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Temperature variations in an SF₆-N₂ mixture arc plasma

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Résumé. — Nous présentons des mesures de température axiale T_0 d'un arc brûlant dans les mélanges SF₆-N₂, en fonction de l'intensité du courant. Suivant la proportion de SF₆ dans le mélange, les courbes de variation de la température en fonction du courant se croisent pour une valeur de 50 A environ correspondant à une valeur de température de 12 000 K environ. De plus, pour un courant supérieur à 50 A, les valeurs de T_0 dans un mélange contenant 20 % de SF₆ sont inférieures à celles obtenues pour tous les autres mélanges (de 10 à 100 % de SF₆). Ces propriétés ont été confirmées par une modélisation supposant l'équilibre thermique et s'expliquent en analysant le bilan d'énergie. A fort courant ce sont les arcs dont les pertes radiatives sont les plus importantes qui possèdent un plus fort champ électrique et une plus faible température axiale : dans l'azote T_0 est plus faible que dans le SF₆. Le comportement des arcs non dominés par le rayonnement est plus complexe ; il dépend des variations des conductivités électrique et thermique en fonction de la température. Il en résulte dans certains cas que la valeur de la température dans un mélange n'est pas intermédiaire entre celles obtenues dans les gaz purs constituants ce mélange.

Abstract. — We present measurements of the axial temperature T_0 in an arc burning in SF₆-N₂ mixtures, as a function of current intensity I . The $T - I$ curves with SF₆ proportion in the mixture as a parameter intersect for a current value of about 50 A, corresponding to a temperature around 12 000 K. In addition, for currents above 50 A, the values of T_0 in a 20 % SF₆ mixture are lower than those obtained with all other SF₆ proportions in the range 10 to 100 %. These properties are confirmed by a modeling work assuming thermal equilibrium ; they can be explained in terms of energy balance. At high current the arcs having the highest radiative losses exhibit the highest electric field and the lowest axial temperature : T_0 is lower in nitrogen than in SF₆. The behaviour of non radiation dominated arcs is more complex and depends on the variations of electrical and thermal conductivities with temperature. In certain cases this results in that the temperature values in a mixture are not intermediate to those obtained in the pure gases constituting the mixture.

1. Introduction.

The properties of thermal plasmas obtained from gas mixtures have been the object of extensive theoretical studies in recent years. These studies mainly concern the computation of the thermodynamic properties and the transport coefficients ; for plasmas in local thermodynamic equilibrium (LTE) a bibliographical review is given in reference [1], and we have recently published the results of a calculation in the case of SF₆-N₂ plasmas [2]. The choice of this type of mixture is determined by technological applications : under severe weather conditions the pressurized SF₆ contained in circuit-breakers may partially liquefy. The replacement of pure SF₆ by gas mixtures in general and by SF₆-N₂ mixtures in particular has been considered a possible solution to this problem.

The experimental study of these mixed plasmas, except for the case of air, has been less extensively studied. We present here the results of temperature measurements in a steady state arc plasma burning in an SF₆-N₂ mixture. This experimental study is coupled with a modeling of the arc plasma. From the particular characteristics measured and calculated in SF₆-N₂ mixtures a general analysis of the behaviour of stationary arcs as a function of the thermodynamic properties of the plasma gas will be proposed.

2. Experimental study.

2.1 THE SET-UP. — A wall stabilized arc of Maecker type has been used. The arc chamber is constituted by a stack of 8 water cooled copper disks separated by bakelite rings. The discharge channel is 4 mm in

diameter. The two tungsten electrodes at both ends of the channel are slightly shifted from the axis to allow end-on measurements (Fig. 1a). The gas mixture under study ($\text{SF}_6\text{-N}_2$) is injected in the central zone of the chamber and the electrodes are shielded by an argon flow. The pressure is atmospheric. Figure 1b shows a stabilizing disk with gas and water paths.

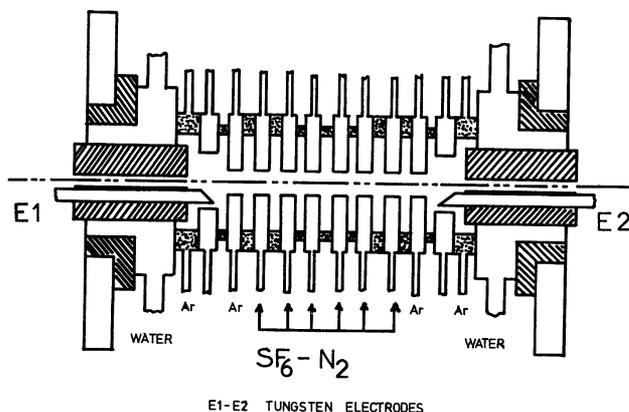


Fig. 1a. — Schema of the arc chamber.

