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Effect of Metal Vapours on Thermodynamics and Transport Properties of an Arc Plasma

A.M.A. Amry, G.A. Yahya, Thahbah G. Alzahrani

Abstract –Theoretical investigation of nitrogen-iron arc transport phenomena and an arc plasma model in stationary state have studied at low temperature i.e. between 3,500K and 15,000K at atmospheric pressure. Results showed that the presence of small amounts of metal vapours, which have low ionization potential such as iron, modify the plasma parameters. The solution of Elenbaas-Heller gives us some information about the effect of metal vapours emitted from electrode on the characteristics of the arc column. We concluded that a small fraction of metal vapours in the arc column modify the electric field, current and the axial plasma temperature.
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Index Terms— Arc Plasma, metal vapours , nitrogen-iron arc , transport phenomena.

1 Introduction

THE plasma surrounding a metal vapour arc has long been source of experimental uncertainty. Compton, in early arc discharge work [1], performed experiments in order to investigate plasma properties in an arc. Much has been since them, yet, the field is still in somewhat of a confused state. The lake of effective information transfer from the realm of the physicist to the hands of engineer is, in my view, the primary cause of this confusion. Therefore, to the end of improving the transfer of information, a rather fundamental viewpoint is taken in this section so that the salient point do not become bogged down in details.

There has been much interest in the effect of metal vapour on the transport properties of gas. The electrical and thermal conductivities of contaminated with electrode metal vapour from copper electrode have been measured experimentally by Jaya Ram[2]. By making a comparison between the obtained results with those for uncontaminated arc in air, be found that the presence of metal vapours increase the conductivities. Theoretical studies (Shylar *et. al.* [3] and Abdelhakim *et. al.*[4]) for copper –nitrogen mixture have been shown that the metal vapours emitted from arc electrodes modify the properties of the arc plasma. The same results have been obtained theoretically , for a copper- argon arc plasma, by Mostaghimi-Tehrani *et. al.*[5].

An experimental study of copper vapour movements in the arc chamber has been made by Rahal *et. al.*[6]and Abbasi *et. al.* [7]. It was based on the propagation of perturbation in neutral copper light emission along the chamber axis. They measured the propagation velocity of copper vapour inside the arc chamber.

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By fabrication of high speed computers, the modeling of thermal plasma, thermal plasma processing and plasma reactors became the most important research tool. A basic requirement for any modeling work, however, is a data base of thermodynamic and transport properties.

Recently, significant influence of metal vapours in many applications such as arc welding and minerals have been studied [8, 9,10, 11,12,13,14,15].

This paper is concerned with theoretical study on the effect of metal vapour emitted from iron electrode on the arc plasma.

2 PLASMA COMPOSITION

There are many experimental diagnostic methods in the arc plasma investigations. The most popular of them is the optical emission spectroscopy, mainly because it is not a disturbing manner. This method allows obtaining plasma temperature, electron density, rotational and vibrational temperatures of molecules in plasma, etc.[16]. Due to the lake of experimental facilities and by the huge development of computer devices a theoretical model have been used as a theoretical diagnostic method. Given the geometrical symmetry and constancy of operating conditions, the wall stabilized arc is usually modeled using steady-state and axi-symmetric flow models. Furthermore, thermal plasmas are traditionally described using models based on the Local Thermodynamic Equilibrium (LTE) assumption. The kinetic energy of heavy-species (molecules, atoms, ions) and the free electrons in a plasma in LTE, due to the high collision frequencies among its constituent particles, can be characterized by a single temperature [17]. The LTE approximation is largely valid in the core of the arc plasma, but it is often invalid when the plasma interacts with another medium, such as solid electrodes or a surrounding cold gas. In this computational research, the wall stabilized arc is described using the assumption of LTE model.

