

EVALUATION OF THE COMPOSITION OF XENON-ARGON PLASMA WITH HYDROGEN AS ADDITIVE

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The concentrations of components, the ionization degrees and the pressures of plasma formed in the mixture of xenon and argon with hydrogen as additive are evaluated for temperature ranging from 10 000 to 40 000 K, provided that volume is constant and that the conditions of Local Thermodynamic Equilibrium (LTE) are fulfilled. Interaction between the plasma and vessel walls was not taken into account and plasma was taken to be weakly non-ideal. The results were obtained numerically with the initial parameters $p_0 = 30\,000$ Pa and $T_0 = 293$ K.

1. Introduction

The evaluations that follow were undertaken in conjunction with the special purpose of particular plasma mixtures which are used in pulse gas lamps for optical pumping of a laser. The electrical characteristics of pulse gas lamp depend on the concentrations of components. In the lamp the gas volume is constant, and the lamp is filled with a mixture of known composition at room temperature, containing xenon and argon with hydrogen as additive.

2. Review of used relations

In the evaluations given below, it was assumed that, apart from the atoms of xenon, argon and hydrogen, as well as the ions of these elements obtained as a result of process of the first thermal ionization, the plasma considered contains also the ions of xenon and argon obtained in the process of the second, the third and the fourth thermal ionizations. The presence of the molecules H_2 , as well as that of the ions Xe^{5+} and Ar^{5+} were estimated as unimportant in the temperature range considered. Thus, including the electrons, a total of eleven sorts of particles were taken into account. In the determination of the composition of the plasmas studied, the initial composition of the mixture and values of all the relevant ionization potentials must also be borne in mind.

The compositions of plasma mixtures examined were evaluated on the ground of a system of equations. It comprises the equation of the gas state^{1,2)}:

$$\sum_i n_i = \frac{p_0}{kT_0} \quad (1)$$

(n_i denoting the concentration of the particles of i -th species and k standing for the Boltzmann constant), the condition of charge neutrality of the plasma:

$$\sum_i z_i n_i - n_e = 0 \quad (2)$$

(z_i being the charge numbers the i -th species of ions, and n_e representing the concentration of electrons), the relations which specify the initial composition of gas mixture:

$$\begin{aligned} n_{Ar}^0 &= \gamma_1 n_{Xe}^0, \\ n_H^0 &= \gamma_2 n_{Xe}^0 \end{aligned} \quad (3)$$

(γ_1 and γ_2 specify the abundances of argon and hydrogen, where n^0 denote the initial concentrations), the equations of constancy of the numbers of heavy particles:

$$\begin{aligned} n_{Ar}^0 &= n_{Ar} + n_{Ar^+} + n_{Ar^{2+}} + n_{Ar^{3+}} + n_{Ar^{4+}}, \\ n_{Xe}^0 &= n_{Xe} + n_{Xe^+} + n_{Xe^{2+}} + n_{Xe^{3+}} + n_{Xe^{4+}}, \\ n_H^0 &= n_H + n_{H^+}, \end{aligned} \quad (4)$$

and seven equations expressing the law of mass action applied to the ionization processes taken into account³⁾:

$$\frac{n_e n_{A_{z+1}}}{n_{A_z}} = K_z, \quad (z = 0, 1, 2, 3). \quad (5)$$

The equilibrium constants K_z in the last group of equations were expressed by the following expressions^{4,5)}:

$$K_z = 2 \frac{Q_{z+1}}{Q_z} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} \exp \left(- \frac{W_z - \Delta W_z}{kT} \right). \quad (6)$$

Here Q denote the partition functions, W stands for the ionization energies, and ΔW are the lowerings of the ionization energies due to electrostatic screening, m_e is the electron mass and h is Planck's constant. The decrease of the ionization energy is determined with the aid of the following formula⁴⁾:

$$\Delta W_z = 23.1 \cdot 10^{-28} (z+1) \frac{1}{r_D} \quad (7)$$

in which r_D is the Debye's radius, pertaining to the electrostatic screening in the plasma, and given by:

$$r_D = 68.99 \left[\frac{T}{n_e (\langle z \rangle + 1)} \right]^{1/2} \quad (8)$$

with

$$\langle z \rangle = \frac{\sum_i z_i^2 n_i}{n_e} \quad (9)$$

representing the average electrical charge number of the ions.

The pressure of the plasma is not taken merely as the sum of partial pressures, but the negative correction term, arising due to Coulomb interaction in the plasma, is also included. Thus:

$$p = \sum_i p_i - \frac{1}{3} \frac{kT}{8\pi r_D^3}, \quad (10)$$

since it is assumed that the plasma is weakly non-ideal.

The system of equations (1)–(5), by means of which the compositions of the weakly non-ideal plasmas assumed in LTE are determined, form a system of partly linear and partly non-linear algebraic equations. The system is solved numerically by an iteration procedure⁶⁾. The programme used was given in the FORTRAN IV⁷⁾.

3. Results and discussion

Fig. 1 represents graphically the evaluated equilibrium concentrations of the plasma components as the functions of temperature, for the mixture in which $\gamma_1 = 0.06666$ and $\gamma_2 = 0.04444$ (in the initial state, the mixture contains 6% of argon and 4% hydrogen atoms).

