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Influence of metal vapours on arc properties

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Abstract : The plasmas formed by mixtures of gas and metallic vapours have properties quite unlike those of the plasmas of the pure gases. Even at low concentrations (0.1 % for example) metal vapours can strongly modify the coefficients of electrical and thermal conductivity and more generally, the transport coefficients. In particular the radiation of a plasma can be greatly increased in the presence of vapours. This effect does not depend on the vapor alone but also on the gas with which it is mixed. In the energy balance at the electrodes, it is necessary to take the influence of the vapours into account. It must also be take into account in the calculation of the power received by a particle vapourised in a plasma for plasma projection applications.

Introduction

During operation of an electric arc, the electrodes become eroded. The material the electrode is made of - usually a metal - becomes partially vapourised, the vapour becoming mixed in with the gas. The plasma formed is then an inhomogeneous mixture of gas and metal vapours. Although the partial pressure of the vapours is generally low with respect to that of the gas, the properties of the plasma formed from the mixture are very different from those of the pure gas plasma. The local values of the temperature, the transport coefficients and the radiation are modified. This can lead to a notable modification of the behaviour of the arc and in particular of the local electric field. Arc discharge models should therefore take this process into account, particularly in the balance of energy at the electrodes.

The influence of the metal vapours is strong in the immediate vicinity of the electrodes through a volume that depends on the experimental conditions. It happens that this volume can be small enough to have no influence on the overall properties of the discharge. This, however, is clearly not the case for projection torches for instance, where the metal powder injected into the discharge becomes vapourised throughout the whole volume of the plasma and strongly influences its characteristics, in particular for the radiated power. One particular case is that of arcs under vacuum operating in the metal vapours produced from the electrodes. This type of rather special arc with its dilute plasma that is usually not in local thermodynamic equilibrium will not be considered in the present study.

Modifications of arc plasma parameters by metal vapours

Thermal and electric conductivity

The electrical and thermal conductivity coefficients are calculated by resolving the Boltzmann equation using a method derived by Hirschfelder et al (1). It applies to a very slightly inhomogeneous medium. So, the composition of the plasma is calculated assuming the hypothesis of local thermodynamic equilibrium.

Below, we present examples obtained with various gases and metal vapours. The values recorded clearly depend on the components of the plasma but the modifications introduced by the metal vapours are generally the same in all cases. Figures 1 and 2, which concern an argon plasma at atmospheric pressure, present the electron density and the electric conductivity, respectively, for several percentages of copper vapour introduced into the plasma (2). Considering the lower ionisation potential of the metal atoms, the electron density and the electric conductivity are very strongly increased for low temperatures in the mixture with respect to the pure gas.

Unlike for the electric conductivity, the presence of a low percentage of metal vapours does not notably modify the thermal conductivity of the plasma. This is no longer the case with high percentages of vapour, especially in the presence of a molecular gas presenting one or several strong reactional thermal conductivity maxima due to dissociation. In this case, the increase in translational thermal conductivity due to the increase in electron density does not compensate for the loss of reactional thermal conductivity (3)

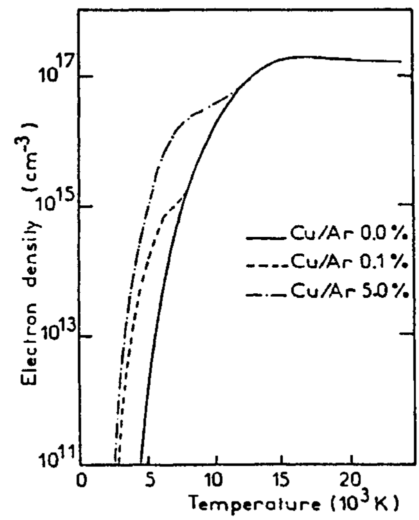

Fig. 1 - Electron density of an atmospheric-pressure Cu/Ar-plasma (2)

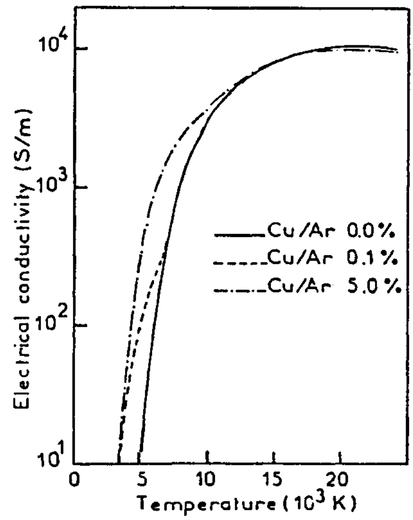

Fig. 2 - Electrical conductivity of an atmospheric-pressure Cu/Ar plasma (2)

Radiation

In high power arc applications, radiation can represent a proponderant term in the energy balance and it becomes essential to be able to quantify the influence of metal vapours on the radiation of the arcs. The net emission coefficient is defined as the difference between the emitted and absorbed radiated power in a control volume. The approach is based on the following assumptions (4) :

- homogeneous and isothermal cylindrical plasma
- local thermodynamic equilibrium
- spectral emission and absorption obeys Kirschhoff law.