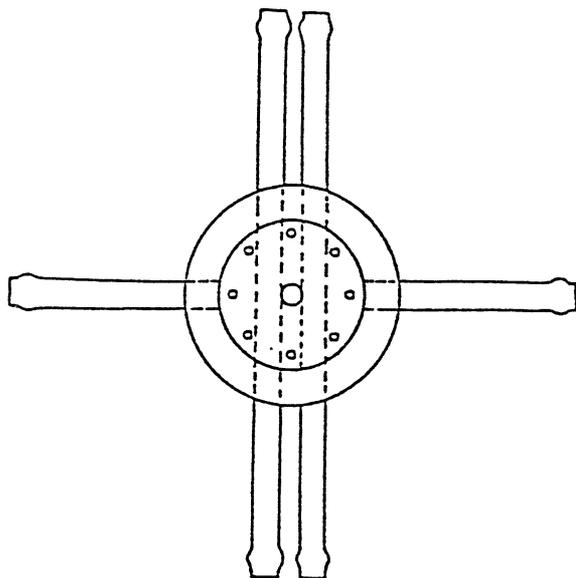


Fig. 1b. — Schema of a stabilizing disk.

We use 3 stabilized power supplies delivering a total current of 100 A and a total voltage of 350 V operating in current regulation mode. The voltage is applied through a ballast resistor of about 3 Ω . When the discharge is stable, the voltage fluctuations are lower than 1 %.

For the spectroscopic measurements the optical system provides a magnification of 1. The monochromator of focal distance 1 m has 1 200 grooves/mm grating, giving a linear dispersion of 8.3 $\text{\AA}/\text{mm}$. To

measure the line intensities the exit slit is open so as to select a spectral interval wider than the total line width. The adjacent continuum radiation is then measured and subtracted.

In the case of end-on measurements, the precise determination of the plasma length is necessary. This has been carried out by measuring the total intensity of the non-absorbed SI triplet at 469.5 nm for different chamber lengths (obtained by changing the number of water cooled disks), at constant arc current.

In the case of side-on measurements, the absence of argon in the central zone was spectroscopically checked. The calibration used a tungsten ribbon lamp.

2.2 EXPERIMENTAL METHOD. — In SF_6 plasmas the departures from equilibrium composition are mainly due to the demixing effect [3-4]. This arises from the combination of diffusion and ionization mechanisms and results in an underpopulation in sulfur (atoms + ions) on the axis of an SF_6 arc: the real value of the concentration ratio M of fluorine and sulfur is greater than the stoichiometric value of 6. To take this effect into account, the temperature has been measured following the method proposed by Schulz-Gulde in the case of SF_6 [3]: all the LTE laws, except the dissociation equilibrium, are assumed valid. In such conditions the measurement of the absolute intensities of one line of SI and one line of SII allows the determination, in an SF_6 plasma, of the temperature T , ratio M and all the other number densities deduced from these parameters using the laws of LTE.

In $\text{SF}_6\text{-N}_2$ mixtures the proportion of N_2 is an additional parameter. Two options are possible: measuring the absolute intensity of a line of NI or considering that nitrogen in the mixture is not subjected to the demixing effect and that its proportion remains equal to the value corresponding to the original mixture. Both cases have been studied.

In the first option the method can be summarized as follows:

- 1) Measurement of the absolute intensities of a line of SI (ϵ_S), of a line of SII (ϵ_{S^+}) and of a line of NI (ϵ_N).
- 2) Choice of an arbitrary value of T .
- 3) Computation of the partition functions.
- 4) Determination of the total densities of S, S^+ and N from Boltzmann's law.
- 5) Determination of the electron density and the total densities of S^{++} and N^+ from Saha's law. Computation of the density of N_2 from the law of Gulberg-Waage.
- 6) Electrical neutrality provides the density of F^+ ions.
- 7) Determination of the density of F atoms from Saha's law.

8) Determination of the total pressure from the perfect gas law.

