax: +381 18 24488

A STUDY OF BASIC PROPERTIES OF HIGH-PRESSURE AND LOW TEMPERATURE THERMAL ARGON PLASMA WITH SODIUM AS ADDITIVE

Nadežda V. Novaković
Božidar S. Milić*
Stojan M. Stojilković**

Faculty of Philosophy, Dept. of Physics, P.O.B. 91, 18001 Niš
*Faculty of Physics, P.O.B. 550, 11001 Belgrade
**Faculty of Electronics, Niš

Abstract: Results of a theoretical evaluation of number densities and electrical conductivity, regarded as functions of pressure and temperature, for high-pressure ($0.1\,MPa$ to $2.5\,MPa$) and low-temperature ($2000\,K$ to $20000\,K$) argon plasma containing up to 10% of added sodium are presented. The numerical calculations were based on the assumption that the system is kept under constant pressure and temperature and that it attained local thermodynamical equilibrium. Use was made of a previously derived modified Debye radius which allowed to regard the plasmas investigated as weakly non-ideal and to calculate their composition from a set of Saha equations for the relevant ionization stages of both Ar and Na. The results arrived at were compared to those for pure argon plasma obtained by the same evaluation methodology. It was found that the addition of little as 1% of Na profoundly alters the properties of the plasma. The electrical conductivity is enhanced, with respect to the values in pure Ar plasma, by about two orders of magnitude below $10000\,K$, and by about half an order of magnitude above that temperature, provided that the pressure is not less than $0.5\,MPa$. For pressures around $0.1\,MPa$, the electrical conductivity in pure argon plasma is somewhat greater at higher temperatures (above $14000\,K$) than with 1% of sodium added. This is due to a specific change in the pressure dependence of the electrical conductivity: the $p^{-1/2}$-dependence specific for pure argon plasma abruptly switches to $p^{1/2}$-dependence observed in alkaline vapours if just 1% of Na is added. Further increase of the conductivity, as the amount of sodium is augmented to 10%, is comparatively small and noticeable only between $10000\,K$ and $14000\,K$. Physical factors bringing about these features are discussed.

1. Introduction

Low-temperature and high-pressure plasmas, virtually in the state of local thermodynamical equilibrium (LTE), are encountered in numerous laboratory situations (for example, flashing lamps for lasers, plasma chemistry, MHD-generators, etc.). The knowledge of

UDK: 533.92; Received 26. August 1995.

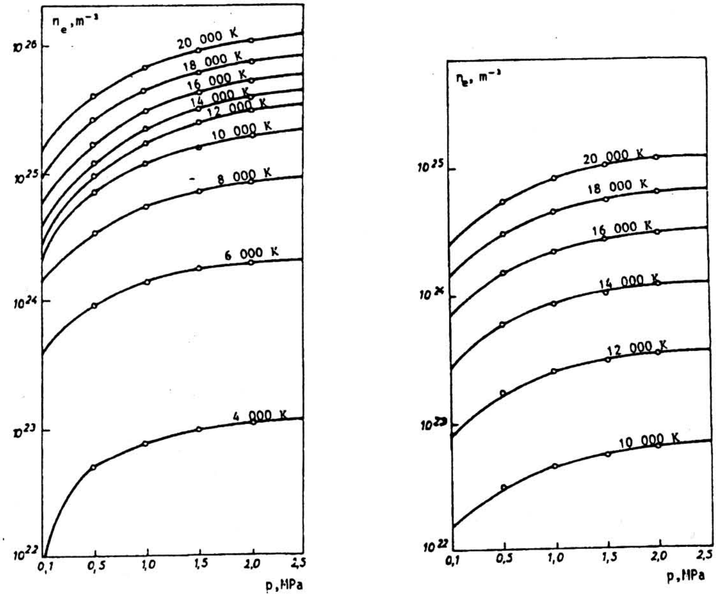
basic characteristics of these plasmas, such as the number densities of their constituents or their electrical conductivity, as functions of pressure and temperature of the system, is of obvious interest. Unfortunately, data obtained in direct experimental measurements of these quantities are often lacking in the publicly available literature, especially for plasmas formed in mixtures of gases and/or vapours. On the other hand, low-temperature and high-pressure thermal plasmas in mixtures of this kind are encountered quite frequently: for example, it is customary to increase the low-temperature electrical conductivity of many plasmas by contaminating them with a small amount of some alkaline vapour.