The temperature field is divided into a number of distinct control volumes in which the plasma is assumed to be homogeneous and isothermal. The net emission coefficient can be written in this case as :

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

B_ν is the Planck function, K'_ν the monochromatic absorption coefficient and R the discharge radius.

Figure 3 shows a comparison between the net specific volumetric emission for Ar-Fe, Ar-Al and Ar-Si mixtures under the same conditions (760 Torr, plasma radius 1 mm and metal vapour contration 1 % molar fraction) (5). All the results show that the presence of metal vapours leads to an increase in the power radiated, especially at lower temperature (6)(7).

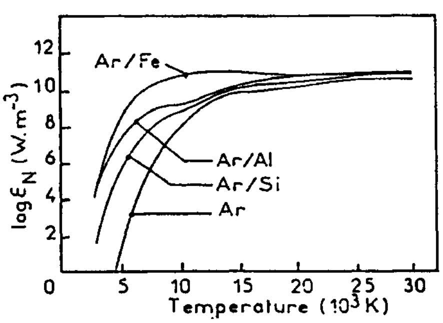

Fig. 3 - Comparison of the net emission coefficient of the argon plasma in the presence of 1 % molar fraction metal vapors for a plasma column radius of 1 mm (5)

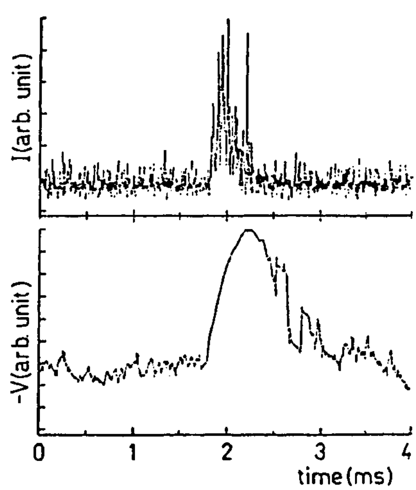

Fig. 4 - Simultaneous recordings of the voltage V and the Cu I line at 510.5 nm (8)

Arc voltage - Electric field

Figure 4 represents the spectroscopic recording of the line at 510.5 nm in the vicinity of the copper anode of an arc operating in nitrogen at atmospheric pressure. The signal is composed of a continuum due to the steady vapourisation of the anode and of "puffs" of vapour emitted at irregular intervals. The signal is correlated to the potential difference between the anode and a plasma stabilising disc located 1.5 cm from the anode. The appearance of a puff of copper vapour gives rise to a drop in the voltage between the electrode and the probe. Thus, we can conclude that the increase in the density of the copper gives rise to an increase in the electron density through an enhancement of the electric conductivity and hence to a lowering of the local electric field and the arc voltage. It will be shown below that this process must be take radiative phenomena into account. This also shows that certain fluctuations of the arc voltage are due to the irregular emission of metal vapours (8).

Temperature

It has long been observed that the presence of metal vapours reduces the local value of the plasma temperature (9).

Figure 5 gives an example of a temperature profile measured in an argon arc at atmospheric pressure for a current of 90A. When a very efficient cooling system is used, the emission of vapours can be eliminated. A decrease of temperature is observed at around 2000K in the presence of metal vapours produced by the anode. This effect has two causes:

- firstly, the presence of metal vapours increases the electric conductivity σ of the plasma for temperatures lower than 10 000K. This is a general result. Figure 6 gives the radial profiles of the local electrical conductivity for two different percentages of copper in an arc discharge in nitrogen at atmospheric pressure (I = 20 A). The temperature profiles used were obtained by computation resolving the classical Elenbaas Heller equation:

$$\sigma E^2 = -1/r \ \ \partial/\partial r\,(r\lambda\ \partial T/\partial r) \qquad (2)$$

λ being the thermal conductivity and E the electric field. This equation is coupled to the current equation where the intensity is given by

$$I = 2\pi E \int_0^R \sigma(T) r dr \qquad (3)$$

A widening of the conduction zone is observed leading to the cooling of the plasma (18).

- secondly, the presence of the metal vapours increases energy losses through radiation: the electron structure of the metal atoms includes more states with a low excitation energy than in the gas and therefore more numerous lines in the low-temperature spectrum.

