

Modelling of Electrical Conductivity of a Silver Plasma at Low Temperature

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Abstract During the working of electrical fuses, inside the fuse element the silver ribbon first begins to melt, to vaporize and then a fuse arc appears between the two separated parts of the element. Second, the electrodes are struck and the burn-back phenomenon takes place. Usually, the silver ribbon is enclosed inside a cavity filled with silica sand. During the vaporization of the fuse element, one can consider that the volume is fixed so that the pressure increase appears to reach pressures higher than atmospheric pressure. Thus, in this paper two pressures, 1 atm and 10 atm, are considered. The electrical field inside the plasma can reach high values since the distance between the cathode surface and the anode surface varies with time. That is to say from zero cm to one cm order. So we consider various electrical fields: 10^2 V/m, 10^3 V/m, 5×10^3 V/m, 10^4 V/m at atmospheric pressure and 10^5 V/m at a pressure of 10 atm. This study is made in heavy species temperature range from 2,400 K to 10,000 K. To study the plasma created inside the electric fuse, we first need to determine some characteristics in order to justify some hypotheses. That is to say: are the classical approximations of the thermal plasmas physics justified? In other words: plasma frequency, the ideality of the plasma, the Debye-Hückel approximation and the drift velocity versus thermal velocity. These characteristics and assumptions are discussed and commented on in this paper. Then, an evaluation of non-thermal equilibrium versus considered electrical fields is given. Finally, considering the high mobility of electrons, we evaluate the electrical conductivities.

Keywords: electrical conductivity, silver, fuses, non-ideal plasma, Debye-Hückel approximation, drift velocity, thermal velocity, thermal non-equilibrium, electrical fields

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(Some figures may appear in colour only in the online journal)

1 Introduction

Electric fuses are a powerful set up to interrupt a fault current [1,2]. For several years, researchers and industrial partners have been trying to elaborate a physical model of the (working) operation of a fuse [3,4] in order to upgrade them and to extend their application domains. All fuses have a metallic notched ribbon [5,6] which is surrounded by silica sand as filler and arc quenching material. After a period of current flow the notch melts and then there is a pre-arcing period [7,8] constituting a plasma first of metal and second of fused silica and metal [6,9,10] after the electric fuse arc ignition (typically considered as the cathode anode voltage drop occurrence). Silver is widely used for the ribbon or fuse element. From a previous work [11] we have shown that the

vaporisation temperature of liquid silver is made at atmospheric pressure around 2400 K and the vaporisation temperature is higher for higher pressure. So in this work we will only consider the plasma and gas phase with a starting point calculation at 2400 K just after the pre-arcing time. At this step, the plasma consisting mainly of silver is at low pressure (atmospheric pressure) and that then begins to increase. The pressure has not reached its maximum and the current is not yet back to zero. Then during the arcing time a high electrical field exists that can reach high values as 10^4 V/m [12] and a pressure as high as 30 atm [13] when the silica around the silver starts to vaporize. So we have chosen to study two plausible pressures of 1 atm and 10 atm when the plasma is mainly made of silver.

The fuse behaviour during its working depends on

the network and on the electrical fault. If the fuse works in a good way the two following phases appear: the pre-arcing period and the arcing period consisting of plasma. In this latter step, one can assume the chemical equilibrium that can be estimated to be reached after 1 ms at atmospheric pressure, and the time will be lower for higher pressure. A plasma consisting of a mixture of electrons, ions and neutral chemical species is overall electrically neutral. Several thermodynamic states (complete thermodynamic equilibrium CTE; local thermodynamic equilibrium LTE; partial local thermodynamic equilibrium PLTE; chemical equilibrium and thermal equilibrium) can be defined, allowing the use of statistical thermodynamic formulation as a Planck function, Maxwell distribution, Boltzmann distribution [14–18]. So to characterize and to justify the assumptions made in this kind of complex plasma, researchers and engineers need basic data. Due to their high mobility the electrons inside the plasma are the first particles reacting by an external electrical signal. The plasma frequency determines the time scale of a plasma submitted to external electric perturbations. So to guarantee assumptions of the plasma neutrality, the plasma frequency has to be higher than electrical frequency signal [15]. One has to estimate the drift velocity of electrons versus thermal velocity allowing the use of the Maxwellian distribution for electrons and heavy particles. The plasma ideality can be estimated by a comparison of electrostatic energy versus thermal energy. The validity of the Debye-Hückel approximation has to be verified. As a matter of fact, if the density of charged particle is high enough then collective effect is important and the use of thermodynamic properties is not valid. We can then add a corrective term in the Debye-Hückel approximation to the thermodynamic properties [15,17]. The quasi electrical neutrality assumption has to be checked [14–17]. This latter is satisfied if lower dimension of the plasma volume is higher than several Debye lengths. When an electrical field is applied on plasma, a non-thermal equilibrium characterized by a ratio between the electronic temperature and heavy species temperature θ can appear [17–19]. By an energy balance one can estimate the thermal non-equilibrium parameter θ versus electrical field. Then one can calculate the electrical conductivity from the mobility of electrons [14–17]. The advantage of this method is that it depends directly on the physical parameters notably for the study of the sheaths or in the arc roots studies and it will give available results. Unlike the Chapman-Enskog method, this is a little more complex to program and gives more precise results only if all of the parameters as collision integrals are well known.