9) Check this pressure value : if different from the atmospheric pressure (within 10^{-5}) a new value is chosen for T and the procedure is started again from stage 3.

The successive values of temperature are chosen by dichotomy. The ionization potential lowering is recalculated at each iteration before the application of Saha's law. The density of species F⁻, S⁻, F⁺⁺, S₂, N₂⁺ and S₂⁺ is neglected since their relative concentration is lower than (or of the order of) 10^{-5} .

In the second option where nitrogen is taken into account in mixtures such as p_1 % SF₆ + p_2 % N₂, the intensity ε_N is not measured. Between stages 2 and 3, an arbitrary value is chosen for the total N atom density ; a check on the ratio p_1/p_2 is performed between stages 7 and 8 allowing the determination by dichotomy of the N atom density.

In general, the method based on the measurement of ε_S , ε_{S^+} and ε_N has been used when the proportion of nitrogen in the mixture is higher or equal to 20 %. In the other cases only the values of ε_S and ε_{S^+} were measured.

2.3 RESULTS. — The characteristics of the lines studied are represented in table I, the A_{mn} being taken from [5]. The evolutions with arc current of the axial temperature T_0 are represented in figure 2 for different mixture proportions. It is observed that the $T_0(I)$ curves intersect for a current around 50 A. It is also to be noted that at high current the 20 % SF₆ curve is not intermediate between the curves corresponding to 10 % and 80 % SF₆. The question arises whether the uncertainty on the measurement of T is low enough for this intersection to be considered as real.

Table I. — Characteristics of the used lines (wavelength, energy and statistical weight of the upper level ; spontaneous emission coefficient).

λ	E_m (cm ⁻¹)	g_m	A_{mn} (s ⁻¹)
S = 469.5 nm	73 917	15	$7.4 \times 10^5 \pm 25 \%$
S ⁺ = 545.4 nm	128 599	8	$7.8 \times 10^7 \pm 25 \%$
N = 493.5 nm	106 479	2	$1.58 \times 10^6 \pm 10 \%$

If account is taken of the uncertainty on the spontaneous emission coefficients A_{mn} of the studied lines (25 % for sulfur lines and 10 % for that of nitrogen) and of a relative uncertainty of 15 % on the absolute line measurements, a maximum uncertainty of 2.5 % on the temperature is obtained. Now if one examines the relative evolutions of tempera-

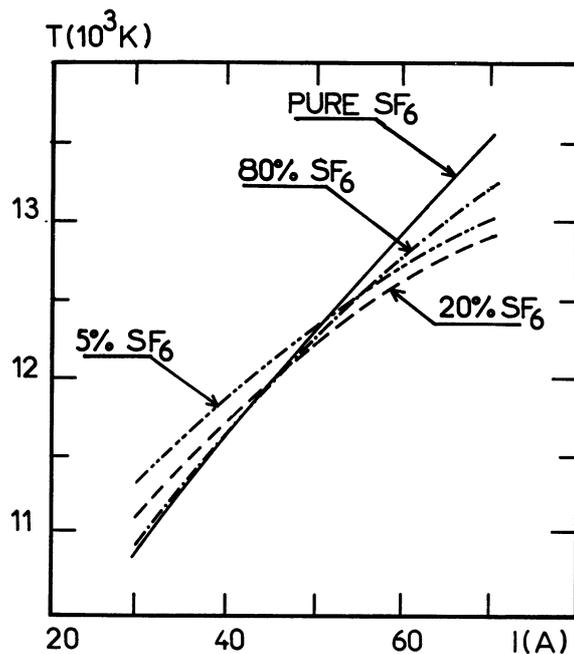


Fig. 2. — Experimental variations of the axial temperature versus current intensity.

ture with current intensity and with the mixture composition (determined with the same values of A_{mn}) the temperature fluctuations due to measurement errors are lower or of the order of 1 %.

Furthermore, even though the temperature determination is based on all LTE laws (with the possibility of dissociation non equilibrium), the final value of T has little dependence on departures from LTE. This is due to the fact that the measuring method of T corresponds somewhat to the method of relative intensities of 2 lines which necessitates only the statistical equilibrium of the species considered, and we have already shown [6] that statistical equilibrium for sulfur is achieved when the electron density is above 9×10^{15} cm⁻³ ; this condition is fully satisfied in our case.