Transport properties of different metal/gas mixtures can be studied only if their compositions (thermal plasma properties) are known. The arc column considered in this calculations consists of the following species: $N_2, N_2^+, N, N^+, Fe, Fe^+, e$. It was assumed that multiple ionization below 14,000 K is negligible. LTE has been assumed to calculate arc plasma composition and the plasma in this situation is optically thin. This means that net emission parameter taken into consideration. To determine the densities of the above mentioned species, a system of non-linear equations must be solved. The equations describing the densities are :

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1. Saha-Eggerrt equation

This equation relates the concentrations of the same type but with different ionization charge and can be written in the form:

$$\frac{N_e N_{N^+}}{N_N} = \frac{(2\pi m_e kT)^{3/2}}{h^3} \frac{2F_{N^+}}{F_N} \exp\left(-\frac{E_N - \Delta E_N}{kT}\right) \qquad (1)$$

$$\frac{N_e N_{Fe^+}}{N_{Fe}} = \frac{(2\pi m_e kT)^{3/2}}{h^3} \frac{2F_{Fe^+}}{F_{Fe}} \exp\left(-\frac{E_{Fe} - \Delta E_{Fe}}{kT}\right) \qquad (2)$$

Where $N_e, N_N, N_{N^+}, N_{N_2}, N_{N_2^+}, N_{Fe}, N_{Fe^+}$ are $e, N, N^+, N_2, N_2^+, Fe, Fe^+$ densities respectively; F_N, F_{N^+}, F_{Fe}, F_{Fe^+} are the partition function of N, N^+, Fe, Fe^+; m_e is the electron mass; ΔE is the reduction in the ionization potential due to electric microfields in the plasma; *h* Planck's constant; and *k* Boltzmann's constant.

2. ***Dalton's law*****:** One of the most important predictions made by Avogadro is that the identity of a gas is unimportant in determining the *P-V-T* properties of the gas. This behavior means that a gas mixture behaves in exactly the same way as a pure gas. (Indeed, early scientists such as Robert Boyle studying the properties of gases performed their experiments using gas mixtures, most notably air, rather than pure gases.)

$$p = (N_N + N_{N^+} + N_{N_2} + N_{N_2^+} + N_{Fe} + N_{Fe^+} + N_e).kT \qquad (3)$$

3. ***Charge equilibrium in LTE conditions*****:** To calculate the particle densities from Saha's equation the assumption of quasi-neutrality was made, i.e

$$N_e = N_{N^+} + N_{N_2^+} + N_{Fe^+} \qquad (4)$$

4. ***Percentage of metal vapours in gas*****:** The percentage of iron vapour in the arc plasma *X* is

$$X = (N_{Fe} + N_{Fe^+}) / \Sigma N \qquad (5)$$

Where ΣN would include all host metal and gas species, for example, in case of iron-nitrogen mixture, $N_{Fe} + N_{Fe^+} + N_N + N_{N^+} + N_{N_2} + N_{N_2^+}$.

The partition function for nitrogen and iron species have been tabulated for the condition of interest [18- 19]. J. Halenka and J. Madej[20] tables of the atomic partition function for iron ions, Fe I – Fe *X*, and discuss details of the computational method. The partition functions are given in wide range of temperatures, 10^3 K < T < 10^6 K, and lowering of ionization energy *(0.001 eV < LIE < 5.0 eV)*.

Equations (1)-(5) for a closed non-linear system from which the electron density N_e can deduced. This equation is solved using Newton-Raphson iterative method after this the densities of the other species are then easily calculate.

Calculated electron densities of nitrogen and iron plasma at atmospheric pressure are plotted in Fig. 1. Due to the lowering ionization potential of metals the electron density increases by increasing iron concentration. At temperature relevant for most circuit breakers applications it is it is possible to simplify the calculations by neglecting the effects of doubly–ionized species.

