NET EMISSION COEFFICIENT FOR THERMAL PLASMAS
in H_2, O_2, C, H_2O, CF_4 and CH_4

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ABSTRACT:
This communication deals with the calculation of the net emission coefficient in various gases or vapours in the temperature range between 5000 and 30 000 K at atmospheric pressure, assuming isothermal and LTE plasmas. The results show that the nature of the species has a great influence on the net emission coefficient, carbon being more emissive than oxygen and hydrogen. In spite of their strong self-absorption, resonance lines constitute in general the main contribution to the total net emission.

1 - INTRODUCTION

In several applications of plasma torches, the thermal plasma is created in molecular gases and in the hottest regions the molecules are dissociated. For modelling these plasmas or for calculating the energy balance, the radiative transfer is often required. In fact, in numerous cases, only the radiation losses from the hottest regions, taking into account the self-absorption within the plasma, is needed. This term can be estimated, with a good approximation if the temperature gradients (and the concentration gradients in case of gas mixtures) are not very sharp, by computing a net emission coefficient for an isothermal and homogeneous plasma. This term corresponds to the difference between the power radiated by a unit volume and the radiation proceeding from other regions of the plasma and absorbed in this unit volume.

In this communication we present the calculation of the net emission coefficient, ε_N, in thermal plasmas of carbon, hydrogen, oxygen, water, methane and carbon tetrafluoride, at atmospheric pressure, in the temperature range between 5 000 K and 30 000 K. For these values of temperature the molecules are dissociated and we consider that the plasma is in local thermodynamic equilibrium (LTE). This coefficient is also function of the plasma thickness which is represented by the radius of a cylindrical and isothermal plasma. All the particle number densities needed in the general calculations have been computed assuming the equilibrium composition of the plasma for given values of pressure and temperature.

2 - CALCULATION METHOD

The bases of the calculation were described previously for other gases or mixtures of gases [1]. For a spherical isothermal plasma of radius R_p, ε_N is defined by :

$$\varepsilon_N = \int_0^\infty K'_\nu B_\nu \exp\left(-K'_\nu R_p\right) d\nu \qquad (1)$$

where K' is the absorption coefficient corrected by induced emission. In a non-spherical plasma R_p may be considered as a plasma thickness. For a cylindrical plasma relation (1) is a rather good approximation considering R_p as the radius.

In relation (1) K' represents the total absorption coefficient, which means the sum of the continuum coefficient and the coefficient due to the lines. For the continuum coefficient, radiative recombination, bremsstralhung and radiative attachment are taken into account with usual relationships [1]. The main contribution to the continuum is due to radiative recombination with the following emission coefficient (the absorption coefficient may be deduced from Kirchhoff's law which is valid under the assumption of LTE) :

$$\varepsilon_\nu = C \frac{N_e N_i}{U_i} \frac{z^2}{\sqrt{T}} \left[1 - \exp\left(-\frac{h\nu}{kT}\right)\right] g_1 \xi \qquad (2)$$

with $C = 5.44 \ 10^{-52} \ Jm^{-3}sr^{-1}K^{-1}$, N_e the electron number density, N_i and z the density and charge of the considered ions, T the temperature, U_i and g_1 the partition function and the ground state statistical weight of the ion. ξ is the Biberman-Schlüter factor accounting for the non-hydrogenic structure of the ion (or atom) of charge (z-1). For oxygen and carbon, the ξ -factor has been calculated by Hofsaess [2].

The treatment of the self-absorbed lines is difficult because it needs to calculate the line profiles. The line emission coefficient is given by:

$$\varepsilon_1 = \frac{\pi e^2}{m_0 c} f_a N_u P(\nu) \qquad (3)$$

where f_a is the absorption oscillator strength, N_u the number density of the upper level of the transition and $P(\nu)$ the normalized line profile which depends on the following broadening mechanisms [3-4] :
- Doppler effect leading to a Gaussian profile;
- pressure effects when the radiating particle is perturbed by a neutral atom. We take into account resonance and Van der Waals effects;
- Stark effect when the interaction of the emitter atom occurs with charged particles. Except for hydrogen, we use the relations given by Traving [3] based on impact theory (quadratic effect, adiabatic polarization and quadripole contribution) and corrected by Griem [4] to take into account ion effects. For hydrogen, where Stark effect is linear, tabulated values of line profiles based on impact approximation near the line center and on quasi-static theory in the line wings [5] are used.

