Radiative properties of SF_6-C_2F_4-Cu mixtures in High Voltage Circuit Breakers Arc Plasmas: Net Emission Coefficient and mixing rules.

L. HERMETTE[1,2], Y. CRESSAULT[1*], A. GLEIZES[1] , C. JAN[1,2] and K. BOUSOLTANE[2]

[1]Université de Toulouse; UPS, INPT, CNRS; LAPLACE (Laboratoire
Plasma et Conversion d'Energie), 118 route de Narbonne, F-31062
Toulouse cedex 9, France
[2]SIEMENS T&D E T HP GS R&D D G R1, 1 rue de la Neva, BP 178
38004 Grenoble, France
Corresponding author's e-mail: cressault@laplace.univ-tlse.fr

ABSTRACT

In this paper, we tried to estimate the radiative properties of SF_6-C_2F_4-Cu thermal plasmas existing in High Voltage Circuit Breakers (HVBV). The calculation was realized assuming the Local Thermodynamic Equilibrium (LTE), binary and ternary mixtures with mass concentrations, temperatures from 300K to 30 000K and pressures of 1 bar and 8 bar. Two methods were used to estimate these properties: the Net Emission Coefficient (NEC) by neglecting the lines overlapping and the mixing rules using either the NECs of the pure gases or the NECs of a given SF_6-C_2F_4 mixture and of pure Cu plasma. Some results are proposed and discussed. The tone of the conclusion is that the linear interpolation seems to be a good approximation for low pressure and high temperatures.

1. INTRODUCTION

High Voltage Circuit Breakers (HVCB) play an important role in the power delivery. Its function is to disconnect High Voltage lines in the case of fault current. This disconnection is characterized by the creation of an electric arc between two separated contacts. The physical phenomena are very complex since electric arcs involve high temperatures, high current, magnetic forces, electric field, radiative energy transfer, compressible flows and solid material ablation. The radiative energy plays an important role in HVCB through three main effects: cooling down the hottest regions; heating of the surrounding regions; ablation of the walls in PTFE (C_2F_4) and of the electrodes (Cu). Thus, we are in presence of SF_6-C_2F_4-Cu plasma. In our team, many works have already been done on HVCB with pure SF_6 [1] or SF_6-C_2F_4 [2] mixtures. Consequently, this work is the logical continuity with the consideration of copper. Several methods are available in the literature to characterize the radiation losses in the plasma. The Net Emission Coefficient (NEC) is one of them [3] and is often used in numerical modelling to calculate directly the divergence of the radiative flux $\vec{\nabla} q = 4\pi \cdot \varepsilon_N(T)$ in the case of pure plasma or binary mixtures [4]. Few numerical modelling consider the presence of the copper metallic vapours in the SF_6-C_2F_4 mixtures for different reasons: the software are not adapted to treat ternary mixtures; Author may assume that copper, in small concentration in the plasma, can be neglected during the Current Zero phase; the databank is too significant and difficult to implement in the model due to the numerous parameters (temperature, pressure, composition, size of plasma). Another solution is then to make use of mixing rules to calculate the properties of such plasmas [5]. This method is less accurate but simpler to implement and faster to execute in the simulations.

The first part of this paper is devoted to the calculation of the total atomic and molecular radiation. This calculation was performed for binary and ternary plasmas, pressures of 1bar and 8bar, temperatures between 300K and 30kK, different mass concentrations, and assuming the LTE. These properties were estimated using the method of the NEC assuming spherical, isothermal and homogeneous plasma. In order to reduce the simulation time, we neglected the lines overlapping. Nevertheless, a comparison is proposed between the NECs obtained with a fine description of the spectrum and with the use of the escape factor. The second part focuses on the mixing rules and their validity in the case of ternary mixtures. Different tests are proposed using either the NECs of the pure gases or a combination of a SF_6-C_2F_4 mixture with the NEC of pure copper plasma.

2. CALCULATION OF NET EMISSION COEFFICIENT

The NEC represents the radiative power emitted per volume unit and solid angle. For spherical geometry, the NEC is given by [3]:

$$\varepsilon_N(T) = \int_0^\infty L^0_\lambda(T).K'_\lambda(T).e^{K'_\lambda(T).R_p}.d\lambda \qquad (1)$$

where λ (m) is the wavelength, T is the local temperature, L^0_λ (W/m²/sr/m) is the Planck function, R_p is the radius of the sphere assimilated to the plasma's size and K'_λ (m^{-1}) the monochromatic absorption coefficient corrected by the induced emission and correlated with the local emission coefficient by the Kirchhoff law.

