Optica Applicata, Vol. XXXVIII, No. 2, 2008

Net emission coefficients of low temperature thermal iron-helium plasma

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Net emission coefficients of low temperature thermal iron-helium plasma mixture at atmospheric pressure are presented. The calculations are made assuming the plasma is in the local thermodynamic equilibrium at a pressure of 0.1 MPa. The results are presented for several values of helium mass fraction in the mixture (between 0 and 1), for a temperature range 3000–25000 K and three characteristic plasma dimensions; 0 – corresponding to the optically thin case, and 1 mm and 10 mm. The values of net emission coefficients allow the estimations of total radiation losses in iron-helium plasmas.

Keywords: net emission coefficients, iron-helium plasma.

1. Introduction

Iron plasma appears in many laser technological applications. Plasma, which appears during laser processing of materials, has a considerable influence on the processing conditions and was therefore studied by many authors [1]. Plasma strongly absorbs laser radiation and significantly changes energy transfer from a laser beam to a material. Plasma effects are especially relevant in welding metals using a CO_2 laser because the absorption of 10.6 μm laser radiation by the metal surface usually does not exceed 15%. In the case when plasma is attached to a surface and a keyhole is formed, the absorption of laser beam energy and its transfer to metal can increase to 100%. Since infrared radiation is strongly reflected from a metal surface, the plasma can improve thermal coupling between the laser beam and the target with its own radiation and thermal conduction. On the other hand, dense plasma over the keyhole can block laser radiation on the path of a few millimetres.

Experiments and calculations [2–4] show that the plasma plume is a mixture of a shielding gas and metal vapour. Knowledge of net emission coefficients of Fe-Ar and Fe-He plasma is most useful because such plasma mixtures are often met in laser or hybrid (laser and arc) welding. The values of the net emission coefficients allow the estimations of total radiation energy of a plasma plume.

To date, there exist some theoretical calculations of net emission coefficients for iron-argon plasma. The recent is by MENART and MALIK [5], where the calculation results for iron mole fractions ranging from 0 to 1 with different radiation path lengths and plasma temperatures are presented.

In this paper, net emission coefficients of low temperature thermal helium plasma mixed with iron vapour are presented. Contrary to previously published results [6] where results were presented for two partial pressures of helium, these results are presented for several values of helium mass fraction and for broader range of temperatures and are therefore more useful for estimations of total radiation losses in iron-helium plasmas. Comparisons with previously published data of pure iron plasma for a number of different path lengths are also made.

2. Net emission coefficient

The net emission coefficient ε_N takes into account the self-absorption of radiation [7]. In the case of a homogeneous, plane layer of isothermal plasma the net emission coefficient of the radiation in the direction of a line of sight is

$$\varepsilon_N = \int_0^\infty B_\lambda(T)\kappa'(\lambda)\exp\left[-\kappa'(\lambda)L\right]\mathrm{d}\lambda \tag{1}$$

where $B_\lambda(T)$ is the intensity of the blackbody radiation, $\kappa'(\lambda) = \kappa(\lambda)[1 - \exp(-hc/\lambda kT)]$ is the total absorption coefficient including the induced emission where $\kappa(\lambda) = \kappa_{\mathrm{line}} + \kappa_{\mathrm{continuum}}$ and L is characteristic plasma dimension. Equation (1) represents radiation of one-dimensional plasma in one direction [8]. It is easily seen that in the case of small absorption ($L \to 0$) the expression under integral is the well known emission coefficient $\varepsilon(\lambda) = B_\lambda(T)\kappa'(\lambda)$.

The line absorption coefficient is given by [8]

$$\kappa_{\mathrm{line}} = \frac{\lambda^4}{8\pi c} A_{ki}\, g_k\, P_\lambda \frac{n_{z-1}}{U_{z-1}(T)} \exp\left(-\frac{E_i}{kT_e}\right) \tag{2}$$

where n_{z-1} is the density of atoms or ions, λ – the wavelength of the spectral line, A_{ki} – the transition probability, g_k – the statistical weight of the upper level, c – the light velocity, P_λ – the line profile, $U_{z-1}(T)$ – the partition function, E_i – the energy of the lower level, T_e – the electron temperature, k – the Boltzmann constant.