We assume that pressure and quadratic Stark effects give Lorentzian profiles so that all the profiles but those of hydrogen lines, are Voigt profiles. Line shift is not considered here because the plasma is homogeneous and isothermal. It is also assumed that line overlapping has a negligible effect on radiative transfer. So, for each line we

define an escape factor Λ_{ul} as the ratio of the radiation escaping from the plasma to the radiation of a completely transparent plasma [6]. In the case of a Voigt profile Λ_{ul} depends on two parameters: the monochromatic optical depth and the ratio of the Gaussian to the Lorentzian broadenings. For hydrogen Lyman lines, the escape factor has been calculated from the profiles given by Vidal et al [5] as a function of temperature and electron number density.

3 - RESULTS FOR ONE-ELEMENT GAS OR VAPOUR

The total net emission coefficient ε_N calculated with relation (1) is composed of three components: the continuum; the resonance lines which are partially self-absorbed within the plasma; the other lines which are not absorbed. Among the results, we can calculate the total emission coefficient corresponding to the fictitious case of a completely transparent medium, putting $R_p = 0$ in Eq. (1). Whatever the considered gas or vapour, the emission coefficient computed for $R_p = 0$ is essentially due to the resonance lines. All the results presented here correspond to a pressure of 10^5 Pa; other results show that the net emission coefficient is roughly proportional to the pressure.

The influence of the plasma thickness R_p on ε_N is shown in figure 1 for a pure carbon plasma. We can observe a strong absorption of radiation with a plasma thickness of a few mm, leading to a decrease of one order of magnitude of the emission coefficient between 0 and 2 mm. This phenomenon is due for a small part to the absorption of the UV continuum, and mainly to the absorption of resonance lines. Nevertheless, we can see in figure 2 that, in spite of their strong absorption, the resonance lines remain the major contribution to the net emission coefficient in real carbon plasmas, at temperature higher than 7 000 K. At lower temperature the three components play a similar role which is not always the case for other gases or vapours.
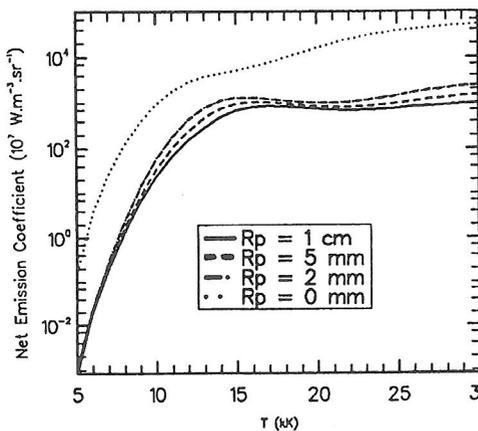

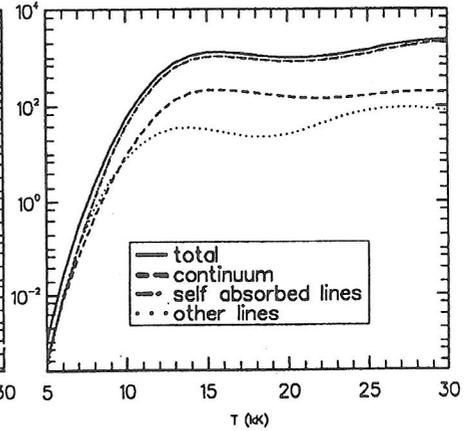Fig.1: Influence of R_p on carbon emission

Fig.2: Components of the net coefficient for carbon ($R_p = 2$ mm)

Some results relative to hydrogen plasmas are given in <u>figure 3</u>. The peculiarity of hydrogen in this study, is that the variations of ε_N versus temperature presents a maximum between 15 000 and 19 000 K when R_p varies from 0 to 1 cm. The monotonous decrease of ε_N at high temperature is explained by two facts: there is no H^+ line; the total particle number density decreases when temperature increases because of the constant pressure.