In the present paper, the argon plasmas containing some sodium (up to 10%) as additive and pertaining to the above mentioned type (high pressure, low temperature, LTE) are studied, and a theoretical evaluation of their basic parameters is presented. The problem of the non-ideality according to standard criteria is circumvented by using an appropriately modified Debye radius r_D^*, rather than the conventional one, r_D [1]. This procedure was already used by the same authors in a study of xenon plasma with sodium as additive [2]. Number densities of all the relevant constituents and electrical conductivity of argon plasmas with 1% and 10% of sodium are presently evaluated numerically, for relatively low temperatures, ranging from $2000\,K$ to $20000\,K$, and for relatively high pressures, ranging from $0.1\,MPa$ (atmospheric pressure) to $2.5\,MPa$. The results are compared with those for pure argon plasma, arrived at by the same evaluation procedure. Much as could be expected beforehand, the addition of sodium significantly enhances both electron number density and electrical conductivity at temperatures below some $10000\,K$. For example, only 1% of sodium increases the electrical conductivity by about two orders of magnitude in this temperature range. Above $10000\,K$, the increase of the electrical conductivity brought about by addition of 1% of sodium is considerably smaller and amounts to about half an order of magnitude, if the pressure is not lower than $0.5\,MPa$. For the pressure of $0.1\,MPa$, the addition of 1% of sodium has the effect of slightly diminishing the electrical conductivity of the plasma at temperatures above some $14000\,K$. This is brought about by the inversion of the electrical conductivity pressure dependence: being proportional to $p^{-1/2}$ in pure argon, the electrical conductivity of the plasma with as little as 1% of sodium becomes proportional to $p^{1/2}$, which was observed in pure alkaline vapours [17]. The augmentation of the amount of sodium (up to 10%) is found to have comparatively little effect: the most remarkable further enhancement of electrical conductivity, as compared with the situation when 1% of sodium is present, sets in at temperatures between $10000\,K$ and $14000\,K$, increases with the pressure, and attains about half an order of magnitude for $2.5\,MPa$.

A comparison with the analogous previous study of xenon plasma with the added sodium [2] discloses that the relation between the ionization energies of the species present is the factor of primary significance in determining the outlined argon plasma specificities.

2. Evaluation of the plasma composition

The object studied in the present work is the argon plasma contaminated by a relatively small amount (up to 10%) of sodium. It was taken that the plasma is kept under constant pressure, ranging from $0.1\,MPa$ (atmospheric pressure) to $2.5\,MPa$, and at a constant temperature, varying between $2000\,K$ and $20000\,K$, which justified the assumption of LTE [3,4]. Similar previous studies [1,2] disclosed that noble gas plasmas with alkaline additives can be treated as weakly non-ideal in the pressure and temperature ranges indicated above, if the evaluations are based on the modified Debye radius r_D^* rather than on the standard one, r_D, and this point of view was adopted in the present work. Furthermore, if the energies of ionization are borne in mind ($15.75\,eV$ and $27.62\,eV$ respectively for Ar and Ar^+, $5.14\,eV$ and $47.29\,eV$ for Na and Na^+ [5]), it can be inferred *a priori* that the presence of ions with charge numbers higher than 2 can be ruled out with certainty in the temperature range considered. (It turned out *a posteriori* that even the presence of Ar^{++} and Na^{++} is negligible.) Hence, the plasma composition was evaluated from the standard set of equations, consisting of the charge conservation condition, the requirements of conservation of the total numbers of both argon and sodium nuclei, and four Saha equations pertaining to the two ionization stages of these atomic species, with the effective ionization energy lowerings taken in the usual form [6]. These equations were solved numerically, by an iteration procedure, neglecting the ionization energy lowerings in the zeroth order and using tables [5] of ionization energies, energy level multiplicities and ion radii (these last quantities are required in evaluating r_D^*). For the sake of comparison, the analogous system of equations for pure argon was also solved, with the use of the same evaluation technique. Some of the more interesting results are given below.



a b

Fig. 1. Dependence of the evaluated electron number density on pressure, with temperature as parameter, for argon plasma with 10% of sodium (a) and for pure argon (b).

Figure 1a shows the dependence of the electron number density n_e on pressure, with temperature as parameter, in argon plasma with 10% of sodium. Analogous results for pure argon are given in Fig. 1b. The fact that n_e is an increasing function of the pressure (with temperature kept constant) is amenable to the use of the Saha equations. It can be seen that the presence of sodium remarkably raises the values of n_e: with 10% of added sodium the enhancement is about two orders of magnitude below 10000 K and about one order of magnitude above that temperature. One can also notice a lower sensitivity of the electron number density to temperature variations above 10000 K with the sodium added. Both features are easily accounted for by the fact that sodium has about three times smaller energy of the first ionization than argon. Hence, sodium is massively ionized at lower temperatures, ensuing a tremendous enhancement of n_e below 10000 K. Above this temperature, practically all the sodium is ionized to Na^+, and the formation of Ar^+ ions becomes dominant source of further electron number density growth. This inference is further corroborated by the results given in Figs. 2 and 3.