The total continuous absorption coefficient is

$$\kappa_{\mathrm{continuum}} = \sum_\lambda \kappa_{\mathrm{continuum}}(\lambda) = \sum_\lambda \left[\kappa_{\mathrm{ff}}^{\mathrm{ei}}(\lambda) + \kappa_{\mathrm{fb}}(\lambda) + \kappa_{\mathrm{ff}}^{\mathrm{ea}}(\lambda)\right] \tag{3}$$

where indices fb and ff denote free–bound and free–free transitions, respectively and ei and ea denote electron–ion and electron–atom collisions. Formulas for κ_{fb} and $\kappa_{\mathrm{ff}}^{\mathrm{ei}}$ were taken from [8] and for $\kappa_{\mathrm{ff}}^{\mathrm{ea}}$ from [9] and are written below (in SI units)

$$\kappa_{\mathrm{ff}}^{\mathrm{ei}}(\lambda) = \frac{16\pi^2 k e_0^6}{3\sqrt{3}\,h^4 c(4\pi\varepsilon_0)^3}\frac{\lambda^3 T_e}{c^3}\sum_{z=1} z^2 n_{z-1}\frac{2U_z}{U_{z-1}}\exp\left(-\frac{\chi_{z-1}}{kT_e}\right) \tag{4}$$

$$\kappa_{\mathrm{fb}}(\lambda) = \frac{32\pi^2 k e_0^6}{3\sqrt{3}\,h^4 c(4\pi\varepsilon_0)^3}\frac{\lambda^3 T_e}{c^3}\sum_{z=1}\left\{z^2 n_{z-1}\frac{g_{z,1}}{U_{z-1}}\exp\left(-\frac{z^2\chi_H}{kT_e}\right)\right.$$
$$\left.\times\left[\exp\left(\frac{hc}{\lambda kT_e}\right)-1\right]\xi_{\mathrm{fb}}^{z}(T_e,\lambda)\right\} \tag{5}$$

$$\kappa_{\mathrm{ff}}^{\mathrm{ea}}(\lambda) = \frac{16 e^2\lambda^3}{3hc^4(4\pi\varepsilon_0)}\left(\frac{k}{2\pi m_e}\right)^{3/2} n_0 n_e T_e^{3/2}\sigma_{\mathrm{ea}}(T)$$
$$\times\left[1+\left(1+\frac{hc}{\lambda kT_e}\right)^2\right]\left[1-\exp\left(-\frac{hc}{\lambda kT_e}\right)\right] \tag{6}$$

where $g_{z,1}$ is the statistical weight of the parent ion, z is the ion charge seen by the radiating electron, n_0 is the atom density, n_e is the electron density, $\sigma_{\mathrm{ea}}(T)$ is the average cross-section for electron–atom collisions and ξ_{fb}^{z} is the factor that was introduced by Biberman [2] and takes into account a real structure of the energy levels. For iron $\sigma_{\mathrm{ea}}(T)$ value was taken from [10].

It has been assumed that iron vapour and shielding gases are ideal gases in the local thermodynamic equilibrium. The calculations were made for the wavelength region 300–25000 Å. The plasma composition was calculated at a pressure of 0.1 MPa. In the case of iron the transition probabilities necessary to calculate the line absorption coefficients were taken from [11, 12] available in the electronic form (courtesy of dr. Sultana Nahar, Department of Astronomy, the Ohio State University). They consist of 42934 transitions; 15096 Fe I transitions, 18448 Fe II transitions and 9390 Fe III transitions. The partition functions were taken from [13, 14]. To calculate line profiles, the analytical approximation of the Voigt function was used [15]. It has been assumed that the line profile is a convolution of the Lorentzian and the Gaussian profiles resulting from the Stark and Doppler effects. The Stark broadening parameters for iron were taken from [16, 17]. The van der Waals broadening has been neglected. This type of broadening plays a role only in lower temperatures (below 5000 K) where the emission is very low and does not matter in plasma energy losses. The comparison with MENART and MALIK [5] data (see Fig. 1) shows that its possible influence is not critical. The Biberman factors for iron were taken from [6].

In the case of helium 328 of He I lines were used. Since the calculations are restricted to 25 kK the radiation of He II was found negligible. Data necessary for calculations of emission coefficients of helium were taken from the NIST atomic database [18]. The Stark broadening parameters for helium were taken from [19, 20]. The Biberman factor was taken from [21].

For the iron-helium mixture, the total absorption coefficient $\kappa(\lambda)$ results from the summation over all iron and helium atoms and ions.

