Emission coefficients of low temperature thermal iron plasma

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Iron plasma appears during material processing with laser, electric arc etc., and has considerable influence on the processing conditions. In this paper emission coefficients of low temperature thermal iron plasma at atmospheric pressure are presented. Net emission coefficients ε_N have been calculated for pure iron plasma as well as for Fe–Ar and Fe–He plasma mixtures. To calculate the recombination radiation the knowledge of the Biberman factors $\xi^z_{\mathrm{fb}}(T_{\mathrm{e}}, \lambda)$ is necessary and they have been calculated from the iron photo–ionization cross sections. The calculations allow estimation of energy losses, energy radiated by plasma plume and its comparison with the energy absorbed from laser beam.

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1 Introduction

Iron plasma appears in many laser technological applications. Plasma, which appears during laser processing of materials, has 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 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 the laser radiation on the path of a few millimetres. During strong vapor bursts the pressure of the metal vapour reaches 10^5 Pa and the electron density is about 2.5×10^{23} m^{-3}. Under these conditions the absorption coefficient can reach several cm^{-1}. Even if the Fresnel absorption is the dominant absorption mechanism, as it is in the case of high welding velocities, the plasma's behaviour reflects the process of absorption of the laser beam in a keyhole and therefore the whole process of welding. Knowledge of plasma parameters may be used to assess the models of interaction between laser radiation, material, and shielding gas, and in turn, to control technological process.

In this paper the emission coefficients of low temperature thermal iron plasma are presented. Net emission coefficients have been calculated for Fe–Ar and Fe–He plasma mixtures most often used in technological applications. To calculate continuous plasma radiation the knowledge of the Biberman factor [2] is necessary and therefore such calculations have also been made. The calculations allow estimation of energy losses, energy radiated by plasma plume and its comparison with the energy absorbed.

2 Calculations and results

2.1 Biberman factors

The Biberman factors $\xi^z_{\mathrm{fb}}(T_\mathrm{e}, \lambda)$ have been calculated from the iron photo–ionization cross sections [3, 4]. This factor is also useful for determination of plasma parameters from continuous radiation. By definition $\xi^z_{\mathrm{fb}}(T_\mathrm{e}, \lambda) = \kappa^z_{\mathrm{fb}}(T_\mathrm{e}, \lambda)/\kappa^{\mathrm{H}}_{\mathrm{fb}}(T_\mathrm{e}, \lambda)$, where $\kappa^{\mathrm{H}}_{\mathrm{fb}}(T_\mathrm{e}, \lambda)$ is the absorption coefficient of the free–bound radiation for hydrogen–like atoms [2] in MKS units

$$\kappa^{\mathrm{H}}_{\mathrm{fb}}(T_\mathrm{e}, \lambda) = \frac{32\pi^2 k_\mathrm{B}}{3\sqrt{3}ch^4}\left(\frac{e_0^2}{4\pi\epsilon_0}\right)^3 n_{z-1}\frac{2g_{z,1}}{U_{z-1}}\frac{z^2 T_\mathrm{e}\lambda^3}{c^3}\exp(-\frac{E_\mathrm{j}}{k_\mathrm{B}T_\mathrm{e}})(\exp(\frac{hc}{k_\mathrm{B}T_\mathrm{e}\lambda}) - 1), \quad (1)$$

where n_{z-1} is the density of parent atom or ion in m^{-3}, T_e the electron temperature, z denotes ion charge seen by free electron, $g_{z,1}$ is the statistical weight of the parent ion, $U_{z-1}(T)$ partition function, and E_j ionization energy.

The results of $\xi^z_{\mathrm{fb}}(T_\mathrm{e}, \lambda)$ for Fe I and Fe II at the temperature of 5000 and 15000 K are shown in Figs. 1 and 2. Values of $g_{z,1}$ are taken for lowest multiplets (terms) of Fe II and Fe III, 30 and 25, respectively. The partition functions are taken from [5].