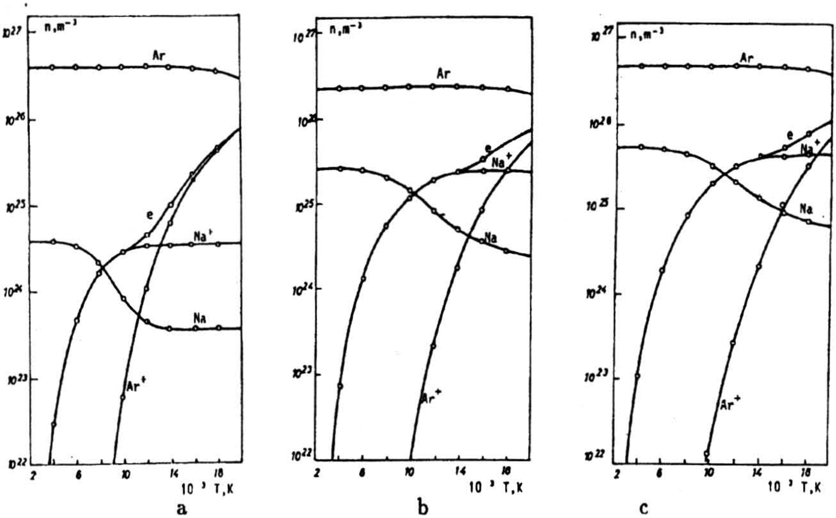


Fig. 2. Temperature dependence of evaluated number densities for the basic constituents of argon plasma with 1% of sodium at $p = 1.5\,MPa$ (a) and with 10% of sodium at $p = 1.0\,MPa$ (b) and $p = 2.0\,MPa$ (c). Curves pertaining to Ar^{++} and Na^{++} are far below the segment of the ordinates shown.

Figure 2 shows the dependence of the evaluated number densities of various constituents on temperature, for some pressures and percentages of sodium. The curves giving the number densities of the doubly ionized atoms, Ar^{++} and Na^{++}, are not seen as they lie well below the segments of ordinates shown in these Figures, much as could be expected for the temperature interval studied, in view of the high energies of second ionization for both Ar and Na. It can be seen that, at lower temperatures, the ionization of sodium is quite considerable and the Na^+-curves rise very steeply, with the n_e-curves adhering to them, since practically all the electrons present below 10000 K originate in the process of the first ionization of sodium ($Na \rightarrow Na^+ + e$). Around 10000 K this process is accomplished and the Na^+-curves attain a plateau. The same goes for the Na-curves which drop to a plateau corresponding to a few percent of the initial sodium number density. Above

10000 K the Ar-curves begin to decrease noticeably, Ar^+-curves rise and the n_e-curves come off the ones for Na^+ and approach those for Ar^+, which is particularly clearly seen in Fig. 2a. Figure 3 pertains to pure argon plasma with $p = 0.1\,MPa$, and it confirms the role of sodium in the plasma formation below some 10000 K.

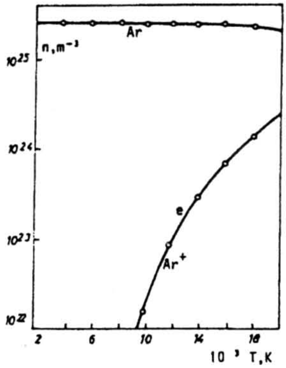


Fig. 3. Dependence of evaluated number densities on temperature in pure argon plasma at $p = 0.1\,MPa$. The Ar^{++}-curve lies far below.

	4000 K	8000 K	12000 K	16000 K	20000 K
0.1 MPa	15 (4)	16 (2)	10 (2)	8 (2)	7 (2)
0.5 MPa	18 (3)	15 (1)	14 (1)	8 (1)	6 (1)
1.0 MPa	21 (2)	18 (1)	18 (1)	8 (1)	5 (1)
1.5 MPa	25 (2)	23 (1)	21 (1)	8 (1)	5 (1)
2.0 MPa	29 (2)	26 (1)	24 (1)	8 (1)	4 (1)
2.5 MPa	32 (2)	28 (1)	26 (1)	8 (1)	4 (1)

Table I. Debye numbers in argon plasma with 10% of sodium evaluated with modified Debye radius r_D^* in the present work. (Figures in brackets give analogous results obtained with the standard Debye radius r_D. [1,2])

	4000 K	8000 K	12000 K	16000 K	20000 K
0.1 MPa	0.04	0.04	0.07	0.08	0.06
0.5 MPa	0.04	0.04	0.05	0.08	0.11
1.0 MPa	0.03	0.04	0.04	0.08	0.13
1.5 MPa	0.03	0.03	0.03	0.08	0.17
2.0 MPa	0.02	0.03	0.03	0.08	0.17
2.5 MPa	0.02	0.02	0.03	0.08	0.17

Table II. The non-ideality parameter $\Gamma^* = e^2/(4\pi\varepsilon_0 r_D^* kT)$ for argon plasma with 10% of sodium.