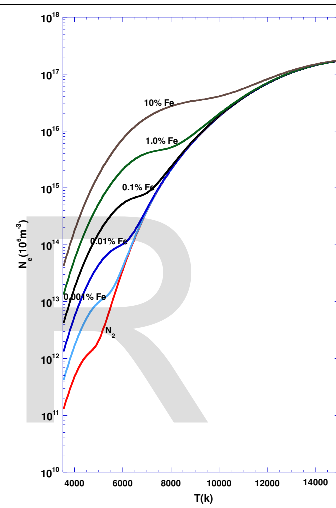

Fig. 1. Variation of the electron density as a function of temperature for different concentration of Fe vapour at P=1 atm.

Calculation of the plasma compositions obtained is given in Figs.2, for different concentrations of iron vapour. These diagrams show that at nearly 5000 K the electron density is about two orders of magnitude higher than that of pure nitrogen. This is due to the ionization potential of iron *(7.7eV)* which is lower than that of nitrogen *(14.5 eV)*. Up to 6000K the electrons are mainly supplied by the ionization of iron atoms and above *7000 K* by the ionization of nitrogen atoms.

Note that secondary ionization does not appreciable until *T≤14,000K*. Most metal vapours will become doubly ionized at lower temperatures, but generally above the point at which gas atoms are already strongly ionized. Therefore, for a low concentration of metal vapour in the plasma gas, the electron density inside the plasma is not significantly altered. It is important to consider the first and second ionization potentials of all species present in a particular application before making

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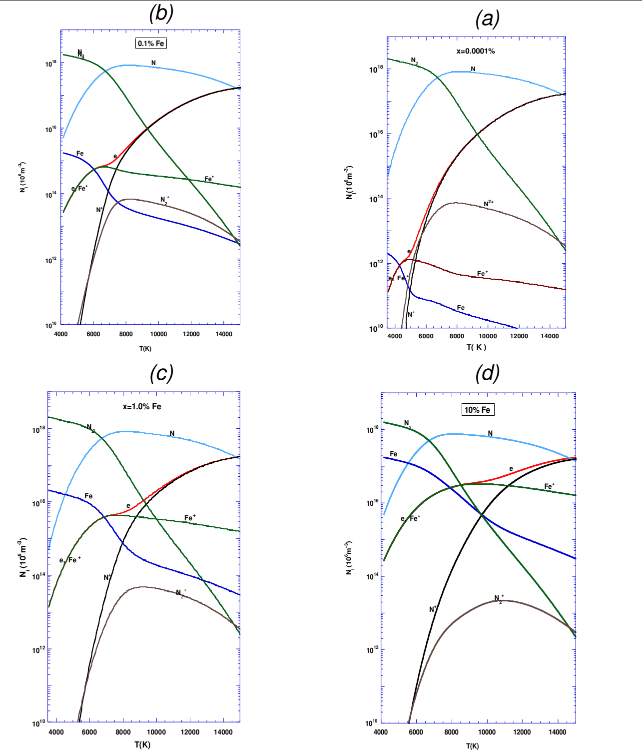

Fig.2. Plasma composition as a function of temperature for nitrogen – iron mixture at different concentration of iron and P=1atm.

this simplification. Only singly-ionized species are considered in the following discussion.

3 TRANSPORT PROPERTIES

Transport properties in a fluid are the processes in which mass, energy, or momentum are transport from a region of a fluid to another under the influence of gradient in composition, temperature or velocity. It can be expressed by phenomenological equations (empiric equations obtained from a summary of experiments and observations). Two of these properties have been studied in this division. First one is the electrical conductivity which is defined as migration of electric charges along the direction of electric potential gradient and the second is the thermal conductivity which is a migration of energy toward the direction of temperature gradient.

In this work we use a simple method to predict accurate transport properties, at least for pure components and mixtures. This opens up the perspective that also more sophisticated mixtures, like those including a chemical reaction, may be better understood by this technique. The method allows the dissociation of the components of total thermal conductivity which are the thermal conductivities of translation and of reaction (the internal thermal conductivity of the mixture is only slightly different from that of pure nitrogen). It is thus possible to follow the lowering of the reaction thermal conductivity coefficient of the nitrogen-iron mixture, as the percentage of iron increases, the energy of the reaction being due to the dissociation of the nitrogen molecule and the ionization of the atom. All calculations are made at atmospheric pressure.