3. Results

3.1. Comparison with existing data

The results obtained from the Nahar's data compared with the results obtained by MENART and MALIK [5] are shown in Fig. 1. The comparison is made for pure iron plasma for the optically thin case, as well as for 1 mm and 10 mm thick plane plasma layer. The calculations were done for 3000–25000 K plasma temperature range at a plasma pressure of 0.1 MPa. The same spectrum region 300–25000 Å is used in both works.

The agreement with results from MENART and MALIK [5] is quite good. The differences come from the different databases for the transition probabilities, as well as different Stark broadening parameters and Biberman factors. It is worth noting

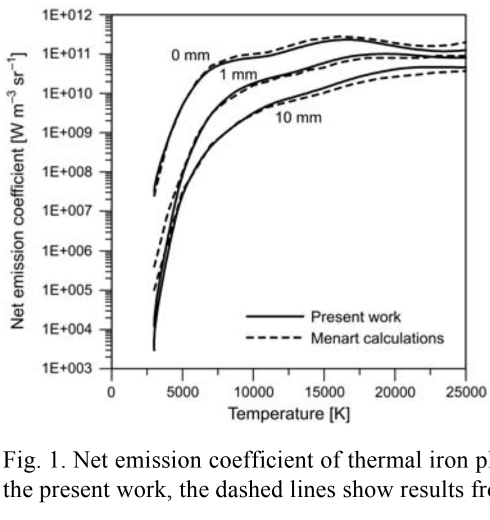

Fig. 1. Net emission coefficient of thermal iron plasma at 0.1 MPa. Solid lines show results obtained in the present work, the dashed lines show results from MENART and MALIK [5].

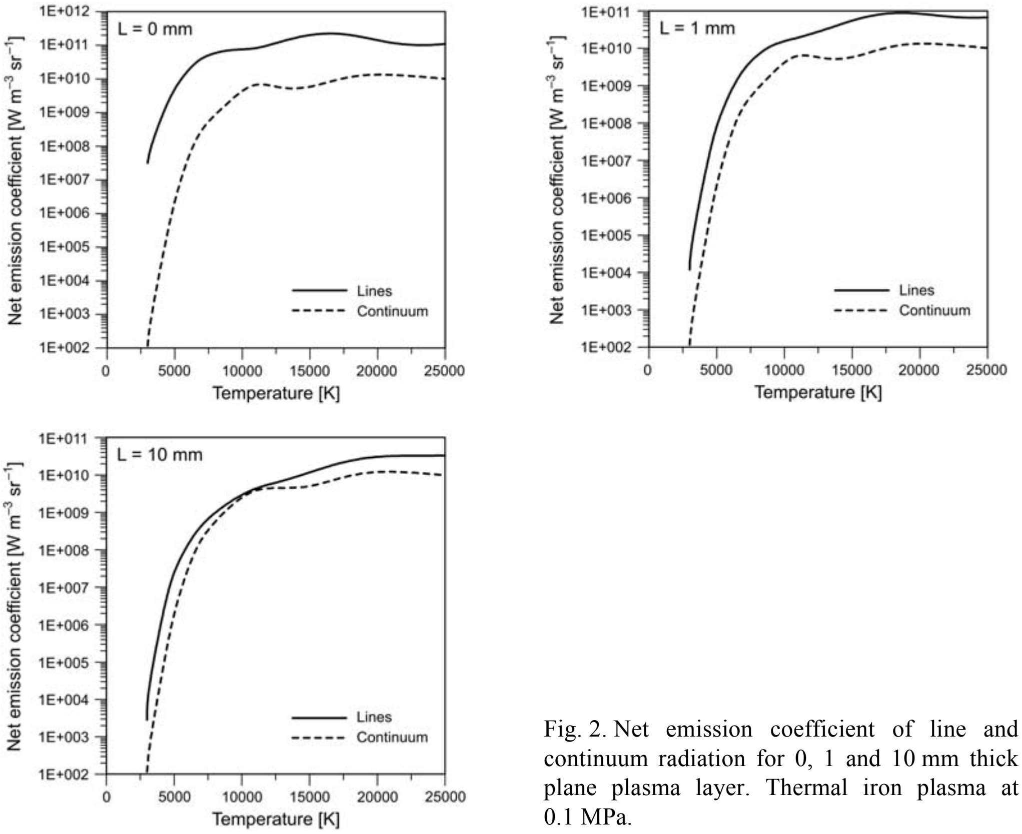

Fig. 2. Net emission coefficient of line and continuum radiation for 0, 1 and 10 mm thick plane plasma layer. Thermal iron plasma at 0.1 MPa.

that the line radiation of iron plasma is by a factor of ~10 stronger than the continuum radiation in the optically thin case and its role decreases with the increase in the plasma dimension (Fig. 2).