The spikes seen in the figures results from the photo–ionization with simultaneous excitation of the arising ion ($h\nu$ + Fe I $\rightarrow e$ + Fe $\mathrm{II_i}$ and $h\nu$ + Fe II $\rightarrow e$ + Fe $\mathrm{III_i}$, where subscript i describes excited state) as well as from resonance transitions to auto–ionized states [3, 4].

2.2 Net emission coefficients

The self–absorption can be taken into account by calculating so called net emission coefficient ε_N [6]. For a homogeneous, isothermal plasma the net emission coefficient of the radiation in the direction of x–axis is [2, 6]

$$\varepsilon_N = \int_0^\infty B_\lambda(T)\kappa'(\lambda)\exp(-\kappa'(\lambda)L)d\lambda, \quad (2)$$

where L is characteristic plasma dimension, $B_\lambda(T)$ is the intensity of the blackbody radiation, $\kappa'(\lambda) = \kappa(\lambda)(1 - \exp(-hc/\lambda k_\mathrm{B}T))$ is the total absorption coefficient including the induced emission where $\kappa(\lambda) = \kappa_{\mathrm{line}} + \kappa_{\mathrm{ff}} + \kappa_{\mathrm{fb}}$. Expressions for the absorption coefficient of free–free radiation due to electron–ion collisions $\kappa^{\mathrm{ei}}_{\mathrm{ff}}$ can be found in [2] and for the absorption coefficient due to electron–atom collisions $\kappa^{\mathrm{ea}}_{\mathrm{ff}}$ in [7]. The average cross section for electron–atom collisions $\sigma_{\mathrm{ea}}(T)$ which appears in the expression for $\kappa^{\mathrm{ea}}_{\mathrm{ff}}$ is taken from [8]. It is easily seen that in the case of small absorption ($L \rightarrow 0$) the expression under the integral (Eq. 2) is the well known emission coefficient $\varepsilon(\lambda)$.