Finally, the comparison of the net emission coefficients calculated respectively for carbon, oxygen and hydrogen, at atmospheric pressure and for $R_p = 5$ mm, is shown in figure 4. Carbon is much more emissive than oxygen and hydrogen because of the electronic structure of this species having low excitation and ionisation potentials. This structure leads, first, to rather high values of the electron number density at low temperature (T < 10 000 K) in comparison with the compositions of H_2 or O_2 plasmas, and second, to an important line spectrum.
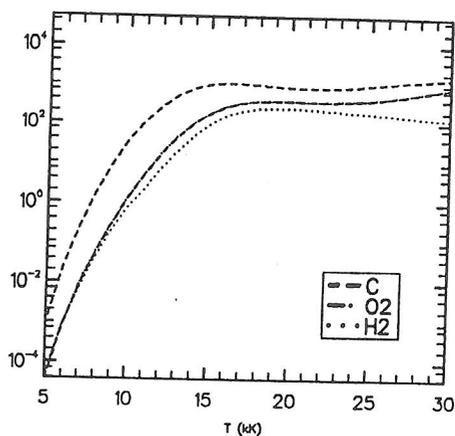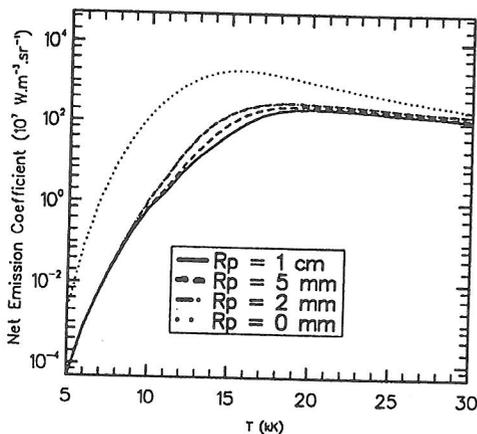
<u>Fig.3</u>: Influence of R_p on the net emission of hydrogen

<u>Fig.4</u>: Comparison of ε_N for C, O_2 and H_2, at $R_p = 5$ mm

4 - RESULTS FOR TWO-ELEMENT GAS OR VAPOUR

We consider here the radiation emitted by thermal plasmas established in H_2O, CH_4 or CF_4. First of all, it is interesting to compare the net emission coefficient of a water plasma with those of pure oxygen or hydrogen. These variations are drawn in figures 5 and 6 for $R_p = 0$ (optically thin plasma for all radiations) and $R_p = 2$ mm. At $R_p = 0$, the emission coefficient of water follows that of hydrogen when T < 15 000 K, because of the strong emission of Lyman lines, whereas it is more influenced by oxygen at higher temperatures (the absence of H^+ lines decreases the radiation of hydrogen in the high temperature range). Note that the emission of water is not systematically intermediate between those of pure hydrogen and oxygen. At $R_p = 2$ mm (Fig. 6), we can see that the net emission coefficient of water is very close to that of pure oxygen. This is mainly due to the strong absorption of the hydrogen Lyman lines.
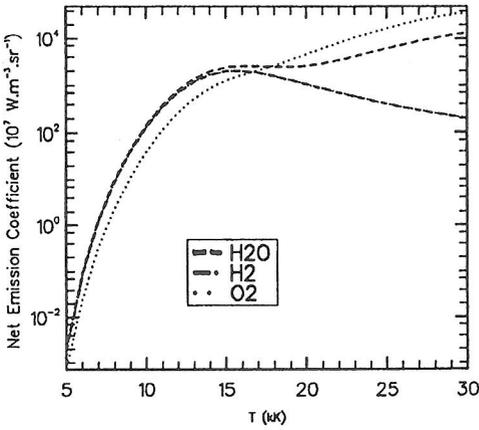
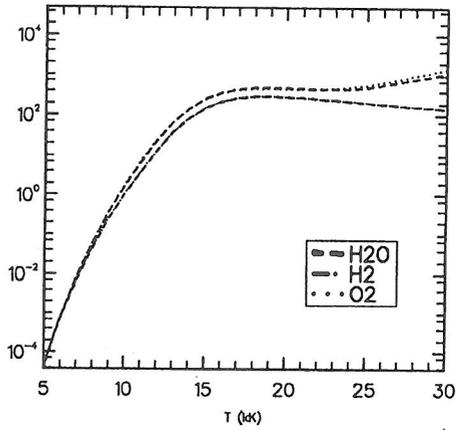**Fig.5**: Emission coefficient for H_2O, O_2 and H_2, for $R_p = 0$

Fig.6: Net emission coefficient for H_2O, O_2 and H_2 ($R_p = 2$ mm)