3.2. Net emission coefficients for different mass fractions

The net emission coefficients of iron-helium mixture at different temperatures are shown in Figs. 3–5. Figure 3 shows the net emission coefficient for optically thin plasma ($L = 0$), Figure 4 for radiation of a plane layer 1 mm thick, and Fig. 5 for a plane layer 10 mm thick. It is clear that iron plasma radiates much more energy than helium. Helium net emission coefficient is negligible at temperatures below 15 kK. In higher temperatures the radiation of helium is still small and for the $L = 0$ is relevant only when mass fraction of iron vapour in the Fe-He mixture is lower than 25%. The increase of the radiation path length results in further decrease of the importance of helium radiation.

In pure iron vapour, the continuous emission coefficient does not exceed 11 per cent of total radiation for the optically thin plasma ($L = 0$), but its role increases with the radiation path length and becomes significant for $L = 10$ mm.

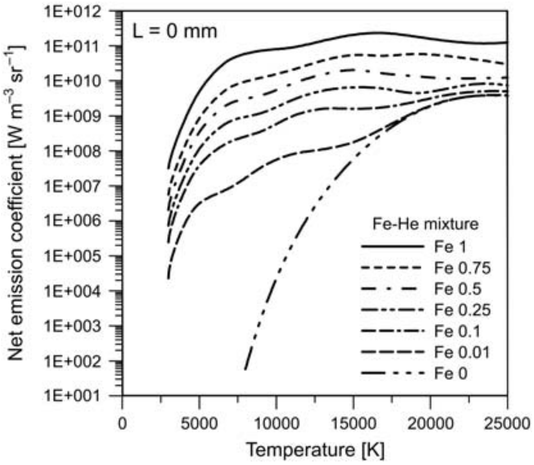

Fig. 3. Net emission coefficient of iron-helium plasma for different mass fractions of iron. Optically thin plasma $L = 0$. Total pressure 0.1 MPa.

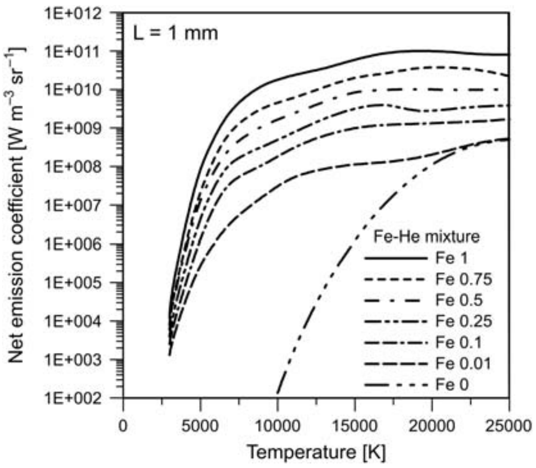

Fig. 4. Net emission coefficient of iron-helium plasma for different mass fractions of iron. Plane layer 1 mm thick. Total pressure 0.1 MPa.

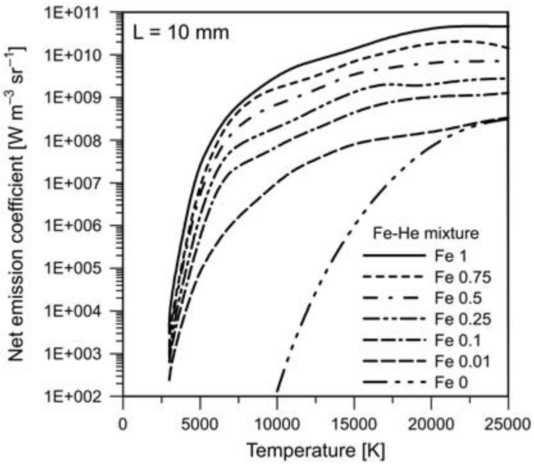

Fig. 5. Net emission coefficient of thermal iron-helium plasma for different mass fractions of iron. Plane layer 10 mm thick. Total pressure 0.1 MPa.