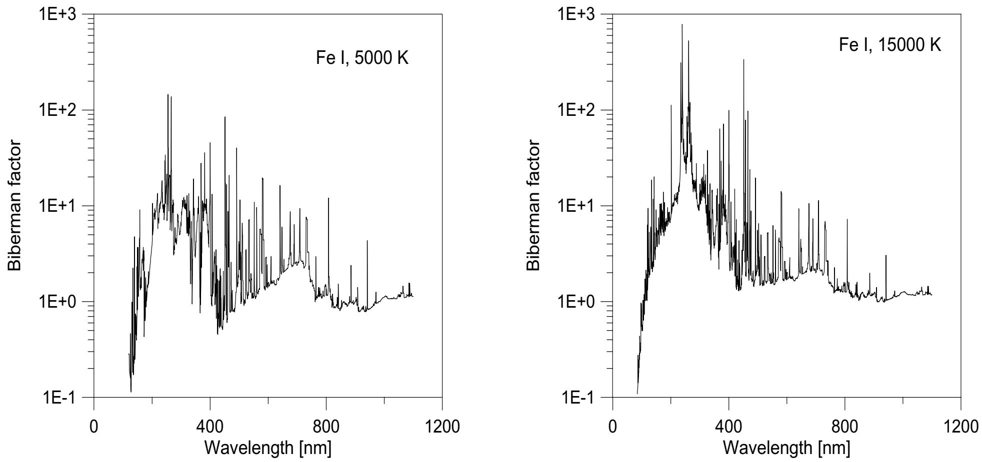

Fig. 1. Biberman factor ξ_{fb}^{z} for Fe I at temperatures of 5000 and 15000 K

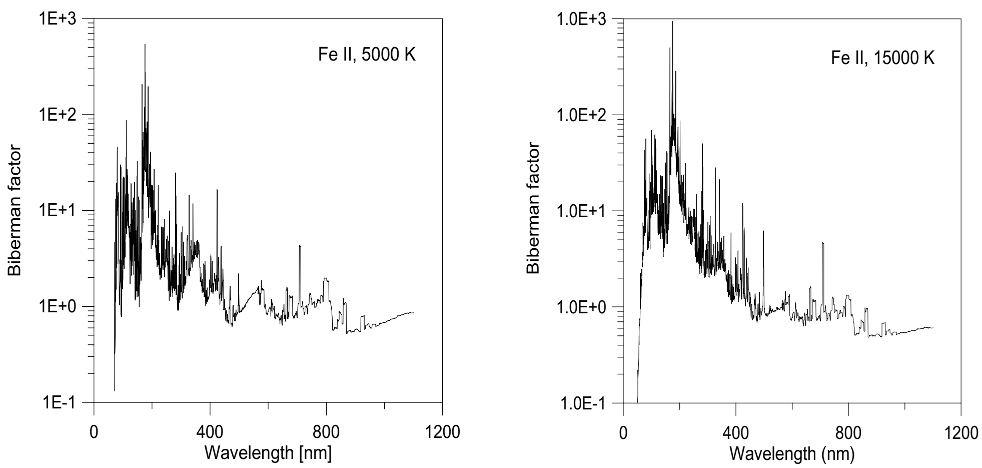

Fig. 2. Biberman factor ξ_{fb}^{z} for Fe II at temperatures of 5000 and 15000 K

Similarily for a homogeneous, isothermal, spherical plasma of diameter D

$$\varepsilon_N = \int_0^\infty B_\lambda(T)\kappa'(\lambda) f(\alpha) d\lambda, \tag{3}$$

where $\alpha = \kappa'(\lambda)D$ and function f is given by

$$f(\alpha) = \left((1+\alpha)\,\mathrm{e}^{-\alpha} - 1 + 0.5\alpha^2\right) 3\alpha^{-3} \tag{4}$$

(for $\alpha \to 0$ expansion $f(\alpha) = 1 - \alpha 3/8 + \ldots$ should be used instead).

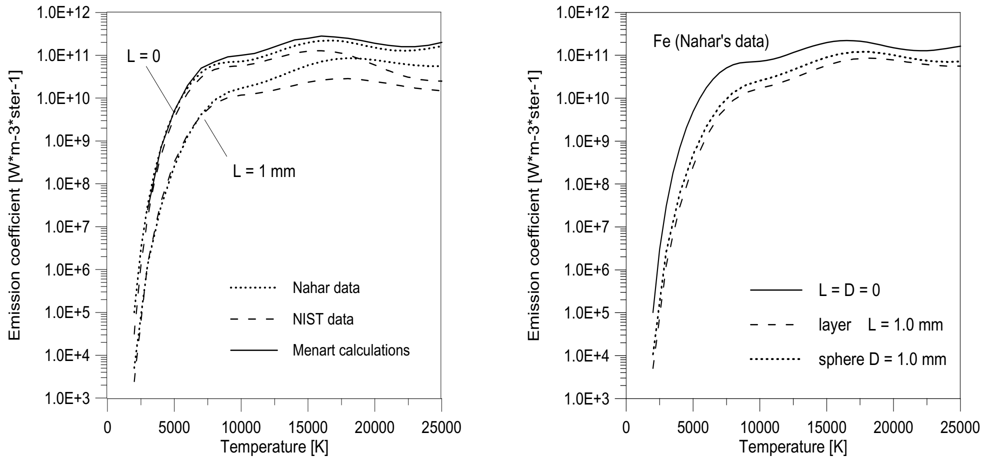

Fig. 3. Net emission coefficient of thermal iron plasma at 0.1 MPa

The calculations have been made for the region 800÷25000 Å. The plasma composition is calculated at the pressure of 0.1 MPa assuming the local thermodynamical equilibrium. The transition probabilities necessary to calculate the absorption of the iron lines are taken from [3, 4] (available in electronic form). They consist of 42934 transitions, 15096 Fe I transitions, 18448 Fe II transitions and 9390 Fe III transitions. The line profiles are assumed to be due to the Stark effect only and the broadening parametrs are taken from [9, 10]. Doppler broadening has been neglected. In view of uncertainties in the Stark broadening parameters it makes no sense to include correction to the line width, which is considerable only at a temperature of 4000 K. As a consequence the line profile is lorenzian and we do not have to calculate the Voigt function.