After the plasma composition is established, the assumption of weak non-ideality, adopted in the present calculations, can be verified ***a posteriori***. Two criteria were investigated to this aim, and the results are given in Tables I and II. Table I gives the Debye numbers (i.e. numbers of charged particles in the Debye sphere) for the argon plasma with 10% of sodium. With r_D^*, the Debye numbers comply better with the requirement of weak non-ideality ($N_D \gg 1$), the situation becoming somewhat questionable only for pressures and temperatures close to the upper limits of the respective ranges embraced by the present analysis. Table II gives the values of the ratio of mean electrostatic to mean thermal energy, $\Gamma^* = e^2/(4\pi\varepsilon_0 r_D^* kT)$. The requirement of weak non-ideality, $\Gamma^* \ll 1$ [7], is well met for all temperatures and all pressures considered presently. It is worth mentioning that this ratio varied from 0.5 to 4.5 for pressures from 0.3 MPa to 2.0 MPa in pure argon thermal plasma, when r_D was used [8].

3. Electrical conductivity

If a plasma is placed in an external electric field in order to measure its electrical conductivity, the electron velocity distribution function becomes anisotropic in the velocity space. Kinetic theory [13] gives the following formula for the electrical conductivity:

$$\sigma = \frac{4\pi e^2}{3m_e} \int_0^\infty \frac{d}{dv}\left[\frac{v^3}{\nu_e(v)}\right] f_e^{00}(v)dv. \tag{1}$$

Here $f_e^{00}(v)$ denotes the isotropic part of the electron velocity distribution function, and $\nu_e(v)$ is the velocity-dependent electron collision frequency given by:

$$\nu_e(v) = 2\pi v \sum_\alpha n_\alpha Q_{e\alpha}(v), \tag{2}$$

where n_α denotes the number density of the particles of the species α, $Q_{e\alpha}(v)$ is the velocity-dependent momentum-transfer cross section for elastic scattering of electrons on these particles, and the summation in eq. (2) is taken over all the species present (including the electrons). In the present work, the momentum-transfer cross sections for the collisions of electrons with charged particles were accounted for by way of the Rutherford formula (for electron-electron collisions, use is made of the relation $\nu_{ee} = \sqrt{2}\nu_{ei}$ [9]), and the corresponding quantities for the electron-neutral collisions were taken in form of polynomials [2]:

$$Q_{en}^{(s)} = \sum_{r=0}^{9} a_r^{(s)} v^r, \qquad (s = 1, 2), \tag{3}$$

with the superscripts (1) and (2) pertaining to argon and sodium neutral atoms respectively. The coefficients a_r in eq. (3) were determined so as to obtain the best fit to the experimental data for argon [10] and sodium [11]. For this latter atomic species, the coefficients were evaluated previously [2]; for argon they were calculated in the present work and are given in Table III.

r	a_r	r	a_r
0	-20.242	5	$5.683 \cdot 10^{-2}$
1	26.226	6	$-3.620 \cdot 10^{-3}$
2	-13.156	7	$1.421 \cdot 10^{-4}$
3	3.536	8	$-3.140 \cdot 10^{-6}$
4	-0.566	9	$2.988 \cdot 10^{-6}$

Table III. Numerical values of the coefficients a_r in eq. (3) for argon, as obtained on the ground of the data of Ref. [10]. Velocities are taken by way of the equivalent temperature $\left(\frac{1}{2}m_e v^2 = kT_{eq}\right)$ in 10^3 K, and the cross sections are obtained in 10^{-20} m^2.

For the comparatively low temperatures and high pressures considered in the present work, it is justifiable to assume that $f_e^{00}(v)$ is Maxwellian. This is quantitatively corroborated by the numerical values of the dimensionless parameter:

$$\delta = \sum_{\beta} \frac{m_e}{m_\beta} \frac{\nu_{e\beta}}{\nu_{ee}}, \tag{4}$$

with the index β referring to the species of the heavy particles present, and $\nu_{e\beta}$ denoting the effective (mean) collision frequencies for the encounters between electrons and these particles, as given by:

$$\nu_{e\beta} = 4\pi n_\beta \int_0^\infty v^3 Q_{e\beta}(v) f_e^{00}(v) dv. \tag{5}$$

It was shown [12] that the Maxwellian $f_e^{00}(v)$ can be adopted if $\delta \ll 1$, and the figures in Table IV, obtained with the aid of the equations (2) and (3), show that this requirement is indeed well met for the plasma studied. With the Maxwellian $f_e^{00}(v)$, eq. (1), after an integration by parts, gives [2]:

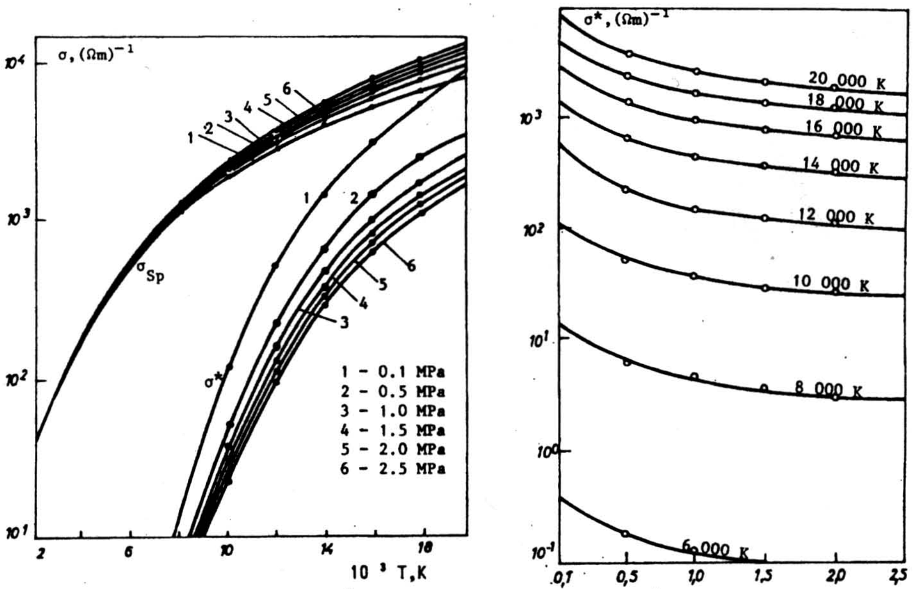
$$\sigma = \frac{2e^2 n_e}{3\sqrt{2\pi}} m_e^{3/2} (kT)^{-5/2} \int_0^\infty \frac{v^4}{\nu_e(v)} \exp\left(-\frac{m_e v^2}{2kT}\right) dv. \tag{6}$$

This formula was used together with eqs. (2) and (3), and with the figures from Table III. Data on plasma composition obtained in Section 2 were also taken into account. The integral in eq. (6) was evaluated numerically, both for argon plasma with sodium added and for the pure argon plasma. The latter type of the plasma was investigated not only for the purpose of elucidating the effects brought about by the addition of sodium, but also as a check on the quality of approximations based on r_D^* rather than r_D. Namely, the comparison of the results of present evaluations with the experimental data on electrical conductivity is possible only for pure argon, as those for its admixtures with alkaline vapours seem to be completely lacking, and this comparison favoured the use of r_D^*.

	$4000\,K$	$12000\,K$	$20000\,K$
$0.1\,MPa$	0.0171	0.0029	0.0028
$0.5\,MPa$	0.0432	0.0036	0.0031
$1.0\,MPa$	0.0691	0.0044	0.0036
$1.5\,MPa$	0.0913	0.0053	0.0042
$2.0\,MPa$	0.1132	0.0063	0.0048
$2.5\,MPa$	0.1341	0.0074	0.0056

Table IV. Numerical values of the dimensionless parameter δ given by eq. (4), for argon plasma with 1% of sodium. (The figures given remain practically unchanged with 10% of sodium.)

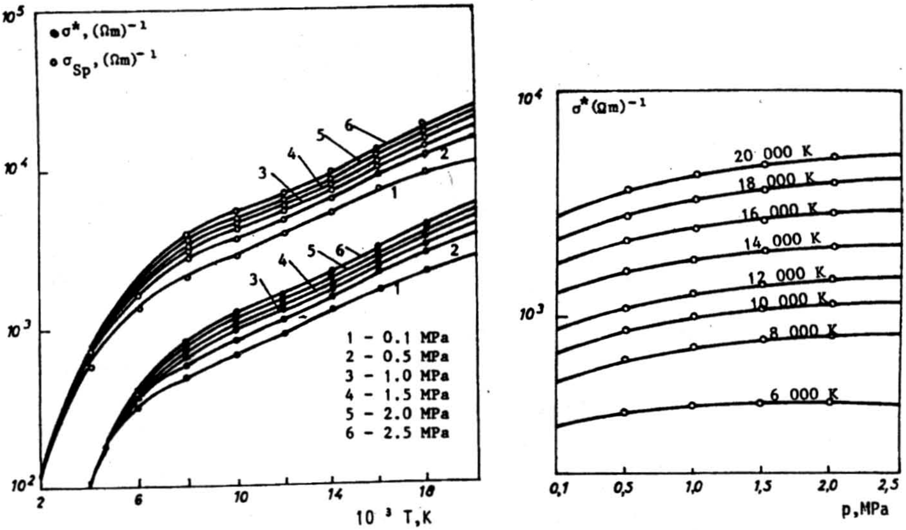
Figure 4a shows the temperature dependence of the electrical conductivity σ^* (the asterisk indicates that the results are obtained by using r_D^*), with pressure as parameter, for the pure argon plasma in the temperature and pressure ranges considered, with the data on the plasma composition obtained by the present procedure (see Fig. 3). The Spitzer conductivity [14], evaluated for the same pressures and temperatures, is also shown. Both σ^* and σ_{Sp} are seen to increase with temperature, which is an easily comprehensible feature ascribable mainly to the increasing thermal ionization. These quantities also depend on pressure, and this dependence is more prominent in σ^* (the σ_{Sp}-curves are more closely packed together). However, the character of the dependence is different for the two conductivities: while σ_{Sp} increases as the pressure is raised, which is in accordance with the data found in the literature [15], σ^* decreases in the process. The dependence of σ^* on pressure is shown in Fig. 4b; the curves given comply to the $p^{-1/2}$-law characteristic for noble gases [16]. Both the discrepancy in the dependences on pressure and the fact that, for any chosen p and T, one has $\sigma_{Sp} > \sigma^*$ are easy to grasp. Namely, the Spitzer conductivity formula [14] is based on the assumption that the plasma is virtually fully ionized and, consequently, it ignores the possible electron collisions with the neutrals, diminishing thereby the denominator in the integrand of eq. (6). This argument is further corroborated by the fact that for $p = 0.1\,MPa$ and $T = 20000\,K$ one finds $\sigma_{Sp} \approx \sigma^*$; for the pressures and temperatures around the values given, the role of electron-neutral collisions, unaccounted for by the Spitzer conductivity formula, is indeed quite small.



