Absorption properties of argon arc plasma

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Abstract

In this paper, attention has been given to the absorption properties of argon arc plasma at the pressure from 0.1 MPa to 5 MPa. The frequency interval (0.01–10) x10^{15} s^{-1} has been divided into several frequency groups. Depending on the absorption properties of the medium for the given frequency group, the average absorption coefficient has been taken as either a group Rosseland or group Planck mean. These mean absorption coefficients were calculated for thermal plasma Ar as a function of plasma temperature in the range (1 000, 35 000) K for each of frequency groups.

Different splitting procedures of the frequency interval have been used to find the optimal values of mean absorption coefficients for further calculations of radiation characteristics. Attention has been given to calculation of net emission coefficients which determine the radiation losses in the arc centre. Net emission coefficients have been derived for isothermal cylindrical plasmas of radii from 0.01 to 10 cm.

Spectral coefficients of absorption

Spectral coefficients of absorption (absorptivities) are proportional to the concentration of the chemical species occurring in the plasma. Concentrations of argon atoms, ions and electrons calculated under assumption of local thermodynamic equilibrium [1] are shown in Fig. 1 for pressures of 0.1 MPa and 2.0 MPa.

Spectral absorption coefficients κ_ν were calculated using semi-empirical formulas described in [2] to represent both continuum and line radiation. Continuous spectrum is formed by bound-free transitions (photo-ionization) and free-free transitions (bremsstrahlung). Spectral variation of the absorption coefficient of a spectral line depends on the profile of the line. The line shape is given by simplified Voigt profile. Our calculations of line broadening account for Stark and Doppler half-widths and line shifts, resonance broadening and polarization shift. Theoretical formulas are given in [2]. The total absorption coefficients given by both continuous and line radiation at temperatures of 5 000 K and 20 000 K are given in Fig. 2.

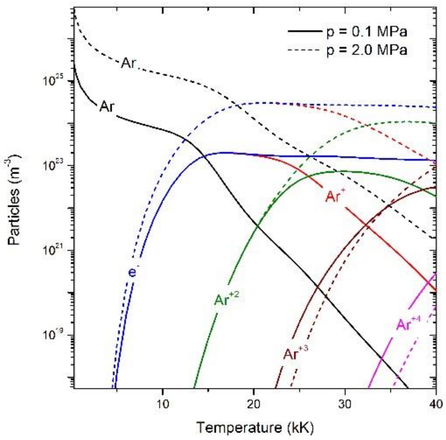

Fig. 1. Equilibrium composition of argon plasma at pressures of 0.1 and 2.0 MPa

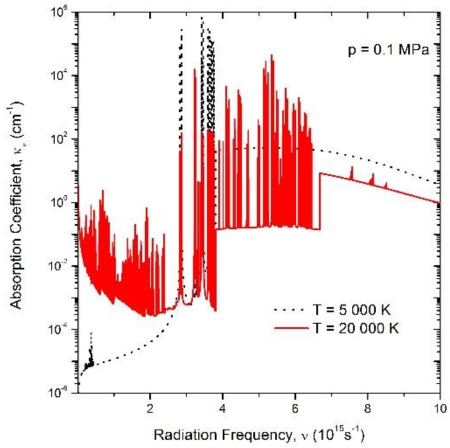

Fig. 2. Absorption coefficient of argon plasma for temperatures of 5 and 20 kK at pressure of 0.1 MPa

Multigroup approximation

The complicated spectral dependence of the plasma can be simplified by splitting the spectrum in several frequency groups in which the absorption coefficient is supposed to be constant with certain average value

$$\kappa_\nu(\nu, T) = \kappa_k(T)\,, \quad \nu_k \leq \nu \leq \nu_{k+1}$$

The splitting frequencies are mainly defined by the steep jumps of the evolution of the continuum absorption coefficient that correspond to individual absorption edges. The larger the number of groups the more accurate approximation. However, the number of groups should be minimized to decrease the computation time. To compare the effect of different splitting frequency interval was divided in

(a) six groups with splitting frequencies (in units 10^{15} s^{-1})

(0.01; 1.25; 2.5; 3.19; 4.6; 6.0; 10.0)

(b) 16 groups with splitting frequencies (in units 10^{15} s^{-1})

(0.01; 0.36; 0.71;1.06;1.41;1.76 2.11; 2.65; 3.19; 3.76; 4.33; 4.9; 5.47; 6.04; 6.61;8.27;10)

The mean values of absorption coefficients were taken as either Planck (κ_P) or Rosseland (κ_R) means:

$$\kappa_P = \int_{\nu_k}^{\nu_{k+1}} \kappa_\nu B_\nu d\nu \left[\int_{\nu_k}^{\nu_{k+1}} B_\nu d\nu\right]^{-1}; \quad \kappa_R^{-1} = \int_{\nu_k}^{\nu_{k+1}} \kappa_\nu^{-1} \frac{dB_\nu}{dT} d\nu \left[\int_{\nu_k}^{\nu_{k+1}} \frac{dB_\nu}{dT} d\nu\right]^{-1}$$

where B_ν denotes the Planck function of equilibrium radiation. The Planck mean is appropriate in the case of optically thin, emission dominated system, on the other hand the Rosseland mean is suitable when the system approaches equilibrium (almost all radiation is reabsorbed).