4 ELECTRICAL CONDUCTIVITY

The Electrical conductivity, for partially ionized gas in LTE, is given to the first approximation by [21]:

$$\sigma = \frac{N_e e^2}{m_e \left(\frac{8kT}{\pi m_e}\right)^{1/2} \sum_i N_i Q_i} \qquad (6)$$

Where m_e is the electron mass and N_i is the number density of the ith particle species and Q_i is the effective electron momentum transfer cross-section which is obtained by Spitzer-Harm for the fully ionized gases.

$$Q_{ei} = \left(\frac{Ze^2}{4\pi\varepsilon_o}\right) \frac{\ln\Lambda}{2\sqrt{3(kT)^2}} \left(\frac{\pi}{2}\right)^{3/2} \frac{1}{\gamma_e} \qquad (7)$$

Where $\gamma_e = 0.582$ for $Z=1$, is the correction factor and Λ is the cut off ratio which is given by:

$$\Lambda = \frac{3}{2Z(N_e \pi)^{1/2}} \left(\frac{4\pi\varepsilon_o kT}{e^2}\right)^{3/2} \qquad (8)$$

For electron-neutral-iron collisions, the estimations of reference [22] is used, where:

$$Q_{e-Fe} = 2\times10^{-18} m^2$$

The electron-molecular-nitrogen and electron-atomic-nitrogen collision cross-section, due to selection of data [23] are taken to be:

$$Q_{e-N_2} = 8\times10^{-20} m^2$$
$$Q_{e-N} = 10\times10^{-20} m^2$$

Figure(6) shows the variation of the electrical conductivity as a function of temperature and concentration of iron vapour. At low temperature i.e, *(T<8000 K)* the electrical conductivity is significantly enhanced by the presence of iron vapour. This is clearly due to the lower of ionization potential of iron *(E_{Fe} ≈7.87eV)* in comparison with that of N_2 molecule *(E_{N_2} ≈15.581eV)* and *N*, hence raises the free electron density. At high temperature i.e *(T>10 000 K)*, iron is nearly fully ionized thus no further contribution to the electrical conductivity of iron vapour as the temperature of the plasma increases.

5 THERMAL CONDUCTIVITY

At low temperatures *(T< 16 000 K)* the concentration of iron vapour in the arc plasma is law. Then the principal effect is still due to changes in the charged particle density. In this paper, the following expression, proposed by Spitzer and Harm (Mitchner and Kruuger[24]) has been used:

$$\lambda = 3.2 \frac{k^2 N_e}{\sum_i N_{ei} Q_i} \left(\frac{T}{8km_e} \right)^{1/2} \quad (9)$$

In this work, we calculated the electrical conductivity using equation (6) for several values of the relative concentration of iron as a function of temperature. Certain variations of σ are given in Fig.(3). A comparison between our results and other works of iron electrode vapour (10% Fe) but in a different ambient gas has been reported in Fig. (4). The results are coincidence with that of argon gas temperature (nearly *6000K*) due to the dissociation on nitrogen molecule. In Fig. (5), a radial electrical conductivity distribution of a 20A arc and 0.3cm arc radius at different concentration of iron vapours. At the beginning the arc is burring in pure nitrogen in which the arc core temperature is higher and also the electrical conductivity. By the time the ejection of iron vapour takes place which decrease temperature of the arc core and the electrical conductivity decreases as well.

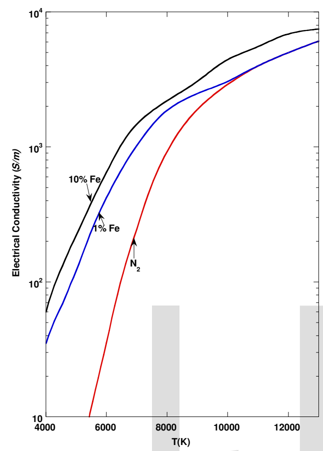

Fig.3. The electrical conductivity as a function of arc temperature at different concentration of iron vapours.

