NET EMISSION COEFFICIENTS OF RADIATION IN THERMAL PLASMAS OF AIR WITH CARBON ADMIXTURE

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Abstract. Net emission coefficients of radiation have been calculated for thermal plasmas of air with admixture of carbon as a function of plasma temperature and the arc radius at various plasma pressures. Net emission coefficients have been derived from calculated absorption coefficients. Calculations take into account continuum and line radiations of atomic and ionic species; attention has also been given to molecular species. Comparisons of net emission coefficients for various plasma mixtures of air and C have been presented.

1. INTRODUCTION

Radiation transfer is a main mechanism of energy balance in arc plasmas. Detailed information about the local arc structure can only be given by mathematical models, which allow the calculation of the distribution of emission and absorption throughout the entire arc plasma volume. Computationally convenient method of accounting of radiation transfer of energy in thermal plasmas is an approximate method of net emission coefficients of radiation defined by Lowke (1974). Application of the net emission coefficients to a prediction of energy balance gives good results for central arc temperatures, but it cannot predict accurate temperature profiles at low temperatures near the edge of the arc, because of the absorption of ultraviolet radiation emitted at the center of the arc at high temperatures. Despite of this fact, the method is widely used in computational flow dynamics.

2. THEORY

If light scattering is neglected and local thermodynamic equilibrium is assumed, the radiative transfer equation can be written

$$\vec{n} \cdot \nabla I_\nu(\vec{r}, \vec{n}) = \kappa_\nu (B_\nu - I_\nu) \qquad (1)$$

where I_ν is the spectral intensity of radiation, κ_ν is the absorption coefficient, B_ν is the black-body radiation, and $\vec{n}(\theta,\varphi)$ is the unit vector defining the radiation direction. The absorption coefficient is related to emission coefficient as $\kappa_\nu = \varepsilon_\nu / B_\nu$. The net emission of radiation in an isotropic medium is given by

$$\nabla \cdot \vec{F}_{R\nu} = 4\pi\varepsilon_{N\nu} = 4\pi(\varepsilon_\nu - J_\nu \kappa_\nu) \tag{2}$$

where J_ν and $\vec{F}_{R\nu}$ are, respectively, the mean radiation intensity and the radiation flux defined by

$$J_\nu = \frac{1}{4\pi}\int_0^{4\pi} I_\nu d\Omega \quad \text{and} \quad \vec{F}_{R\nu} = \int_0^{4\pi} I_\nu \vec{n}\, d\Omega \tag{3}$$

where $d\Omega$ is an element of solid angle. For an isothermal cylinder of radius R, the average spectral intensity J_ν is approximately the same as for the isothermal sphere of radius R, and is given by (Liebermann et al. (1976))

$$J_\nu = B_\nu[1 - \exp(-\kappa_\nu R)]. \tag{4}$$

On substituting J_ν from above Eq. (5) in Eq. (2), the net emission coefficient at the arc center is found to be

$$\varepsilon_N = \int_0^\infty B_\nu \kappa_\nu \exp(-\kappa_\nu R) d\nu . \tag{5}$$

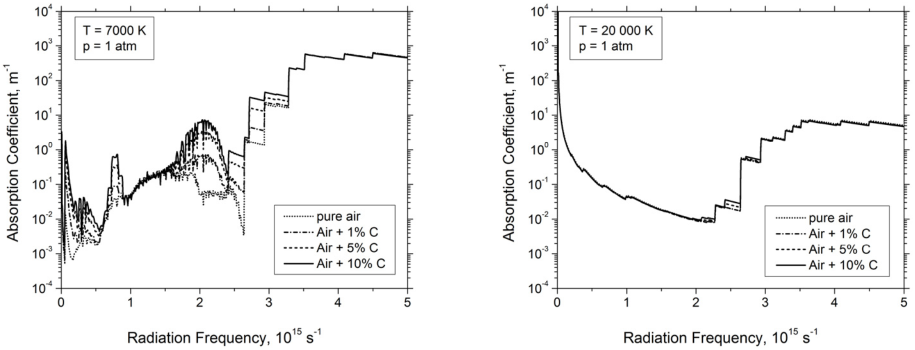
The isothermal net emission coefficient, ε_N, corresponds to the fraction of the total power per unit volume and per unit solid angle irradiated into the volume surrounding the arc axis and escaping from the arc column after crossing a thickness R of the isothermal plasma.

3. CALCULATIONS AND RESULTS

The calculation of the net emission coefficient is based on the knowledge of the plasma composition and subsequently absorption coefficients. An equilibrium composition of air plasma with various carbon concentrations was computed using *Tmdgas* computer code which is part of the database system *The Coufal*, created by Coufal (2005). We have taken into account atoms and up to triple ions of N, O, Ar, C elements, respectively, diatomic molecules O_2, O_2^+, N_2. N_2^+, NO, NO^+, CO, CO^+, CN, CN^+, C_2, C_2^+, C_2^-, and polyatomic molecules CO_2, NO_2, N_2O.