In the first part, we describe the formulation to obtain the characteristic parameters: plasma frequency, thermal and electrostatic energy, mean distance between particles, Debye lengths, thermal and drift velocities, mean free path of electrons and thermal non-equilibrium parameter θ . The prerequisite

is the composition that is obtained from the Gibbs free minimization readily used in plasma out of equilibrium. In the second part we calculate the electrical conductivity at thermal equilibrium and for two pressures 1 atm and 10 atm, and out of thermal equilibrium ($\theta=2$). The assumptions of the modelling are tested. In the third part, we evaluate the thermal non-equilibrium when an electrical field is applied and estimate the electrical conductivity. We discuss the influence of Debye length formulation [20] (depending only on electrons [21], depending on ions and electrons [22] and a new formulation from Ghorui et al. [23]) on electrical conductivity. The assumptions of the modelling are checked and finally the electrical conductivity of silver plasma is presented.

2 Theoretical formulation

The plasma frequency is the characterization of the oscillation of electrons around an equilibrium position due to an external perturbation. As a matter of fact, when the electrons perform a tiny movement due to a perturbation, then the Coulomb force pulls the electrons back. An oscillation occurs at a frequency:

$$f_p = \frac{1}{2\pi} \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}, \quad (1)$$

where n_e is the concentration of the electrons, e and m_e are, respectively, the electrical charge and the mass of an electron.

The criterion of plasma ideality is that the thermal energy is higher than the electrostatic energy and that can be written as [16,24]:

$$\frac{1}{8\pi\epsilon_0\lambda_d} \sum_{i=1}^N n_i q_i^2 \ll \frac{3}{2} \sum_{i=1}^N n_i k T_{tri}, \quad (2)$$

where n_i is the concentration of the i th chemical species, q_i the electrical charge, N the total number of species present in the plasma, λ_d the Debye length, k is the Boltzmann constant, ϵ_0 the vacuum permittivity and T_{tri} the translational temperature of the i th chemical species. This first condition allows the use of Gibbs free energy minimization [25].

To obtain the formulation of the Debye length we have to assume that the mean distance d between particles satisfies the following relation:

$$d \ll \sqrt[3]{4\pi} \lambda_d. \quad (3)$$

This second condition allows the use of Debye-Hückel approximation [14,16].

We have to notice that some discrepancies are observed concerning the choice of Debye length. Several authors assume that the Debye length concerns only the electrons since their mobility due to their lower mass is higher than the one of the heavy species [21]:

$$\lambda_{de} = \left(\frac{1}{k\epsilon_0} \frac{e^2 n_e}{T_{tre}} \right)^{-1/2}, \quad (4)$$

where subscript e denotes electrons.

A complete development of Debye length in plasma out of thermal equilibrium leads to the following relation [22]:

$$\lambda_d = \left(\frac{1}{k\varepsilon_0} \sum_{i=1}^N \frac{q_i^2 n_i}{T_{tri}} \right)^{-1/2}. \quad (5)$$

Recently Ghorui et al. proposed that the ions and the electrons are incorporated in the Debye length but assumed that they are under thermal equilibrium at translational temperature of electrons [23]:

$$\lambda_{dG} = \left(\frac{1}{k\varepsilon_0 T_{tre}} \sum_{i=1}^N q_i^2 n_i \right)^{-1/2}. \quad (6)$$

The assumption of a Maxwellian distribution in order to use the Gibbs free energy method [25] in the presence of electrical field involves that the drift velocity has to be lower than the thermal velocity:

$$v_d \ll \bar{v}_e. \quad (7)$$

This third condition allows the use of the Maxwellian distribution.