According to the equation (1), the determination of the NEC required an accurate description of the total absorption coefficient K'_λ or emission coefficient ε_λ, which is the sum of four basic emissions: the spectral emission coefficient $\varepsilon_\lambda^{line}$ for the lines emission, the free-bound emission $\varepsilon_{f\text{-}b,\lambda}$, the free-free emission $\varepsilon_{f\text{-}f,\lambda}$ and the molecular continuum emission $\varepsilon_{mol\text{-}cont,\lambda}$. The emission of the molecular bands was neglected in this work.

$$\varepsilon_\lambda = \varepsilon_\lambda^{line} + \varepsilon_{f-b,\lambda} + \varepsilon_{f-f,\lambda} + \varepsilon_{cont-mol,\lambda} \qquad (2)$$

The atomic continuum radiation was thoroughly studied in previous papers referenced in [4]. The main characteristics of the total continuum are the radiative recombination and the molecular continuum which can play an important role at low and intermediate temperature if the molecular densities are predominant. In a previous work, Jan [2] selected the main molecular species (C_2, C_2F_4, SF, SF_3) that appear in a SF_6-C_2F_4 plasma. For SF_6-C_2F_4-Cu plasmas, we completed his data with the main molecules containing copper (Cu_2, CuF and CuF_2).

As the properties of the ternary mixtures can constitute a big database, the lines emission was taken into account using the escape factor approximation. This factor Λ is defined by the ratio between the radiative flux escaping isothermal plasmas of thickness R_p with the consideration of the absorption and of the radiative flux without absorption (optically thin plasma). It tends to overestimate the radiation whose values are however acceptable (particularly at atmospheric pressure, the effect of line overlapping increasing with the pressure) assuming the precision of the method [1,2]. The factor is equal to 1 if the lines are not absorbed and 0 if the lines are totally self-absorbed. According to Drawin and Emard [6], this factor was previously computed as a function of optical depths and broadening phenomena. The Net Emission Coefficient for a line is given by:

$$\varepsilon_\lambda^{line}(T,R_p) = C_1\cdot L^o_\lambda(T)\cdot f_{ul}\cdot n_u(T)\cdot\Lambda_{line}(R_p)\cdot\left(1-\exp\frac{-hc}{\lambda k_b T}\right) \qquad (3)$$

where $c1 = \left(\frac{e^2}{4\pi\varepsilon_o}\right)\cdot\left(\frac{\pi}{m_e c}\right)$, Λ_{line} and f_{ul} are the escape factor and the oscillator strength for a transition between the upper level and the lower level, n_u is the number density of the upper level. The energy levels tabulated in NIST [7] and Kurucz [8] were used for all atoms and ions.

To estimate the accuracy of this approximation, the NECs obtained for 50%SF_6-50%C_2F_4 mixture at 1bar and 8bar are proposed in Figures 1 and 2. The full line represents the result obtained using the escape factor whereas the dashed line corresponds to the NEC obtained with a very fine description of the spectrum described by 300 000 wavelength points [1].

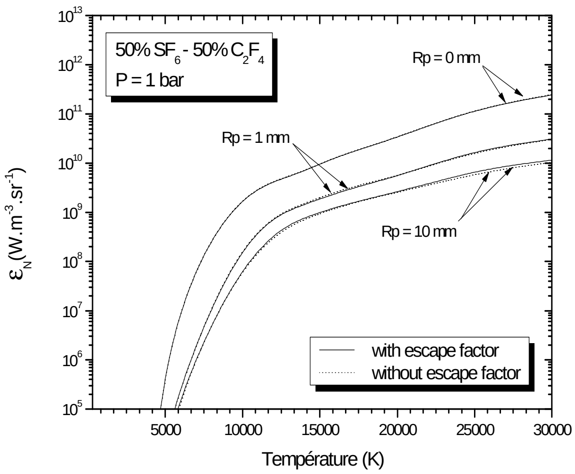


Fig. 1 Influence of lines' overlapping on the NEC for 50%SF_6-50%C_2F_4 plasma at 1 bar

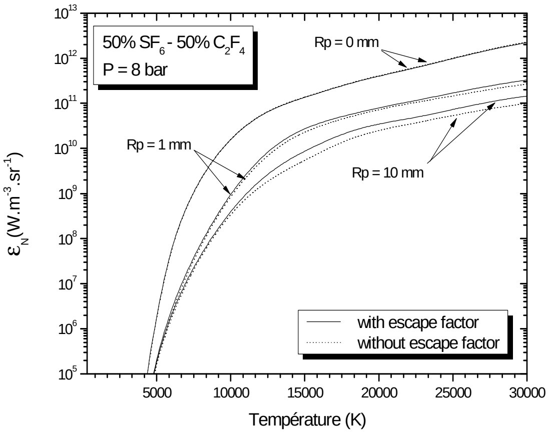


Fig. 2 Influence of lines' overlapping on the NEC for 50%SF_6-50%C_2F_4 plasma at 8 bar

We can observe that lines' overlapping is very small at low pressure but that it may reach 60% of the NEC at 8bar. This behaviour is due to the fact that several lines are very close from one another and that the temperature and/or the pressure increase tend to broaden the lines and favour their overlapping.