To illustrate this low dependence of T on departures from LTE we have studied the influence of the divergence between electron temperature T_e and heavy particle temperature T_g . The difference between T_e and T_g may be estimated from the electron energy balance. If one neglects the energy lost through radiation and diffusion mechanisms, this balance reads [7] :

$$\sigma E^2 = 3 m_e k (T_e - T_g) n_e \sum_h \frac{\bar{v}_{e-h}}{m_h} \quad (1)$$

where σ is the electrical conductivity, n_e the electron density, m_e and m_h the electron and heavy particle mass respectively, \bar{v}_{e-h} the mean electron-heavy particle elastic collision frequency, E the electric field. The use of equation (1) provides a higher limit

for the difference $T_e - T_g$. For SF₆-N₂ mixtures we have used the experimental values of the electric field, the calculated values of σ [2] and we have computed the frequency $\bar{\nu}_{e-h}$ from the cross-sections available in literature [8-9]. For a value of electron density of $4 \times 10^{16} \text{ cm}^{-3}$ the difference ($T_e - T_g$) given by relation (1) is between 350 and 450 K when the proportion of SF₆ varies between 80 % and 10 % in the SF₆-N₂ mixture. We have taken this difference into account in the procedure of determination of T ; to do this, the perfect gas law is replaced by Dalton's law :

$$p = n_e kT_e + kT_h \sum_h n_h. \quad (2)$$

The use of this scheme in the measurement of the temperature in the case of a 20 % SF₆-80 % N₂ mixture leads to temperatures differing only by 1 or 2 K from those where the difference $T_e - T_g$ was not taken into account. This study therefore shows that the temperature determination method is relatively independent of departures from equilibrium when $n_e > 2 \times 10^{16} \text{ cm}^{-3}$ and justifies the relative uncertainties mentioned above. It is to be noted that with relative uncertainties of order 1 %, it cannot be definitely stated that the values of axial temperature measured in a mixture having 20 % SF₆ for $I > 50 \text{ A}$, are lower than the values measured with a 10 % SF₆ mixture. We have therefore tried to interpret quantitatively the curves of figure 2 through a modeling work.

3. Modeling.

This modeling work of a stationary arc was based on the energy balance equation which, in cylindrical coordinates may be written as :

$$\sigma E^2 = \frac{1}{r} \frac{d}{dr} \left(r \kappa \frac{dT}{dr} \right) - u \quad (3)$$

where κ is the thermal conductivity and u the energy lost through radiation by the plasma. To establish this equation the plasma is assumed in thermal equilibrium and we neglect convection and diffusion. Equation (3) is solved by the method of Runge-Kutta. The boundary conditions are $\left(\frac{dT}{dr} \right)_{r=0} = 0$ and $T_w = 300 \text{ K}$, T_w being the wall temperature (at $r = R$). The $T(r)$ profile is computed starting from an arbitrary initial value $T(r = 0)$ of axial temperature ; it is recomputed after adjustment of the initial value $T(r = 0)$ as long as $T(r = R)$ is different from T_w . The value of the uniform electric field E is related to the current by :

$$I = 2 \pi E \int_0^R r \sigma dr. \quad (4)$$

The values of σ and κ are taken from previous studies [2]. For SF₆-N₂ mixtures no data on the radiation loss u is available from the literature. To estimate this term the following procedure was used : the net emission coefficients u_{N_2} and u_{SF_6} for pure nitrogen and pure SF₆ are given in the literature [10, 11]. For a mixture having p_1 % SF₆ + p_2 % N₂ (with $p_1 + p_2 = 100$) the net emission coefficient is written under the following form :

$$u = p_1' \% u_{\text{SF}_6} + p_2' \% u_{\text{N}_2} \quad (5)$$

with

$$p_1' = \frac{7 p_1}{7 p_1 + 2 p_2} \times 100 \quad \text{and}$$

$$p_2' = \frac{2 p_2}{7 p_1 + 2 p_2} \times 100. \quad (6)$$

Equations (5) and (6) allow partial pressures of products derived from SF₆ and those derived from nitrogen to be approximately taken into account. For the temperature range where radiation plays an important role in the energy balance ($T > 10\,000 \text{ K}$) the molecules are dissociated.

The resolution of equations (3) and (4) allows the computation of temperature profile $T(r)$ for arbitrary values of the proportion of SF₆ in the mixture and of the current. In figure 3 we have represented the computed variations of axial temperature with the current intensity for different SF₆-N₂ mixture proportions.