The same kind of results has been obtained comparing the net emission coefficients of methan, hydrogen and carbon, shown in figures 7 and 8, for respectively $R_p = 0$ and 2 mm.
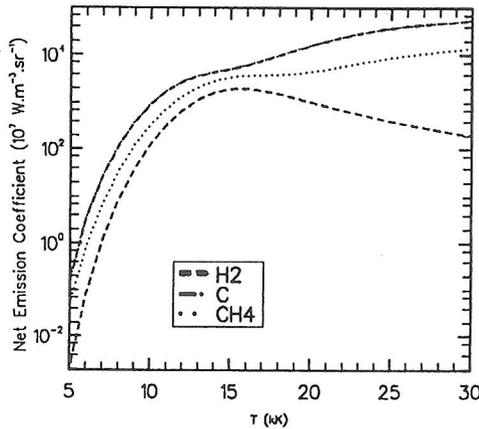

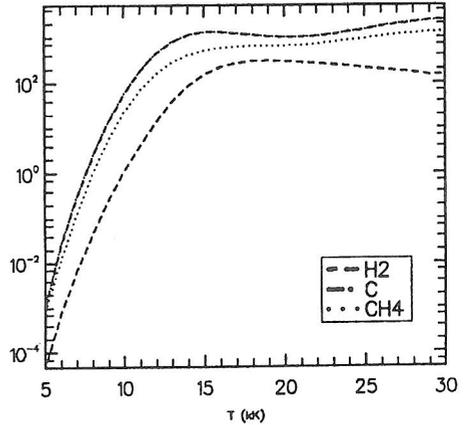**Fig.7**: Emission coefficient for CH_4, C and H_2, for $R_p = 0$

Fig.8: Net emission coefficient for CH_4, C and H_2 ($R_p = 2$ mm)

In this last case, carbon is much more emissive than hydrogen (Fig.7) so that for $R_p = 0$, the emission of CH_4 is mainly due to carbon. The difference between C and CH_4 corresponds to the partial pressure of carbon. The attenuation of ε_N between carbon and CH_4 is lower for $R_p = 2$ mm than in an optically thin plasma. This fact is caused by the decrease of carbon resonance lines absorption between both cases.

Finally we present in figure 9 the variations of the net emission coefficient of H_2O, CH_4 and CF_4, for $R_p = 5$ mm. When T < 15 000 K ε_N for CH_4 and CF_4 are very similar because of the presence of carbon. At high temperature the three plasmas have more or less the same net emissivity because the medium is almost fully ionised.
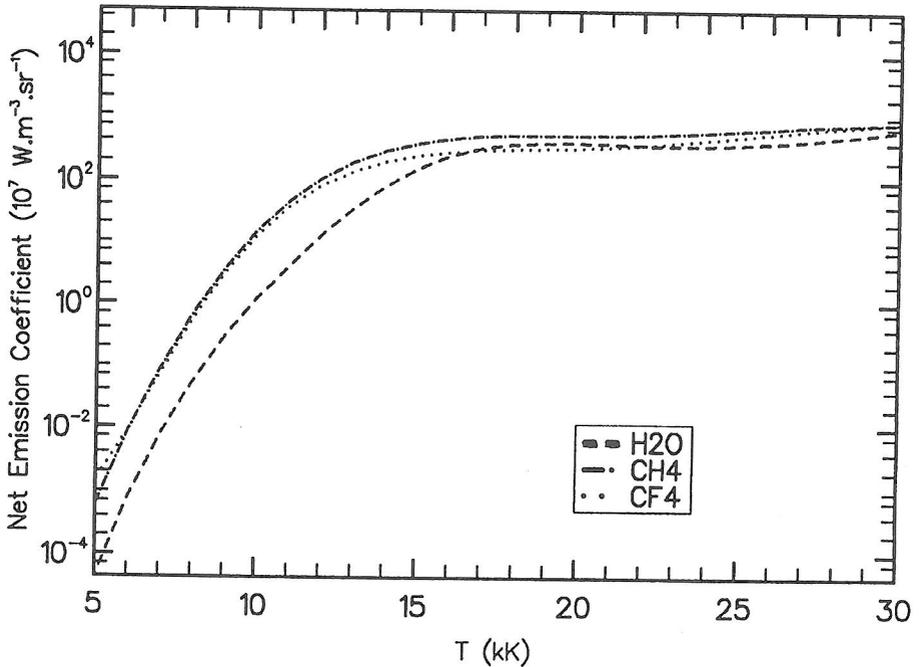

Fig.9: Net emission coefficient for H_2O, CH_4 and CF_4, for $R_p = 5$ mm

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