This study is concerned with study of arc column in a stationary state, in which we discuss one of the plasma models in a stationary state. We determine the temperature profile for

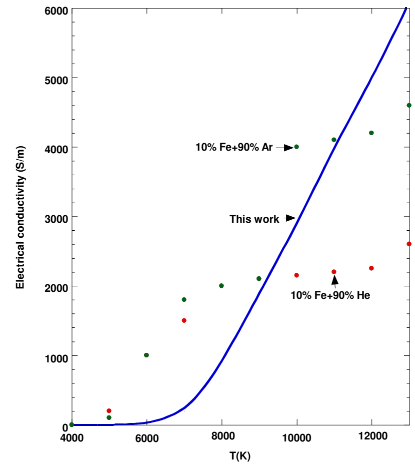

Fig. 4. Evolution of electrical conductivity with the variation of axial temperature for different others.

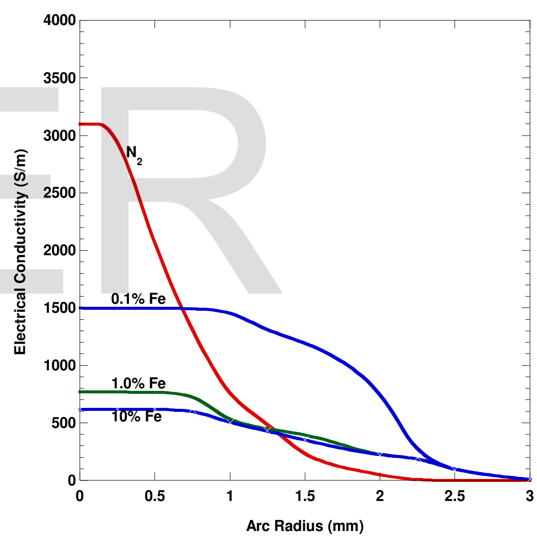

Fig. 5. Radial electrical conductivity distribution for an arc of 0.3cm arc radius at different concentration of iron vapours.

wall stabilized arcs by using the energy balance equation. To solve this equation we needed to calculate the transport coefficient which have been calculated in the last section.

6 ARC PLASMA MODEL IN STATIONARY STATE:

The arc column is defined as a current carrying plasma volume in which the difference between electron temperature and the heavy particle temperature is small. The most important equation for describing the properties and the behavior of the arc column is the energy balance equation. It describes the arc plasma in a stationary state and calculate the temperature profile of the cylindrical arcs. This equation relates the input electrical energy σE^2, due to the electric field E , to losses in energy due to thermal conduction and radiation, where it is assumed that the electrical conductivity σ and thermal conductivity λ can be taken to be equilibrium values from kinetic theory.

6.1 ENERGY CONSERVATION EQUATION

Arcs which are optically thin are approximately isothermal or constructed depending on whether μ/σ an increasing or decreasing function of temperature, where μ is the net emission coefficient [25]. For arcs which are nearly isothermal, it is possible at any value of current and radius to make approximate calculations of:

- The temperature of the arc core.
- The electric field strength.
- The thickness of the outer arc sheath.

- The fraction of the input energy carried to the wall by conduction.

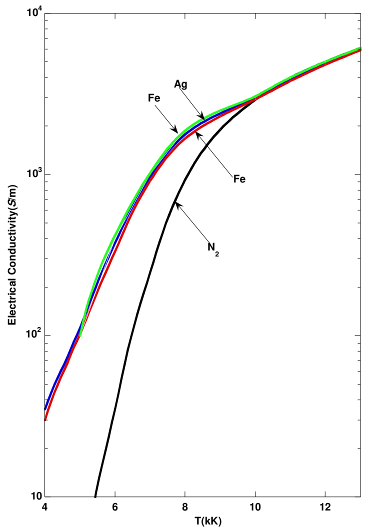

Fig.6. The electrical conductivity as a function of arc temperature at different kind of metal vapours.