The continuous emission coefficients due to bremsstrahlung and recombination radiation do not exceed 4.5 percent of total radiation and can be neglected in approximate calculations.

The net emission coefficients of iron at various temperatures are shown in Fig. 3. The results obtained using the Nahar data have been compared with the results obtained using the experimental data from National Institute of Standard and Technology Database (NIST Atomic Spectra Database [11]) as well as with Menart and Malik calculations [12]. The agreement with the experimental data is very good. For example at the temperatures lower than 15 kK the total radiation power is only 20÷25 % higher than that obtained from the NIST data, which is comprehensible given that, contrary to the NIST data, the theoretical data include all transitions. At higher temperatures the discrepancies are larger because NIST data contains only few Fe III lines.

Since Menart and Malik calculations [12] cover a whole range of possible composition of Fe–Ar plasma at 0.1 MPa our results are shown for pure iron only for comparison (Fig. 3). More results are presented for Fe–He mixture (Figs. 4, 5). The transition probabilities of the helium neutral lines are taken from NIST database and the Stark broadening parameters from [**?**, 14]. The radiation of the helium ions is negligible at these temperatures.

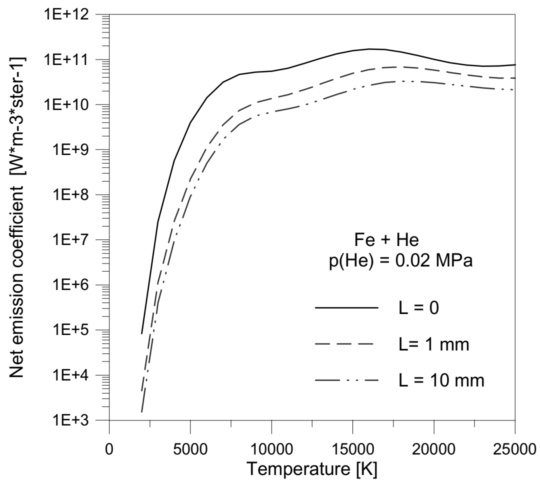

Fig. 4. Net emission coefficient of thermal Fe–He plasma at 0.1 MPa

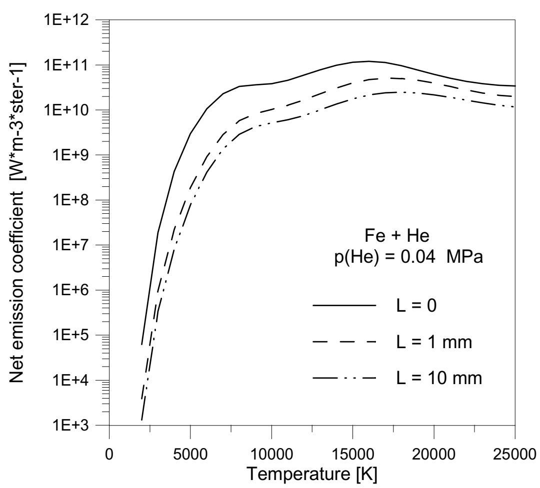

Fig. 5. Net emission coefficient of thermal Fe–He plasma at 0.1 MPa

The contribution of the helium radiation to the total radiation of Fe–He mixture is practically negligible; it reaches merely 5 % at 25 kK for helium partial pressure of 0.06 MPa. It is worth mentioning that the results for Fe–He plasma for temperatures lower than 20 kK are practically the same as the results for pure Fe plasma at the pressure equal to the partial pressure of iron in Fe–He mixture.

3 Summary

The Biberman factors and the net emission coefficients for iron plasma are presented. The results can be used for plasma diagnostics and to assess the models of interaction between laser radiation, plasma plume and material. For example the experiment shows that during welding with 2 kW CO_2 laser the absorption of the laser beam in the plasma plume amounts to 6 % which gives 120 W. According to our results (see Fig. 3b) similar spherical iron plasma with $D = 1$ mm radiates, in a full solid angle, 100÷200 W at temperatures of 8÷11 kK. Since most of the plasma radiation power is radiated back both results are in a good agreement.

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