a b

Fig. 4. Electrical conductivity σ^* in pure argon plasma, shown as function of temperature, with pressure as parameter (a) and as function of pressure, with temperature as parameter (b). Asterisk denotes the use of the modified Debye radius r_D^* in the evaluations. Spitzer conductivity σ_{Sp} is also shown in Fig. 4a, for the sake of comparison, and the curves in Fig.4b comply with the $p^{-1/2}$-law specific for noble gases [16].

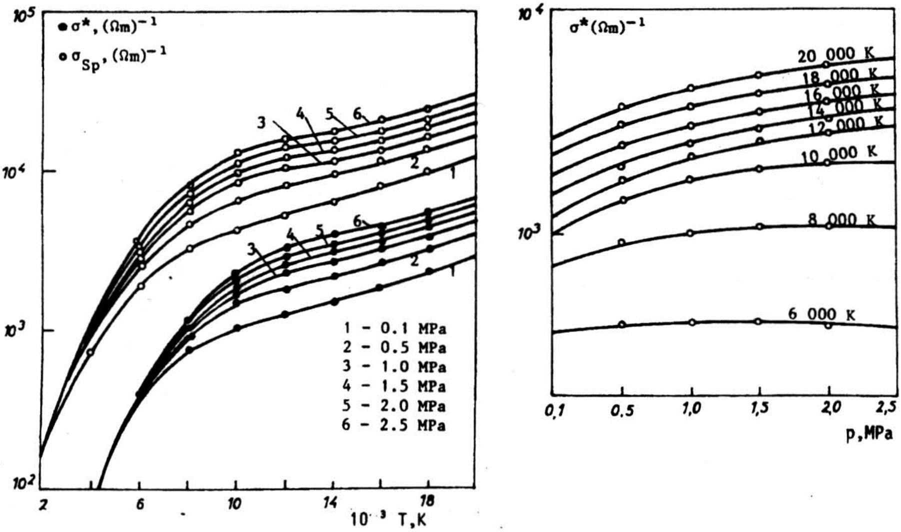
Figure 5 pertains to argon plasma with 1% of sodium, and is analogous to Fig. 4 for pure argon. The most striking difference emerges from the comparison of Figs. 4b and 5b: σ^* is seen to *increase* if the pressure is raised, with 1% of sodium added. The conductivity growth obeys a $p^{1/2}$-law specific for pure alkaline vapours [17]. A comparison of Figs. 4a and 5a discloses some additional differences. Firstly, with 1% of sodium added one invariably (i.e. even for $p = 0.1\,MPa$ and $T = 20000\,K$) has $\sigma^* < \sigma_{Sp}$; roughly, σ^* is about 5 to 6 times smaller than σ_{Sp} for any given p and T. Secondly, the dependence of σ_{Sp} on pressure becomes more prominent (the σ_{Sp}-curves are wider apart here than in Fig. 4a, chiefly due to an increase of the σ_{Sp}-values at higher pressures). Thirdly, the σ^*-values become considerably higher after the addition of sodium, especially in the low-temperature domain. This last feature is probably the most interesting for applications.



a b

Fig. 5. Same as Fig. 4, but for argon with 1% of sodium. It is to be noticed that, even with as little as 1% of added sodium, the pressure dependence is reversed and complies with the $p^{1/2}$-law specific for alkaline vapours [17].