The equation of conservation of energy is used successfully to describe the arc plasma in stationary state This equation relates the input electrical energy *JE*, due to the electric field *E*, to the losses in energy due to thermal conduction and radiation. Considering an optically thin wall stabilized arc at atmospheric pressure and neglecting the radial convection this equation can be written in the form:

$$divQ + \mu - JE = 0 \qquad (10)$$

Where $J\ (=\sigma E\ )$ is the electric current intensity, σ is the electrical conductivity and μ is the net emission of radiation. The heat flux density *Q* is related to the plasma temperature by the following:

$$Q = -\lambda \nabla T \qquad (11)$$

Where λ is the thermal conductivity. Considering that the positive column cylindrical in shape, equation (10) can be written the form:

$$\sigma E^2 - \mu + \lambda \frac{d^2T}{dr^2} + \frac{d\lambda}{dT}(\frac{dT}{dr})^2 + \frac{\lambda}{r}\frac{dT}{dr} = 0 \qquad (12)$$

This equation is a second order differential equation, which has single solution at *r=0* or $dT/dr = 0$, because of symmetrical solving. Then we can write this equation in the following form:

$$\left(\sigma E^2 - \mu + 2\lambda \frac{d^2T}{dr^2}\right)_{r=0} = 0 \qquad (13)$$

To solve this equation we used the assumptions used in the reference [26].

6 .2 THE ASSUMPTION OF CALCULATION

To solve equation(13) the following hypotheses have been taking into consideration:

- Local thermodynamic equilibrium exist through the arc.
- The gas pressure is uniform.
- The particles diffusion is negligible.
- The iron concentration X is uniform.
- The variations of thermal λ and electrical conductivity σ with temperature are known. To be abel to easily solve the equation of conservation of energy, we smoothed these coefficients by polynomials as a function of temperature T.

The hypotheses are used because they correspond to true condition of a stationary plasma arc.

The net emission of radiation μ will be discussed in section (6.4).

6.3 THE STATIONARY STATE RESOLUTION

The resolution method of the stationary state model consists of giving an initial value of the axial temperature taking into consideration the following initial condition:

$$\left.\frac{dT}{dr}\right|_{r=0} = 0$$

The evolution of temperature profile *T(r)* permit to calculate the current intensity of arc discharge using Ohm's Law:

$$I = \int_0^{R_w} 2\pi r \sigma(r) E dt \qquad (14)$$

The method which has been used to solve the system which consists of equations(12) and (14) is the same as that used by Glizes *et. al.*[27]. The solution of equation (13) for different percentage of iron vapour in the arc column, gives us an interesting results concerning the influence of iron contaminating the arc column on the plasma temperature.

6.4 NET EMISSION OF RADIATION

Net emission of radiation is the difference between radiation emitted and radiation absorbed from the arc column. This physical value is not unique function of temperature but also in arc radius and current intensity.

In case of N_2–Fe, and due to the lake of experimental result, the emission of radiation of iron is ignored. Thus we supposed that it is totally absorbed, and the radiation power leaving the arc is that of nitrogen only. In the most of out calculation the temperature is lower than 9000K. In this case radiation plays a secondary roule, thus we neglected it. The results which used is that of Kopainsky *et al* [28].