As in the case of the experimental results, a crossing of $T_0(I)$ curves obtained with different

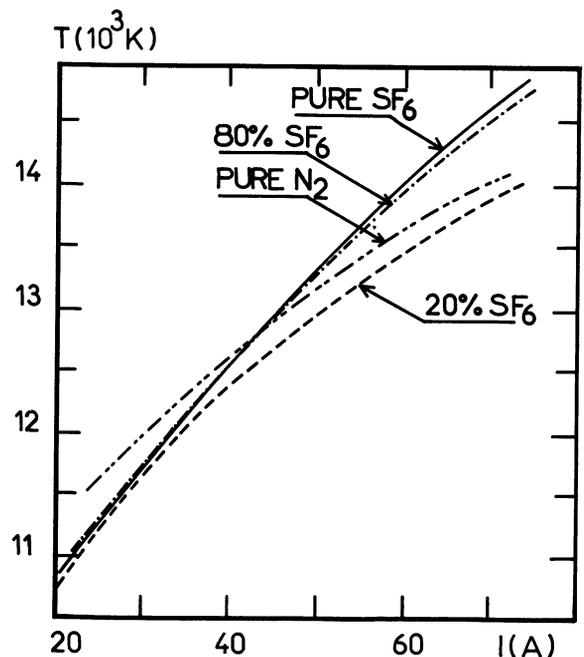


Fig. 3. — Theoretical variations of the axial temperature versus current intensity.

proportions is observed. Although the current value corresponding to the intersection is slightly different in both sets of results the conclusion is that the theoretical variations based on thermal equilibrium are analogous to the experimental variations. The explanation of this therefore does not require consideration of departures from LTE.

4. Discussion.

4.1 COMPARISON BETWEEN SF₆ AND N₂. — The evolution of the temperature of a plasma is controlled by its energy balance.

4.1.1 For high current values ($I > 100$ A for $\phi = 4$ mm). — The energy losses in the central zone are radiation dominated. The energy lost by radiation in a nitrogen plasma is higher than that lost in an SF₆ plasma. It follows (for fixed values of discharge current I and radius R) that the electric field of a stationary nitrogen arc is higher than that in SF₆, whereas the temperature on the axis is lower.

This characteristic is easy to understand if one considers the limiting case of very high current ($I > 500$ A for $\phi = 4$ mm). The energy losses are then radiation dominated and the temperature profile is rectangular: $T = T_0$ for $0 \leq r \leq R$. The value of conductance given by:

$$G = 2\pi \int_0^R r \sigma dr \quad (7)$$

is close to $G = \pi R^2 \sigma_0$ where σ_0 is the value of the electrical conductivity at temperature T_0 . From Ohm's law:

$$I = E \cdot G \quad (8)$$

for a given value of I the conductance G is lower in the arc where E is higher, which is nitrogen in our case and σ_0 will be lower in nitrogen than in SF₆. In addition, for temperatures above 17 000 K, the electrical conductivity σ depends very little on the nature of the plasma and is a monotonous function of T . This implies a lower axial temperature in nitrogen than in SF₆.

When the current intensity is between 100 and 500 A the temperature profile is no longer rectangular as can be observed in figure 4 where curves $T(r)$ in SF₆ and N₂ are given for $I = 185$ A (this value has been chosen since it gives an axial temperature of 20 000 K for SF₆). Nevertheless radiation constitutes a dominant loss term over an important fraction of the arc section around the axis and, in a first approximation the previous discussion corresponding to the rectangular profile still holds.

4.1.2 For low current values ($20 \text{ A} \leq I < 50 \text{ A}$). — The temperature profiles evolve in a different manner in nitrogen and SF₆ when the current intensity

