Radiation Heat Transfer in Thermal Argon Plasma with Iron Vapors

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The objective of this paper consists of approximate calculations of thermal radiation heat transfer in argon arc plasma with admixtures of iron vapors. As a mathematical tool, the P1-approximation has been used. To simplify the calculations, the frequency dependence of absorption coefficients has been handled by means of Planck and Rosseland averaging methods. Calculations has been performed for isothermal cylindrical plasma of various radii (0.01 to 10 cm) in temperature range 1 000 – 30 000 K.

Keywords: radiation transfer, P1-approximation, mean absorption coefficients

1 INTRODUCTION

Radiation heat transfer influence significantly the physical processes occurring in the arc plasma. Due to extreme conditions experimental work only gives global information instead of local ones which may be important to determine the optimum operating conditions in the plasma reactor; theoretical modeling is then of great interest to improve the plasma process. However, the non-linearity of equations describing the radiation field and strong dependency of input parameters on the radiation frequency makes mathematical plasma models very complicated. Several approximate methods of accounting for radiation transfer have been developed (method of net emission coefficient [1-3], method of partial characteristics [4, 5], P1-approximation [6, 7], etc.). In this paper, the P1-approximation was used to study the influence of iron vapor admixtures on the radiation transfer in the argon arc plasma. The net emission coefficients were calculated for comparison.

2 ABSORPTION OF RADIATION

The spectral coefficients of absorption are proportional to the concentrations of the chemical species occurring in the plasma. In the plasma of argon with iron vapors we assumed the following species: Ar and Fe atoms, Ar^{+}, Ar^{+2}, Ar^{+3}, Ar^{+4}, Fe^{+}, Fe^{+2}, Fe^{+3}, Fe^{+4} ions, and electrons. Equilibrium plasma composition was taken from [8].

Both line and continuum radiation was considered in calculations of absorption coefficients. Semi-empirical formulae described in [9] were used for calculation of both continuum and line spectrum. The calculated absorption coefficients as a function of radiation frequency for temperatures of 5 000 K and 30 000 K at the pressure of 1 atm are shown in Fig. 1 for pure argon plasma and for plasma mixture of 10 vol% Ar + 90 vol% Fe. The metal vapors cause a significant increase in number of spectral lines.

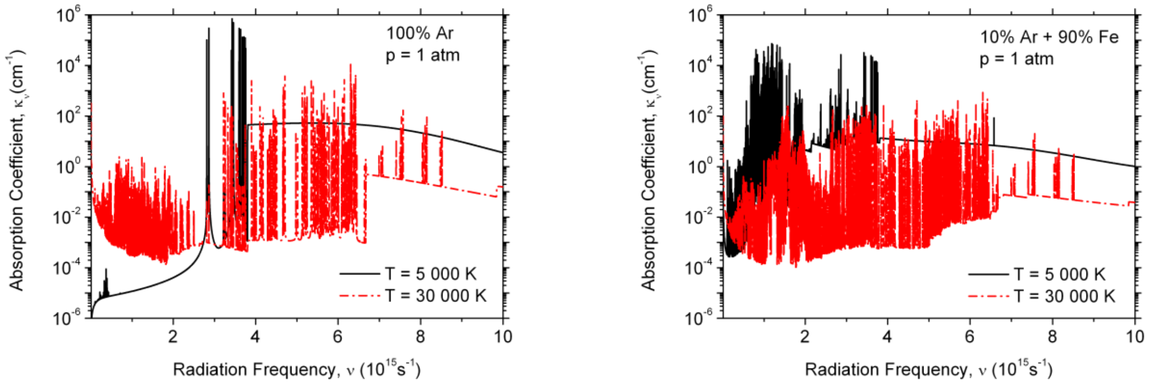

Fig. 1: Absorption coefficients for pure argon plasma and the mixture of argon and iron (volume percentage) at temperatures 5 000 K and 30 000 K

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

$$\kappa_\nu(\vec{r},\nu,T)=\bar{\kappa}_k(\vec{r},T)\,,\quad \nu_k\le\nu\le\nu_{k+1}\qquad(1)$$

The cutting frequencies are mainly defined by the steep jumps of the evolution of the continuum absorption coefficient that correspond to individual absorption edges. In this work, the frequency interval (10^{12} – 10^{16}) s^{-1} was cut into five frequency groups with following cutting frequencies (in units $10^{15}s^{-1}$)

$$(0.001;\ 1.0;\ 2.8;\ 3.8;\ 6.67;\ 10.0)\qquad(2)$$

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

$$\kappa_P=\int_{\nu_k}^{\nu_{k+1}}\kappa_\nu B_\nu\,d\nu\left[\int_{\nu_k}^{\nu_{k+1}}B_\nu\,d\nu\right]^{-1}\qquad(3)$$

$$\kappa_R^{-1}=\int_{\nu_k}^{\nu_{k+1}}\kappa_\nu^{-1}\frac{dB_\nu}{dT}\,d\nu\left[\int_{\nu_k}^{\nu_{k+1}}\frac{dB_\nu}{dT}\,d\nu\right]^{-1}\qquad(4)$$

where B_ν denotes the Planck function. The effect of metal vapors on values of mean absorption coefficients is shown in Fig. 2 for the first two frequency groups. Metal admixtures increase particularly Planck absorption means since the Planck means are more dependent upon the spectral lines.