7 RESULTS

The contribution of the various species to the total thermal conductivity, is shown Fig. 6 . as a function of the temperature. A strong effect of to the total thermal conductivity by the presence of high concentration of iron vapour (10%Fe). Since the Fe vapour is primarily responsible for the electron concentration at these temperature levels, the Fe vapor governs the contribution of the electrons to the thermal conductivity above 8000 K. This figure shows that at low temperature i.e, *(T<8000 K)* the electrical conductivity is significantly enhanced by the presence of iron vapour. This is clearly due to the lower of ionization potential of iron *(* E_{Fe} *≈7.87eV)* in comparison with that of N_2 molecule *(* E_{N_2} *≈15.581eV)* and *N*, hence raises the free electron density. At high temperature i.e *(T>10 000 K)*, iron is nearly fully ionized thus no further contribution to the electrical conductivity of iron vapour as the temperature of the plasma increases.

The thermal conductivity as a function of arc temperature at different concentration of iron vapour is shown in Fig.7. We remark that, the presence of iron vapour (about 0.1%) modify the thermal conductivity of the arc column. This can be interpreted as that an increasing in the electron density N_e emitted from iron is accompanied by decreasing in axial temperature Fig.5. A strong effect of to the total thermal conductivity by the presence of high concentration of iron vapour (10%Fe). Since this vapour is primarily responsible for the electron concentration at these temperature levels, the Fe vapor governs the contribution of the electrons to the thermal conductivity above 8,000 K.

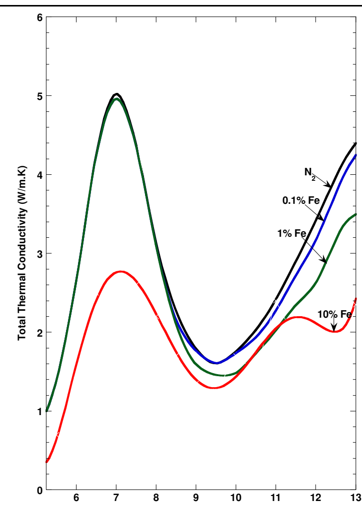

Fig.7. The thermal conductivity as a function of arc temperature at different concentration of iron vapours.

The solution of Eq.(13), for a different concentration of iron in the arc column, shows the effect of metal vapour on the arc plasma axial temperature. Fig.8 represents calculation results of the temperature profile current intensity (I=25A) for an arc burning in homogeneous mixture of nitrogen and iron. The axial temperature is approximately 13000K in pure nitrogen. As the ejection of of a small percentage of iron vapour (~0.01%) the axial temperature decrease to 9500K. This phenomena happened because of the different between the ionization of iron and that of nitrogen atoms. In Fig. 9, a radial electrical conductivity distribution of a 20A arc and 0.3 cm arc radius at different concentration of iron vapours. At the beginning the arc is burring in pure nitrogen in which the arc core temperature is higher and also the electrical conductivity. By the time the ejection of metal vapour takes place which decrease temperature of the arc core and the electrical conductivity decreases as well.

The variation of the axial temperature as a function of arc current for different concentration of iron vapour is plotted in Fig.10. We remark that at low current (~25A) , the axial temperature due to the presence of iron vapours, is maximum.
By increasing the current, the iron arc electrode reaches melting temperature and the arc core strongly contaminated with iron vapour which decrease the axial temperature.

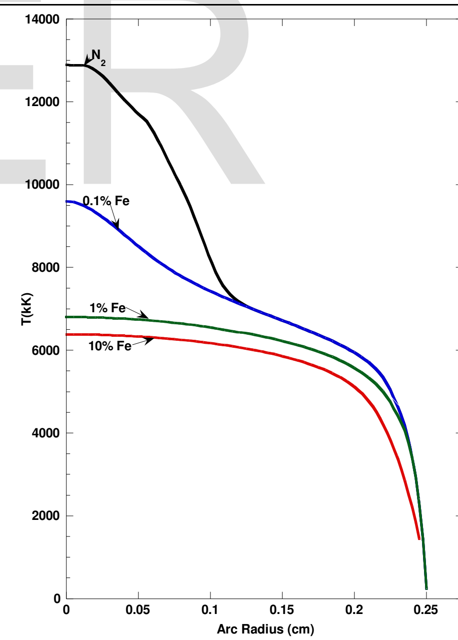

Fig.8. Radial temperature distribution for an arc of 0.25cm arc radius at different concentration of iron vapours.