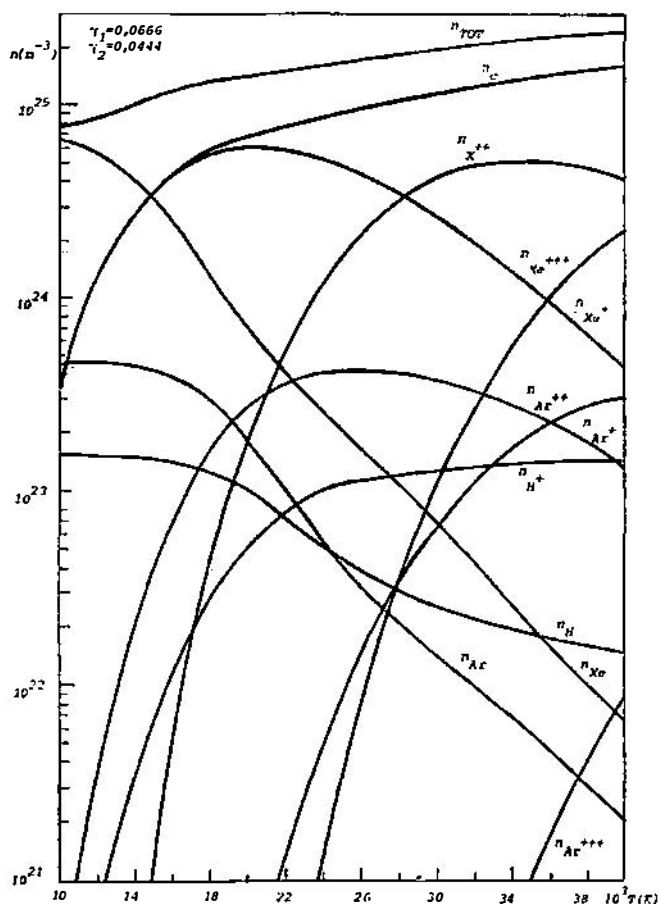


Fig. 1. The dependence of the number densities on temperature for the mixture of xenon and argon, with hydrogen as additive.

The evaluated values for the lowering of the ionization energy, the Debye-radius, the pressure and the decrease of pressure for the plasmas formed in the mixtures of xenon and argon, with hydrogen as additive, in which $\gamma_1 = 0.06666$ and $\gamma_2 = 0.04444$ are given in Table 1.

Since the basic gas is xenon which has the lowest ionization energy, at lower temperatures (below $16 \cdot 10^3$ K) the produced electrons are the result of the first thermal ionization of xenon mainly (concentration curve for n_e coincides with the one for n_{Xe^+}). At temperatures above $18 \cdot 10^3$ K, the values of electron concentration in the mixtures considered are influenced by further thermal ionizations as well. In spite of a greater number of ionization process, the increase of the concentration with the temperature is slower since these processes require greater energy.

TABLE 1.

	$10^{19} \Delta W/J$			$10^9 r_D/m$	$10^{-5} p/Pa$	$10^{-5} \Delta p/Pa$
	$z = 0$	$z = 1$	$z = 2$			
10 000	0.269	0.538	0.807	8.574	11.24	0.00
12 000	0.466	0.933	1.399	4.950	14.52	0.03
14 000	0.657	1.314	1.970	3.513	19.58	0.21
16 000	0.788	1.578	2.364	2.928	26.17	0.68
18 000	0.848	1.696	2.544	2.721	31.42	1.31
20 000	0.871	1.742	2.613	2.649	36.91	1.82
22 000	0.894	1.788	2.783	2.580	42.70	2.17
24 000	0.936	1.873	2.810	2.464	49.31	2.56
26 000	0.993	1.985	2.978	2.342	56.84	3.18
28 000	1.084	2.095	3.143	2.202	65.12	4.08
30 000	1.092	2.184	3.275	2.113	73.65	5.14
32 000	1.125	2.251	3.376	2.050	82.23	6.21
34 000	1.154	2.309	3.463	1.998	91.14	7.23
36 000	1.183	2.367	3.550	1.949	100.44	8.25
38 000	1.214	2.428	3.641	1.901	123.47	9.27
40 000	1.244	2.487	3.730	1.855	121.23	10.24

The values ionization energy lowering (ΔW), Debye-radius (r_D), pressure (p) and decrease of pressure (Δp).

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IZRAČUNAVANJE SASTAVA PLAZME U SMEŠI KSENONA I ARGONA
SA DODATKOM VODONIKA

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Izračunate su koncentracije komponenata, stepen jonizacije i pritisak u plazmi smeše ksenona i argona sa dodatkom vodonika u temperaturnom intervalu od 10 000 do 40 000 K, smatrajući da su ispunjeni uslovi konstantne zapremine i lokalne termodinamičke ravnoteže (LTE). Interakcija između plazme i zidova suda je zanemarena, a plazma je tretirana slabo neidealnom. Rezultati su dobijeni za početne parametre $p_0 = 30\,000$ Pa i $T_0 = 293$ K.