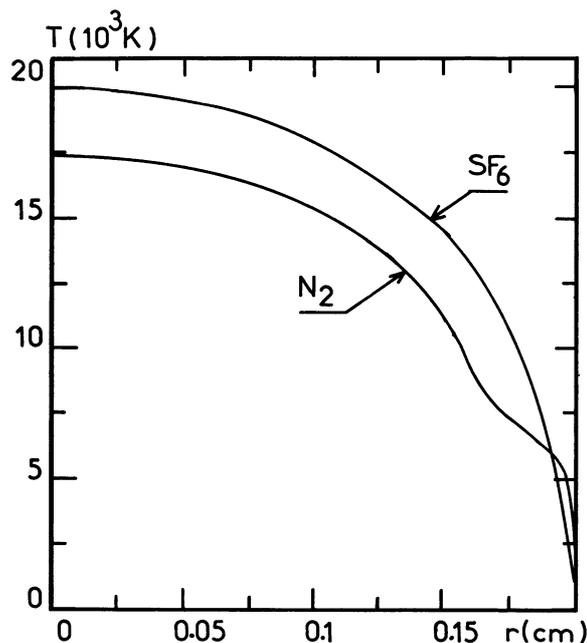


Fig. 4. — Theoretical temperature profiles for a 4 mm diameter arc at 185 A.

decreases. In figure 5 we have represented these computed profiles for a current of 38 A. Since the thermal conductivity of nitrogen exhibits a high maximum around 7 000 K the $T(r)$ profile presents a plateau around this temperature value. The conducting core of the arc is therefore stretched in comparison with that at SF₆ (the 10 000 K isotherm is at $r = 0.76$ mm for N₂ and $r = 1.15$ mm for SF₆); the effect of this is a higher axial temperature in

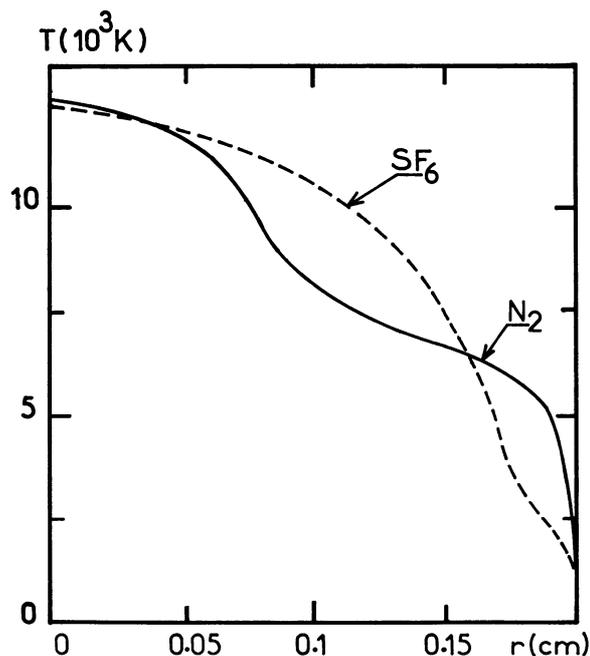


Fig. 5. — Theoretical temperature profiles for a 4 mm diameter arc at 38 A.

N_2 than in SF_6 for $20 \text{ A} < I < 50 \text{ A}$. This effect is accentuated by the higher radiation term in SF_6 than in nitrogen for $T < 11\,000 \text{ K}$. If the radiation loss is neglected in the computation of a 30 A arc, the axial temperatures are roughly identical in SF_6 and nitrogen, the difference being about 200 K when radiation is taken into account.

4.2 SF_6 - N_2 MIXTURES. — In such mixtures all material functions (σ , κ and net emission) are intermediate between those of the pure gases (expression (5) and Ref. [2]). It is therefore expected that curves $T_0(I)$ are intermediate to those of pure SF_6 and pure nitrogen. In reality this is only true when the proportion of SF_6 in the mixture is higher than 50 %. Figure 3 shows the particular case corresponding to 20 % SF_6 which exhibits the highest divergence from the other theoretical curves. The computation shows that for a current between 40 and 80 A the axial temperature in such a mixture is markedly lower than that of nitrogen and SF_6 .

This feature arises essentially from the non linear dependency of the electrical and thermal conductivities on the proportion of SF_6 in the mixture. For a mixture with 20 % SF_6 the peak of thermal conductivity around 7 000 K corresponds to a value of $20 \text{ mW} \cdot \text{cm}^{-1} \cdot \text{K}^{-1}$ compared to $52 \text{ mW} \cdot \text{cm}^{-1} \cdot \text{K}^{-1}$ in the case of pure nitrogen [2]. These markedly lower values lead to a $T(r)$ profile close to that of SF_6 , i.e. having a wider conducting core than in nitrogen. In addition, the electrical conductivity of the SF_6 - N_2 mixture is higher than that of pure SF_6 for $9\,000 \text{ K} < T < 13\,000 \text{ K}$ as can be observed from table II. The overall effect of these two combined properties is to increase the conductance of the SF_6 - N_2 plasma and this is compensated by a decrease in the temperature of the central zone of the arc.