Finally, Fig. 6 shows the $\sigma^*(T)$- and $\sigma^*(p)$-curves for argon with 10% of added sodium (together with the $\sigma_{Sp}(T)$-curves in Fig. 6a). The curves presented qualitatively resemble those in Fig. 5 and show how the alterations in the electrical conductivity of argon, brought about by adding 1% of sodium, are further deepened by the tenfold augmentation of the amount of the additive. It may come as somewhat unexpected that this relatively large change in the percentage of the additive has a generally small effect. The $\sigma^*(T)$-curves in Figs. 5a and 6a show that the electrical conductivity remains practically unchanged both below $6000\,K$ and above $18000\,K$; the same fact can be seen from the $\sigma^*(p)$-curves in Figs. 5b and 6b. On the other hand, only a relatively small enhancement of electrical conductivity is seen to accompany the increase of the percentage of sodium between 6000 *K* and 18000 *K*. This enhancement is pressure-dependent, rises as the pressure increases, and attains a maximum amounting to about half an order of magnitude for 2.5 *MPa* between 10000 *K* and 12000 *K*. All these details are also amenable to the fact that the first ionization of sodium is at its peak around 10000 *K*.



a

b

Fig. 6. Same as Fig. 5, but for argon with 10% of sodium. The reversed pressure dependence is even more prominent than in Fig. 5.

4. Comments and conclusions

All the above results indicate that the presence of the added sodium is indeed quite significant for the composition and the electrical conductivity of the high-pressure and low-temperature thermal argon plasma, especially below and around 10000 *K*. It is demonstrated that even with only 1% of sodium, the electrical conductivity is considerably augmented, in comparison with its values in pure argon, except at 0.1 *MPa* where a slight diminishment is observed above 14000 *K*. The augmentation generally attains some two orders of magnitude below 10000 *K*, and about half an order of magnitude above that temperature. Further increase of the percentage of sodium was found to have comparatively little effect and to lead to an additional increase of the conductivity only at high pressures and at the temperatures between 10000 *K* and 12000 *K*. This additional increase does not exceed some half an order of magnitude as compared with the conductivities attained with 1% of sodium. Hence, it can be inferred that the augmentation of the percentage of sodium, as the means of improving the electrical conductivity of the argon plasma, is justifiable only if $T \geq 10000\,K$ (e.g. in flashing lamps); for lower temperatures of the plasma (e.g. MHD-flows or plasma chemistry, with the typical temperatures not higher than some $6000\,K$), the addition of sodium is an unnecessary waste as it does not result in further conductivity increase. The significance of the sodium additive is also clear from the dependence of the conductivity on pressure: the $p^{-1/2}$-dependence specific for pure argon (and other noble gases [16]) abruptly switches to the $p^{+1/2}$-dependence typical for alkaline vapours [17], even if only 1% of sodium is added.

The above outlined specificities in the electrical conductivity behaviour are mainly due to the multiplier n_e in eq. (6). In the physical situation considered presently, the electron number density is entirely determined by the processes of thermal ionization. The energy of the first ionization of sodium being about three times smaller than that of argon ($5.14\,eV$ and $15.75\,eV$ respectively), it is logical to expect that the largest portion of the electrons present below $10000\,K$ originates from the process $Na \rightarrow Na^+ + e$. This is indeed confirmed by the present evaluations (Fig. 2). Above that temperature, the process $Ar \rightarrow Ar^+ + e$ gains relevance: the n_e-curves come off the ones for Na^+ and approach those for Ar^+. The significance of the multiplier n_e in eq. (6) is further emphasized by comparing Fig. 6a with Figs. 2b and 2c, all pertaining to same percentage of added Na. The changes in the slopes of the n_e-curves in Figs. 2b and 2c as they go from the Na^+-curves over to the Ar^+-curves around $12000\,K$ are clearly reflected in the corresponding (i.e. pertaining to $1.0\,MPa$ and $2.0\,MPa$) conductivity curves in Fig. 6a.

The other possibly significant factor in determining the electrical conductivity, namely the multiplier $1/\nu_e(v)$ in the integrand of eq. (6), seems to be relatively unimportant for the plasmas investigated. This might be somewhat surprising, in view of the large differences in the momentum-transfer cross sections for electron-neutral encounters with atoms of argon and sodium: indeed, the ratio $Q_{en}^{(Ar)}/Q_{en}^{(Na)}$ ranges from 0.11 at low energies (corresponding to the mean energy of thermal motion at $2000\,K$), to about 2.75 at high energies (equivalent to $20000\,K$). However unexpected the relative irrelevance of this multiplier might be, it seems to be strongly corroborated by a comparison with the results of a similar analysis for xenon with sodium as additive [2]. Despite the fact that the momentum-transfer cross sections for electron elastic encounters with xenon atom are considerably larger than those in argon (about 40 times larger at the low energies mentioned above), which tends to lower significantly the conductivity values by diminishing the multiplier $1/\nu_e(v)$ in eq. (6) for xenon, the results arrived at [2] show that these values are larger in xenon than in argon by a factor ranging from 1.5 to 2.5, for the same p and T and the same percentage of sodium added. This can only be the effect of a considerable enhancement of the electron number densities in the xenon plasma, due to lower energies of both first and second ionizations in of xenon ($12.13\,eV$ and $21.20\,eV$ respectively, compared to $15.75\,eV$ and $27.62\,eV$ in the case of argon), and the ensuing more remarkable importance of the process $Xe \rightarrow Xe^{++} + e$ in the temperature range considered.