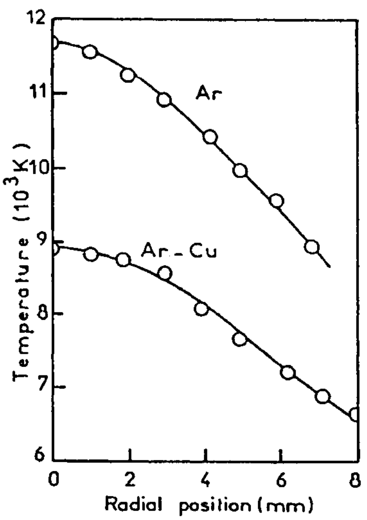

Fig. 5 - Temperature profiles in pure argon, Ar-Cu and Ar-Fe mixtures (17)

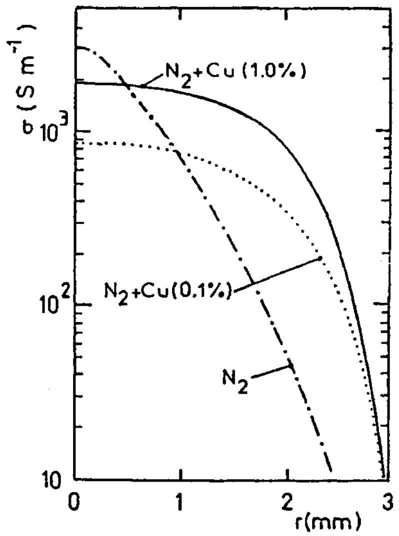

Fig. 6 - Calculated radial profiles of electrical conductivity for I=20A in pure N_2 and in N_2 + 0.1 % Cu and N_2 + 1 % Cu mixtures

However, in certain experimental conditions, the penetration of metal vapour from the anode into the column is limited to a region within 1 mm of the anode. The rather large changes in plasma transport properties that would be expected to occur as a result of the measured concentration of metal vapour near the anode are not sufficient to change the overall structure of the arc (10).

Contradictions can also exist between the published results: for Etemadi et al. (11) the presence of copper in the neighbourhood of the anode leads to a reduction of σ and to an increase of T.

Influence of metal vapours in circuit-breaker arcs

Circuit-breaker arcs are very strongly contaminated with metal vapours emitted by the electrodes (generally made of W-Cu). They are however rather particular systems: the arcs are transient, blown, and of very high intensity (several kA and even several tens of kA). The working gas is generally SF_6 or air. During arc blowing, the metal vapours mostly remain concentrated along the central axis of the arc giving the discharge its characteristic structure: Ikeda et al. (11) measured a temperature of about 16 000K along the vapour- rich axis and 18 000K in the surrounding plasma. The vapours play an important role in the cooling of the plasma through radiation during the intense current phase and at zero current they can maintain the value of σ at a level sufficient to prevent effective cut-off occurring when the voltage is re-established.

Metal particles in a plasma

Plasma projection applications involve the injection of powders of metals or of various other substances that vapourise in the plasma during their time of flight. Plasma-particle heat transfer has been the subject of numerous studies (12) (13). The results obtained show that evaporation severely reduces heat transfer to a particle and in general this effect is more pronounced for materials with a low latent heat of evaporation (14). The presence of small amounts of metallic vapours substantialy increases the radiative losses of the plasma. This radiative loss term must be included in the energy balance around a particle. It is found to have a significant effect on the heat transfer rate, when the effect of the metallic vapours is included in the calculation of the radiative transfer (15).

Conclusion

The presence of vapour in the arc atmosphere has a great influence on the temperature distribution, the heat transfer mechanisms and voltage requirements. This influence is, however, very dependent on the nature of the constituents of the mixture. When the metal vapours are mixed in with a gas of weak ionisation potential; their influence is less clear than in a gas with a high ionisation potential. For example, the temperature of an Ar-Cu mixture is more strongly influenced by the presence of the copper than it is in a SF_6-Cu mixture where the sulphur has an ionisation potential that is hardly any higher than that of copper (16). The metal vapours have an appreciable influence on the electric 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.

In numerous applications, it is necessary to calculate the energy balance at the electrodes and in particular at the anode. It is then indispensible to take the presence of metal vapours into account. Yet, the temperature profiles in the vicinity of the anode are strongly dependent on the materials used for the electrode even in the absence of vapourisation of metal (17). If the influence of metallic vapour on the plasma is not taken into account, the transfer of energy between the arc and the anode. and thus erosion of the anode are greatly overestimated (18).

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