3.3. Net emission coefficient in spherical symmetry

Similarly to the one-dimensional plane layer, the net emission coefficient can be calculated for a homogeneous, isothermal, spherical plasma. The total energy radiated at the wavelength λ from a homogeneous sphere is equal

$$W_\lambda = 4\pi R^2 F_\lambda(\alpha(\lambda)) \tag{7}$$

where R is the radius of the sphere, $\alpha(\lambda) = 2R\kappa'(\lambda)$ and $F_\lambda(\alpha)$ is outward energy flux at any point P on the surface of the sphere. Assuming the origin of the spherical coordinate system in P and z-axis directed toward the centre of the sphere, we have

$$F_\lambda(\alpha) = \int_0^{2\pi} \mathrm{d}\varphi \int_0^{\pi/2} I_\lambda(\alpha, \vartheta)\cos(\vartheta)\sin(\vartheta)\,\mathrm{d}\vartheta \tag{8}$$

where the intensity $I_\lambda(\alpha, \vartheta)$ is equal

$$I_\lambda(\alpha, \vartheta) = \frac{\varepsilon_\lambda}{\kappa'(\lambda)}\left\{1 - \exp\left[-\alpha\cos(\vartheta)\right]\right\} \tag{9}$$

Inserting Eq. (9) into (8) and substituting $\cos(\vartheta) = u$, we have

$$f(\alpha) \equiv \frac{F_\lambda(\alpha)}{F_\lambda(0)} = \frac{3}{\alpha}\int_0^1 \left[1 - \exp(-\alpha u)\right]u\,\mathrm{d}u = \frac{3}{\alpha^3}\left[\exp(-\alpha)(1+\alpha) - 1 + \frac{\alpha^2}{2}\right] \tag{10}$$

The function f is defined as a ratio of the energy losses of the sphere at a given wavelength to the energy losses of the optically thin sphere at the same wavelength. During numerical calculations for $\alpha \to 0$, the expansion $f(\alpha) = 1 - 3\alpha/8 + \ldots$ should be used instead of the analytical integral.

Net emission coefficient ε_N is defined by equation [7]

$$4\pi\varepsilon_N = div\mathbf{F} \tag{11}$$

where $\mathbf{F}$ is the total (integrated over λ) energy flux vector. Using definition (11) and Gauss–Ostrogradsky theorem, one can prove that the mean value (over volume of the sphere) of the net emission coefficient is equal

$$\varepsilon_N^{\mathrm{sphere}} = \int_0^\infty B_\lambda(T)\kappa'(\lambda) f\left(\alpha(\lambda)\right)\mathrm{d}\lambda \tag{12}$$

From the comparison of the equation (12) with (1) for small optical thickness, we have $L \cong 0.75R$. In Figure 6, the comparison of the net emission coefficients for spherical plasma of the radius R and the one-dimensional plasma plane layer of

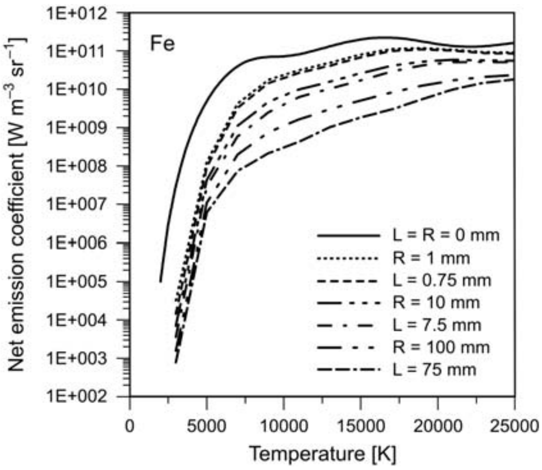

Fig. 6. Net emission coefficients for spherical plasma and plane plasma layer. Pure iron, pressure 0.1 MPa.

the thickness $L = 0.75R$ are plotted. For optically thin plasma $L = R = 0$ mm, the results are the same. For the $R = 1$ mm both coefficients are very close. For $R \geq 10$ mm the difference becomes significant.

4. Summary

The net emission coefficients for iron-helium plasmas in the local thermodynamic equilibrium at a pressure of 0.1 MPa are presented. The calculations are made over a temperature range from 3000 to 25000 K for various mass fractions of iron in the iron-helium mixture, as well as for three different characteristic plasma dimensions – 0, 1 and 10 mm. The results can be used for calculation of the radiation energy losses. They were already used in [4] in calculations of the Fe-He plasma plume induced during laser welding and a good agreement with the experiment was found.

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Received November 19, 2007