In calculation of absorption coefficients, one must deal both with continuous radiation made by photo-ionization and bremsstrahlung processes and discrete radiation which consists of hundreds of spectral lines. Spectral lines broadening and their complex shapes, together with the lines overlapping have been considered. Molecular band contributions to the total absorption must be taken into account for temperatures below 8 000 K. Calculation of absorption coefficients is explained in more details by Aubrecht et al. (2009).

Comparisons of calculated continuum absorption coefficients as a function of radiation frequency for various carbon admixtures (air, air with 1 vol%, 5 vol%, and 10 vol% of carbon, respectively) are shown in Fig. 1a) for the plasma temperature 7 000 K and in Fig. 1b) for temperature 20 000 K at atmospheric pressure. Molecular species contribute to the total absorption coefficients significantly at lower temperatures below 8 000 K at radiation frequencies up to $2.5x10^{15}$ s^{-1}. It can be seen from the figures that the absorption coefficient raises with increasing admixture of carbon.



(a) T = 7 000 K (b) T = 20 000 K

Figure 1: Continuum absorption coefficient for the air thermal plasma with admixtures of 1, 5 and 10 vol% of carbon at temperatures of 7 000 K and 20 000 K.

Fig. 2 shows the contribution of various carbon molecular species to the total absorption coefficient for the plasma system of air with 10 vol% of carbon for the plasma temperature 7 000 K at the atmospheric pressure. Among carbon molecular species, molecules CO and CN bring the greatest contribution to the absorption.

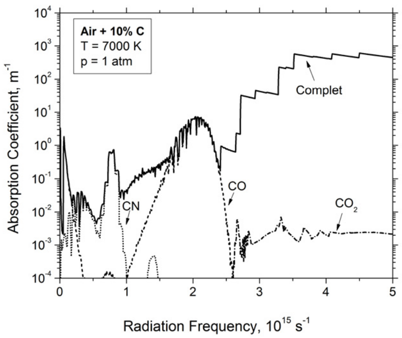


Figure 2: Contribution of various carbon molecular species to the continuum absorption coefficient for the thermal plasma of Air + 10 vol% C.

Effect of amount of carbon admixture on the net emission coefficients is shown in Fig. 3 for the radius of a plasma cylinder of 1 mm at the atmospheric pressure. The greatest influence of carbon admixtures occurs at the temperatures between 5 000 to 10 000 K, and is caused predominantly by molecules CO.

Examples of calculated temperature dependence of the net emission coefficients for various radii of a plasma cylinder of Air + 10 vol% C are presented in Fig. 4. Radius R = 0 corresponds to omitting of self-absorption of radiation. For temperatures below 6 000 K, almost all radiation is emitted from the plasma column. For higher temperatures, the strong effect of the plasma thickness can be seen.

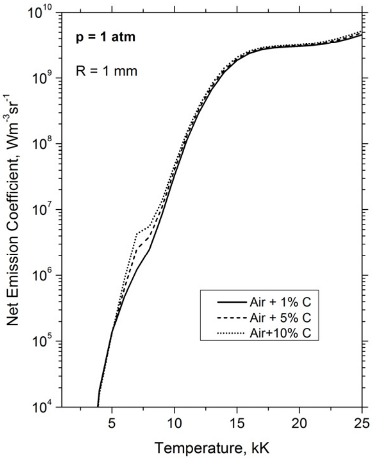


Figure 3: Net emission coefficient of air with various admixtures of carbon.

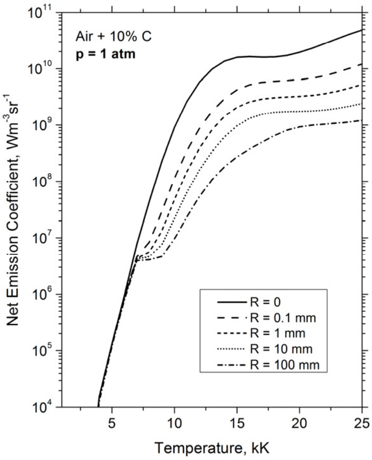


Figure 4: Net emission coefficient of Air + 10% C for various plasma radii.

4. CONCLUSIONS

In the paper we have presented results of the calculations of the net emission coefficients for thermal plasma of air with various admixtures of carbon. Increasing effect of carbon admixture to the net emission coefficients, especially in temperature range from 5 000 K to 10 000 K, is presented. Among carbon containing species, the greatest contribution to the net emission coefficient of pure air gives the molecule CO.

Acknowledgements

Authors gratefully acknowledge financial support from Ministry of Education under projects No. MSM0021630503 and CZ.1.05/2.1.00/01.0014.

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