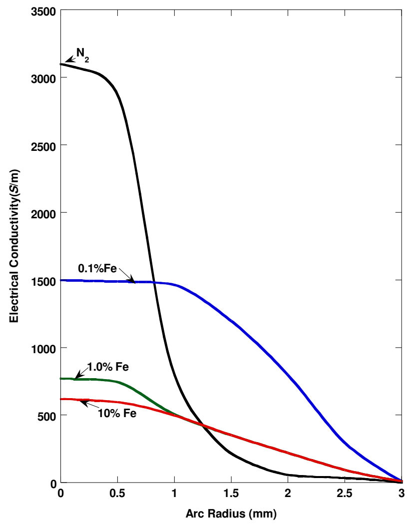

Fig.9. Radial electrical conductivity distribution for an arc of 0.3cm arc radius at different concentration of iron vapours.

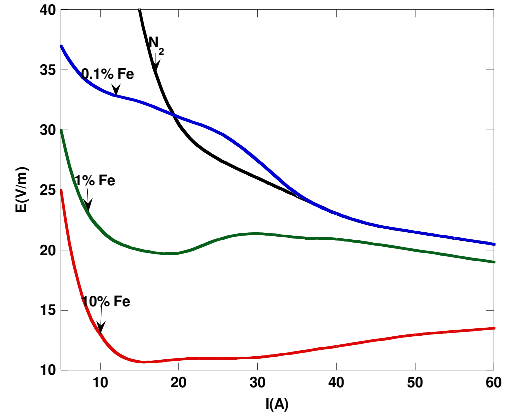

Fig.11. The variation of the electric field with current for different concentration of iron vapours.

The arc characteristic, i.e. the relation between the electric field strength as a function of arc current is shown in Fig.11. at different concentration of iron vapours. We remark that the presence of metal vapour in the arc column modify the arc characteristic for a current of about 25A. This result approaches the concept of the effect of increasing the electrical conductivity at low temperature region of the plasma.

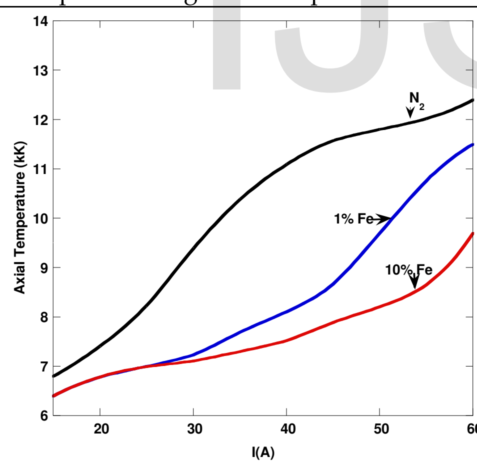

Fig.10. Calculated evolution of axial temperature versus arc current intensity in N_2-Cu mixture and pure N_2.

8 Conclusion

We predict transport properties of metal/nitrogen gas mixtures in the temperature range from 3000 K to 15 000 K, which are important for arc circuit breakers. The presences of metal vapours in the arc column at atmosphere pressure have a significant effect on the temperature distribution, and voltage requirements. This effect is, nevertheless, heavily dependent on the nature of the components of the mixture. When the metal vapours, ejected from electrode, are mixed in with a gas of low ionization potential; their influence is Less obvious than that in a gas with a high ionization potential. This can be observed , if we comparison between the axial arc temperature of an Ar-Fe and N_2-Fe mixtures is more strongly influenced by the presence of the silver than it is in a SF_6-Fe mixture where the sulphur has a higher ionization potential than that is of copper. The metal vapours have an appreciable influence on the electrical conductivity and on the radiation. The results show that the effect on electrical conductivity is preponderant in low-current arcs whereas that on radiation outweighs it at high currents.

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