Table II. — Values of the electrical conductivity (in mho/cm) between 9 000 K and 13 000 K.

	9 000	10 000	11 000	12 000	13 000
SF_6	20.8	25.3	38.5	46	53
20 % SF_6 + 80 % N_2	21.2	26	41	50.5	61
N_2	21.7	27.5	44.5	55.6	66.3

It is to be noted that in a previous study on the modeling of a decaying wall-stabilized arc we have shown [12] that the evolution of axial temperature of a mixture containing 20 % SF_6 was not intermediate to those of pure SF_6 and pure nitrogen (extinction of a 100 A arc with $\phi = 5 \text{ mm}$). This effect originated essentially from the variations of thermal conductivity with temperature and mixture proportion.

When the current intensity is above 100 A, the computation shows that the axial temperature turns out to be intermediate to those of pure SF_6 and pure nitrogen. This comes partially from the fact that at high temperature values the electrical conductivity has little dependence on the nature of the gas (and therefore on the proportion of SF_6) and, to a greater extent from the fact that the energy losses are dominated by radiation whose intensity, for a mixture, lies between those of the pure gases (expression (5)).

4.3 COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS. — Two important properties are shown both by the experimental results and by the modeling work : crossing of $T(I)$ curves obtained with different proportions of SF_6 in the mixture and particular behaviour of the 20 % SF_6 mixture when the current intensity is between 50 and 70 A.

Some difference nevertheless appears between figures 3 and 4 : the experimental values for a 20 % SF_6 mixture are higher than those of pure SF_6 and pure nitrogen, for $I < 50 \text{ A}$; the theoretical values are higher than the experimental ones from 1 000 K to 1 500 K.

Irrespective of the previously discussed accuracy of the measurements and validity of the method, two reasons can be invoked to explain these differences. The first one concerns the uncertainty in the material functions used in the modeling work. These uncertainties are higher for the thermal conductivity near the dissociation zones (around 2 000 K for SF_6 and 7 000 K for nitrogen) and even more for the net emission coefficient. We have recomputed the results in the case of pure SF_6 while arbitrarily doubling the value of the net emission coefficient ; this is not unrealistic, given the uncertainty of its value. The difference between the new values and the experimental ones drops to about 500 K.

The second source of divergence between theory and experiment is the existence of departures from LTE. The procedure for the experimental determination of T allows, in particular, the determination of M ratio of fluorine and sulfur concentrations. We have thus shown the existence of departures from LTE since in certain cases the values of M are greater than 10. A detailed discussion of the values of M and of the departures from LTE will be given in the future : we are presently carrying out measurements of the electron density using techniques independent of the equilibrium conditions : line broadening and laser interferometry. The correlation of these measurements with those of temperature, of sulfur excited atoms and ions, and of ratio M will allow experimental quantification of these departures as a function of temperature and SF_6 - N_2 mixture proportions.

5. Conclusion.

We have shown characteristic evolutions of the axial temperature T_0 in SF₆-N₂ mixtures, and, in particular, the crossing of $T_0(I)$ curves. Another feature which was shown is that under certain conditions, the temperature of the mixture is not intermediate to those of pure SF₆ and pure nitrogen. The good agreement between experiment and modeling allows, despite the existence of departures from LTE, the quantitative interpretation of these results and the prediction of the behaviour of arcs burning in mixtures other than SF₆-N₂. At high currents, when the energy losses are dominated by radiation, the axial temperature is lower in the plasma having a more important radiation term ; this feature is consistent with the results of Lowke [13] concerning

the study of radiation dominated arcs. Since the electric field increases with the increase of energy losses, this property may be visualized as follows : for a fixed value of current intensity (high enough for radiation to predominate in the energy balance in the central region) the axial temperature is lower in the arc with higher electrical power.

When the current intensity is lower (below 100 A for wall stabilized arcs of a few mm in diameter) the axial temperature value is a complex function of radiation, thermal and electrical conductivities. A qualitative prediction, from the knowledge of the properties of each constituent of the mixture is often impossible and in certain cases values of the temperature of the mixture may be observed which are not intermediate to those of the pure gases, for a given current intensity.

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