It is to be concluded from all that was said above that in the high-pressure and low-temperature thermal noble-gas plasmas with alkaline additives, the relations between the ionization energies of the atomic species present (neutral atoms, singly and doubly charged ions) is by far the most significant physical factor in determining the plasma composition and its electrical conductivity.

References:

[1] Milić, B.S., Novaković, N.V. and Stojilković, S.M., *Czech. J. Phys.* **37**, 1238 (1987).

[2] Novaković, N.V., Stojilković, S.M. and Milić, B.S., *Physica Scripta* **41**, 265 (1990).

[3] Uhlenbusch, J. and Fischer, E., *Proc. IEEE* **59**, 578 (1971).

[4] Kolesnikov, V.I., *Proc. FIAN* **30**, 66 (1964).

[5] Radtsig, A.A. and Smirnov, B.M., *A Handbook of Atomic and Molecular Physics* (in Russian). Atomizdat, Moscow (1980).

[6] Griem, H.R., *Plasma spectroscopy*. McGraw-Hill Book Co., New York (1964).

[7] Hess, H., *Beitr. Plasmaphys.* **23**, 513 (1983).

[8] Ivanov, Yu.V., Mintsev, V.B., Fortov, V.E. and Dremin, A.I., *Zhurn. Eksper. Teoret. Fiz.* (USSR) **71**, 216 (1976).

[9] Simpson, S.W. and Kovitya, P., *Appl. Phys. Lett.* **43**, 752 (1983).

[10] Frost, L.S. and Phelps, A.V., *Phys. Rev.* **136**, 1538 (1964).

[11] Visconti, P.J., Slevin, J.A. and Rubin, K., *Phys. Rev.* **A3**, 1310 (1971).

[12] Mitchner, C.M. and Kruger, H.Jr., *Partially Ionized Gases*. John Wiley and Sons, New York (1973).

[13] Huxley, L.G.H. and Crompton, R.W., *The Diffusion and Drift of Electrons in Gases*. John Wiley and Sons, New York (1974).

[14] Zhdanov, V.M., *Transport Phenomena in Multi-Component Plasmas* (in Russian). Energoizdat, Moscow (1982).

[15] Asinovsky, E.I., Kirillin, A.V., Pakhomov, E.P. and Shubashov, V.I., *Proc. IEEE* **59**, 592 (1971).

[16] Devoto, R.S., *J. Plasma Phys.* **2**, 617 (1968).

[17] Renkert, H., Hensel, F. and Frank, E.U., *Ber. Bunsenges. Phys. Chem.* **75**, 507 (1971).

PRILOG IZUČAVANJU OSNOVNIH OSOBINA TERMALNE ARGONOVE PLAZME SA DODATKOM NATRIJUMA NA VISOKIM PRITISCIMA I NISKIM TEMPERATURAMA

N.V. Novaković, B.S. Milić i S.M. Stojilković

Sadržaj: Prikazani su rezultati jednog teorijskog izučavanja koncentracije konstituenata i elektroprovodnosti u funkciji pritiska i temperature kod plazme visokog pritiska (od $0.1\,MPa$ do $2.5\,MPa$) i niske temperature (od $2000\,K$ do $20000\,K$) formirane u argonu sa dodatkom do 10% natrijuma. Numerička izračunavanja zasnivala su se na pretpostavci da se sistem održava na konstantnom pritisku i konstantnoj temperaturi i da je dostignuto stanje lokalne termodinamičke ravnoteže. Korišćen je ranije nađeni modifikovani izraz za Debye-ev radijus, što je omogućilo da posmatrane plazme budu tretirane kao slabo neidealne i da se, shodno tome, njihov sastav odredi na osnovu sistema Saha jednačina za relevantne jonizacione stadijume Ar i Na. Dobijeni rezultati su upoređeni sa onima za plazmu u čistom argonu, izračunatim istom metodologijom. Nađeno je da dodavanje i samo 1% natrijuma bitno menja transportne osobine plazme. Ispod $10000\,K$ elektroprovodnost se povećava, u poređenju sa onom kod čistog Ar, za oko dva reda veličine, a iznad te temperature za oko pola reda veličine,

ukoliko pritisak nije manji od $0.5\,MPa$. Za pritiske oko $0.1\,MPa$, elektroprovodnost u plazmi čistog argona je na višim temperaturama (iznad $14000\,K$) nešto veća nego u prisustvu 1% natrijuma. Ovo se javlja zbog specifične izmene u zavisnosti elektroprovodnosti od pritiska: već pri dodatku 1% natrijuma, zavisnost $\sigma \sim p^{-1/2}$ karakteristična za plazmu u čistom argonu naglo se menja i postaje $\sigma \sim p^{1/2}$, što je tipično za čiste alkalne pare. Dalje povećavanje elektroprovodnosti, kad se količina dodatog Na uvećava do 10%, srazmerno je mala i primetna je samo između $10000\,K$ i $14000\,K$. Prodiskutovani su fizički razlozi za ovakvo ponašanje.