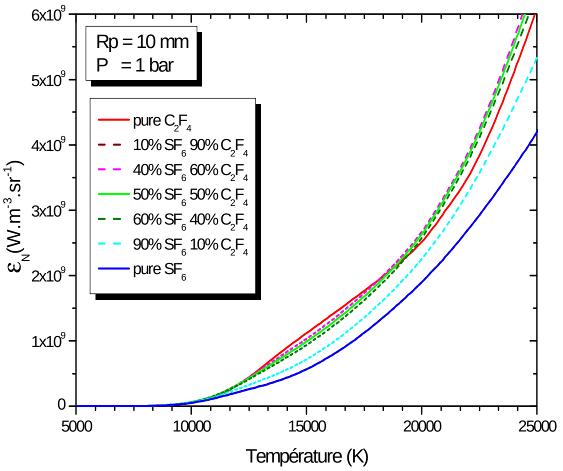


Fig.3 NECs for SF_6-C_2F_4 mixtures at 1bar and R_p=10mm

In a second time, we compared the NECs of SF_6-C_2F_4 for different mass proportions, a pressure of 1bar and a size of plasma equal to R_p=10mm. In the figure 3, the first surprising result concerns the mixtures which can present higher values than those of the pure gases. Then, we can notice that no clear difference appears for temperatures lower than 10kK. Finally, for a given temperature, we can also observe that the maximal value, corresponding to a given mixture, is at most the double of the lowest. This tendency does not really change with the parameter R_p. Since an uncertainty of a factor of 2 on the NEC is considered as acceptable, we decided to use the 50%SF_6-50%C_2F_4 mixture to test the validity of the mixing rules. Pure C_2F_4 or pure SF_6 were also a possibility but we wanted a mixture which could represent the various regions of the plasma: sometimes only consisted of SF_6, sometimes only of C_2F_4, sometimes of a SF_6-C_2F_4 mixture.

3. MIXING RULES

It is difficult to find efficient mixing rules when metallic vapours are present in the plasma. Indeed, the presence of copper vapours, in general, has a significant influence on the NEC, particularly at low and intermediate temperature [4]. In a previous work, Gleizes et al [5] tested several laws on different properties (NEC, mass density, viscosity, thermal conductivity and electrical conductivity). For the radiation properties, they mentioned two points in their conclusions: a linear interpolation with molar proportions is satisfactory for high temperatures (T>12kK); some tendencies have been detected at lower temperatures but mixing rules are rather complicated when metallic vapours exist. In this part, we thus propose two mixture laws. The first one, called "ternary", tries to estimate the NEC of a ternary mixture from the NECs of the pure gases:

$$\varepsilon_N^{\alpha SF_6-\beta C_2F_4-\gamma Cu} = \alpha.\varepsilon_N^{SF_6} + \beta.\varepsilon_N^{C_2F_4} + \gamma.\varepsilon_N^{Cu} \quad (4)$$

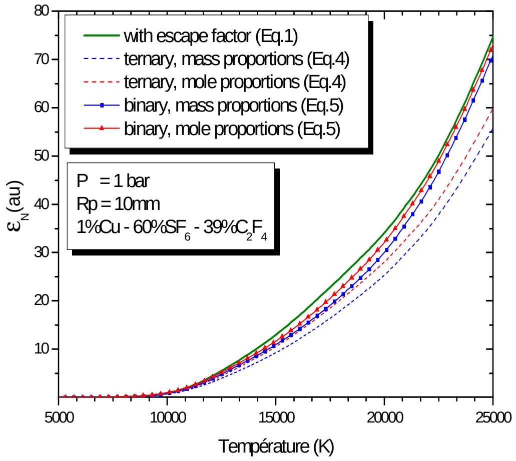
The second one, called "binary", is based upon the results presented in §2, i.e. on the NEC of the 50%SF_6-50%C_2F_4 mixture (in molar proportion for molar interpolation and in mass proportion for mass interpolation) and the NEC of the pure copper plasma:

$$\varepsilon_N^{\alpha SF_6-\beta C_2F_4-\gamma Cu} = (\alpha+\beta)\varepsilon_N^{50\%SF_6-50\%C_2F_4} + \gamma.\varepsilon_N^{Cu}$$

(5)

α, β and γ represent the mass or molar proportion of the mixture.