According to the real spectrum both means can differ in several orders of magnitude especially in frequency regions with large number of spectral lines. In Figs. 3, 4 comparison is given of Planck and Rosseland means in the group (0.01-1.25)x10^{15} s^{-1} for splitting (a) and in the groups (0.01 - 0.36; 0.36 – 0.71; 0.71 – 1.06) x10^{15} s^{-1} for splitting (b). It can be seen that the effect of spectral lines dominates the group (0.01 – 0.36)x10^{15} s^{-1} even though in case of splitting (a) the contribution of the whole group (0.01-1.25)x10^{15} s^{-1} is overestimated in Planck averaging.

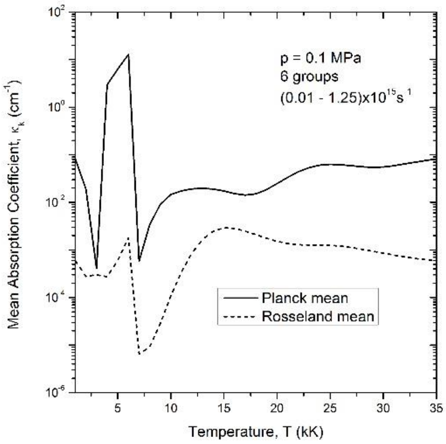

Fig. 3. Planck and Rosseland means in group (0.01-1.25)x10^{15} s^{-1}, splitting (a)

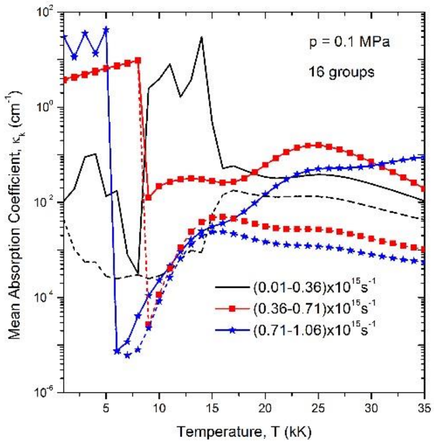

Fig. 4. Planck (full lines) and Rosseland (broken lines) means for first three groups, splitting (b)

P1-approximation

The P1-approximation consists of expanding radiative intensity in spherical harmonics and including only the first order terms. Under this assumption the equation of radiative transfer leads to simple elliptic equation for the group density of radiation U_k

$$\nabla \cdot \left[-\frac{c}{3\kappa_k} \nabla U_k \right] + \kappa_k c U_k = 4\pi B_k \kappa_k$$

where $B_k = \int_{\nu_k}^{\nu_{k+1}} B_\nu d\nu$ and c is the speed of light. In case of cylindrically symmetrical isothermal plasma the coefficients κ_k and B_k are constant and the equation can be solved analytically. The group net emission over the volume of the arc is

$$\left(w_{avg}\right)_k = \frac{2\pi}{\pi R^2} \int_0^R r \nabla \cdot \vec{F}_k(r) dr = \frac{8\pi B_k I_1\left(\sqrt{3}\kappa_k R\right)}{R\left[2I_1\left(\sqrt{3}\kappa_k R\right) + \sqrt{3} I_0\left(\sqrt{3}\kappa_k R\right)\right]}$$

where $I_0(x)$ and $I_1(x)$ are modified Bessel functions, R is the arc radius, and $\vec{F}_k$ is the group radiation flux. The net emission of radiation is then

$$\nabla \cdot \vec{F}_R = \sum_k \left(w_{avg}\right)_k = 4\pi \varepsilon_N$$

where ε_N is the net emission coefficient defined by Lowke [2]. The net emission coefficients have been calculated with both Planck and Rosseland mean absorption coefficients for various plasma radii. Values of the net emission coefficients as a function of temperature and the radius of the isothermal argon arc plasmas are in Fig. 5. Fig. 6 shows comparison of exact calculation of ε_N [3] with results of Planck and Rosseland P1-approximation for various splitting of frequency interval. In case of Rosseland averaging effect of more detailed frequency splitting is negligible. As can be expected from the definition of Planck and Rosseland means, Planck mean leads to overestimation of the radiation emission, and the Rosseland approach underestimates it.

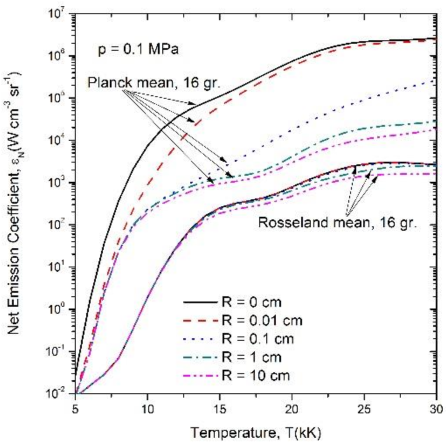

Fig. 5. Net emission coefficients of argon plasma as a function of the plasma temperature and thickness at a pressure of 0.1 MPa

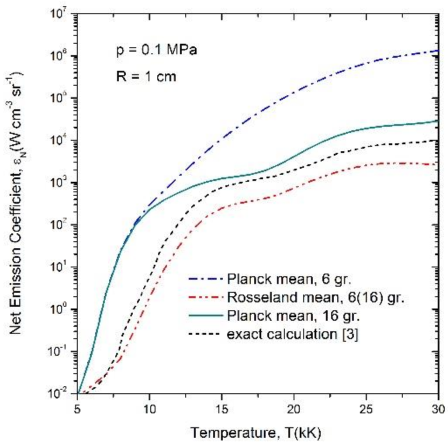

Fig. 6. Net emission coefficients of Ar plasma as a function of the plasma temperature at a pressure of 0.1 MPa and plasma radius of 1 cm – comparison with exact calculation [3]

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