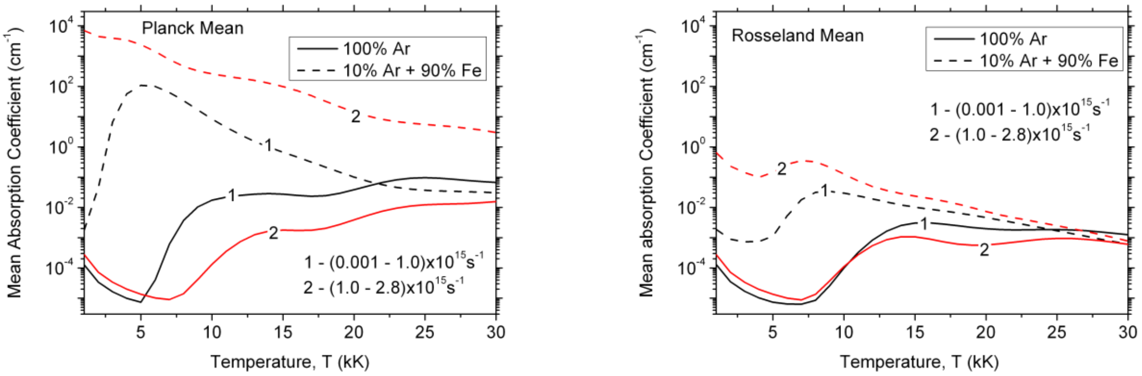

Fig. 2: Planck and Rosseland means as a function of temperature for two frequency groups and two composition variants of Ar and Fe (volume percentage)

3 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

$$\nabla\cdot\left[-\frac{c}{3\bar{\kappa}_k}\nabla U_k\right]+\bar{\kappa}_k c U_k=4\pi B_k\bar{\kappa}_k\qquad(5)$$

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 equation (5) has constant coefficients $\bar{\kappa}_k$ and B_k and can be solved analytically. With boundary condition (no radiation enters from outside), the group net emission over the volume of the arc is

$$(w_{avg})_k=\frac{2\pi}{\pi R^2}\int_0^R r\nabla\cdot\vec{F}_k(r)\,dr=$$
$$=\frac{8\pi B_k I_1(\sqrt{3}\bar{\kappa}_k R)}{R[2I_1(\sqrt{3}\bar{\kappa}_k R)+\sqrt{3}I_0(\sqrt{3}\bar{\kappa}_k R)]}\qquad(6)$$

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

$$\nabla\cdot\vec{F}_R=\sum_k(w_{avg})_k=4\pi\varepsilon_N\qquad(7)$$

where ε_N is the net emission coefficient defined for isothermal plasma cylinder at radius R by Lowke [1]

$$\varepsilon_N=\int_0^\infty B_\nu\kappa_\nu\exp(-\kappa_\nu R)\,d\nu\qquad(8)$$

The effect of the proportion of iron vapors to the argon plasma on the net emission coefficients is shown in Figs. 3 and 4. In Fig. 3, the net emission coefficients were calculated combining equations (6) and (7). Planck and Rosseland mean absorption coefficients were used in calculations, respectively. Admixtures of iron increase the plasma emissivity, particularly at low temperatures. This can be explained by the lower ionization energy of the metal atoms and ions. For comparison purposes, Fig. 4 shows the net emission coefficients calculated by direct frequency integration (8). 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.

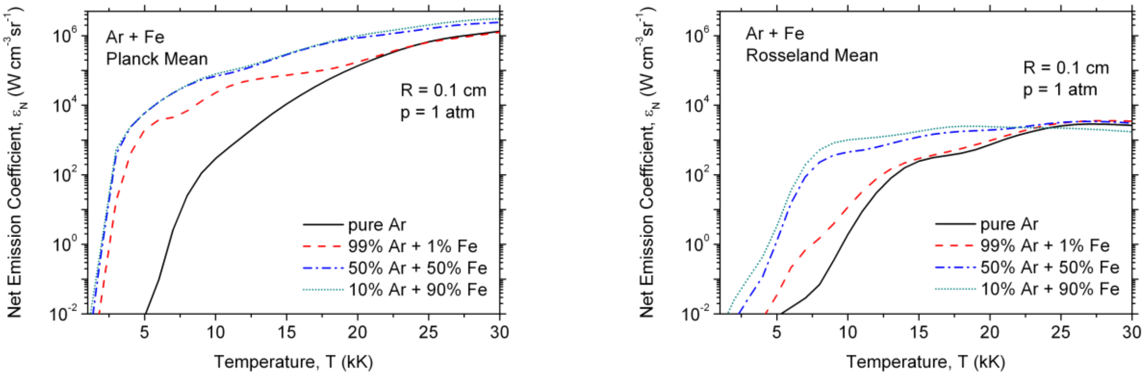

Fig. 3: Net emission coefficient of argon plasma with various mixtures of iron (R = 0.1 cm, p = 1 atm, volume percentage); P1-approximation

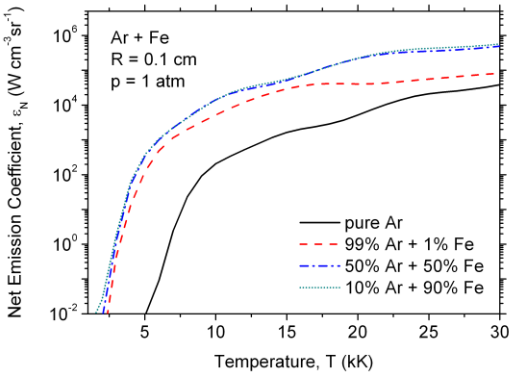

Fig. 4: Net emission coefficient of argon plasma with various mixtures of iron (R = 0.1 cm, p = 1 atm, volume percentage); direct frequency integration (8)

4 CONCLUSIONS

Calculations of the net emission coefficients for argon arc plasma with various admixtures of iron vapors have been performed as a function of temperature. The increasing effect of metal admixtures on the plasma emissivity is presented.

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