Figure 3 compares the relative evolution of the NEC for two given SF_6-C_2F_4-Cu mixtures according relation (1) and the results obtained using the mixing rules (eq.4-5). The legend 'mole' and 'mass' correspond to linear interpolation of the NEC following molar and mass proportions respectively. For a small concentration of metallic vapours (1%), all the approximations give lower values compared to the NEC obtained using the escape factor. The relation (5) with molar proportions seems to be the best mixture law for a pressure of 1 bar. For a higher concentration of copper (30%Cu), the same relation tends to overestimate the NEC, more than the relation (4) with molar proportions.



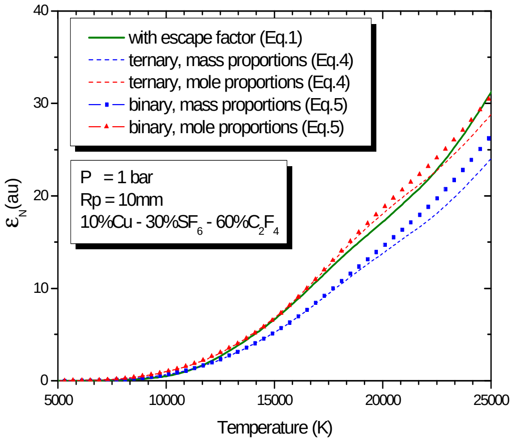


Fig. 4 Simple interpolation laws for the NEC of SF_6-C_2F_4-Cu

4. CONCLUSION

In this paper, we studied the radiative properties of SF_6-C_2F_4-Cu plasmas using the method of the Net Emission Coefficient. In a numerical model, the implementation of these data requires long simulation times and great storage capacities. Consequently, we presented in this paper two mixing rules to simplify the usage of the NEC in the HVCB simulation.

First, we showed that lines' overlapping could lead to significant differences for the high pressures. In order to evaluate correctly the accuracy of the mixing rules, it will be necessary to develop an exact calculation of the NEC for the ternary mixtures SF_6-C_2F_4-Cu.

Then, we showed that the NECs of binary mixtures SF_6-C_2F_4 did not radically change with the proportion of C_2F_4. This behaviour must be studied at higher pressures.

Finally, the last part devoted to the mixing rules highlighted that "binary" interpolation with molar proportions was the best mixing rule to quickly estimate the NEC of a ternary mixture. This law must be tested at higher pressures, higher temperatures, and higher sizes of plasma. New sophisticated laws based on the works of Gleizes et al [5] have to be developed and tested in the future.

AKNOWLEDGEMENT

Partial financing of this work by Siemens Company is acknowledged.

REFERENCE

[1] H.Z. Randrianandraina, Y. Cressault and A. Gleizes, "Improvements of radiative transfer for SF_6 thermal plasmas", J. Phys. D: Appl. Phys., 44, 194012, 2011

[2] C. Jan, Y. Cressault, A. Gleizes and K. Bousoltane, "Calculation of radiative properties of SF_6–C_2F_4 thermal plasmas-application to radiative transfer in high-voltage circuit breakers modelling", J. Phys. D: Appl. Phys., 47, 015204, 2014

[3] J.J. Lowke, "Predictions of arc temperature profiles using approximate emission coefficients for radiation losses", J.Q.S.R.T., 14,111, 1974

[4] Y. Cressault and A. Gleizes, "Thermal plasma properties for Ar–Al, Ar–Fe and Ar–Cu mixtures used in welding plasmas processes: I. Net emission coefficients at atmospheric pressure", J. Phys. D: Appl. Phys., 46, 415206, 2013

[5] A. Gleizes, Y. Cressault and Ph. Teulet, "Mixing rules for thermal plasma properties in mixtures of argon, air and metallic vapours", Plasma Sources Sci. Technol., 19, 055013, 2010

[6] H.W. Drawin, F. Emard, "Optical Escape Factors for Bound-bound and Free-bound Radiation from Plasmas ", Beitr Plasma Physik, 13, 143, 1973

[7] http://www.nist.gov/pml/data/asd.cfm

[8] P. L. Smith, C. Heise, J. R. Esmond, R. L. Kurucz, www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html