In the previous formulations, the chemical species concentration is prerequisite. Several chemical species have to be taken into account for silver plasma: concerning the monatomic species we take into account Ag, Ag⁺, Ag⁺⁺, Ag⁻ and electrons; for the molecules we take into account Ag₂. We assume that the plasma is at chemical equilibrium and out of thermal equilibrium. In the literature, one can find different methods to obtain local chemical equilibrium plasma composition such as the method using the mass action law [26,27]. Nevertheless, we use the Gibbs free energy minimization [11,27]. Moreover, electrons have a higher mobility than other particles. They get a mean kinetic energy higher than those of other charged particles in the electrical field. So, assuming Maxwell-Boltzmann distributions, it can be considered that there are two kinds of translational temperatures: one for free electrons T_{tre} and the other one for heavy species T_{trh} . Furthermore, if it is assumed that populations among different excited states follow Boltzmann distribution with different temperatures, then we define:

a. The atomic excitation temperature T_{ex}^{at} from the electronically excited atomic energy levels for all atomic species.

b. The rotational temperature T_{rot} from diatomic rotational levels for Ag₂.

c. The vibrational temperature T_{vib} from vibrational energy levels for Ag₂.

d. The diatomic excitation temperature T_{ex}^{diat} from electronically excited molecular energy levels.

Some assumptions have to be made about these temperatures [27,28]. It is assumed that rotational temperature T_{rot} and translational temperature of heavy species T_{trh} are equal: $T_{rot} \approx T_{trh}$. Concerning

the excitation temperatures T_{ex}^{at} and T_{ex}^{diat} and vibrational temperature T_{vib} , it is assumed that they are close to the translational temperature of electrons $T_{ex}^{at} = T_{ex}^{diat} = T_{tre}$ even if it is still a discussed point [27]. From these assumptions a θ ratio between the translational temperature of electrons and that of heavy species $\theta = \frac{T_{tre}}{T_{trh}}$ can be defined, which characterizes the thermal non-equilibrium in the plasma.

Chemical equilibrium is reached when the Gibbs free energy is minimal. Several discussions have been made about the available method of composition calculation [26,29]. The results are quite similar if thermal non-equilibrium does not exceed $\theta = 2$. This thermodynamic function is written as:

$$G = \sum_{i=1}^N n_i \times \left(\mu_i^0 + kT_{tri} \ln \left(\frac{n_i T_{tri}}{\sum_{i=1}^N n_i T_{tri}} \right) + kT_{tri} \ln \left(\frac{p}{p^0} \right) \right), \quad (8)$$

with p the pressure of the plasma, p^0 the reference pressure (10⁵ Pa) and μ_i^0 the chemical potential of the i th species. The monatomic and diatomic chemical potentials are calculated as described in Refs. [11, 28]. To solve this equation resulting from $dG=0$ at constant pressure and temperature, two other relationships are needed, respectively those of electrical neutrality and Dalton's law:

$$\sum_{i=1}^N n_i z_i = 0, \quad (9)$$

$$p - \Delta p = \sum_{i=1}^N n_i k T_{tri}, \quad (10)$$

where z_i is the number and the sign of electrical charge of the i th species; Δp is the pressure correction due to Coulombian interactions between charged particles. This pressure correction is written as:

$$\Delta p = -\frac{1}{24\pi\varepsilon_0 \lambda_d^3}. \quad (11)$$

To establish the energy conservation, the free electrons gain energy in the electrical field and they transmit energy to particles by collisions.

For the thermalisation process we introduce the mean free path of free electrons (subscript fe) taking electrons into account [30]:

$$\lambda_{fe} = \left\{ n_{Ag} \bar{Q}_{eAg}^{(1,1)} + \sqrt{2} (n_e) \bar{Q}_{ee}^{(1,1)} + (n_{Ag^+}) \bar{Q}_{eAg^+}^{(1,1)} + (n_{Ag^-}) \bar{Q}_{eAg^-}^{(1,1)} + n_{Ag_2} \bar{Q}_{eAg_2}^{(1,1)} \right\}^{-1}, \quad (12)$$

where n_j is the concentration of chemical species j and $\bar{Q}_{ej}^{(1,1)}$ is the elastic average momentum cross section between electrons and the j th considered chemical species.

$$V(r) = -\frac{1}{4\pi\varepsilon_0} \frac{Z_j e^2}{r} \exp\left(-\frac{r}{\lambda_d}\right), \quad (13)$$

where e is the elementary charge, Z_j is the number of elementary charges (-1 for electrons and Ag^- and the number of positive charge for positive ions) of the j th chemical species, r the distance between the two particles and λ_d is the Debye length. As mentioned previously, we have to notice that there is some debate about the appropriate choice of the Debye length.

To determine the average momentum cross sections $\bar{Q}_{ej}^{(1,1)}$, we use the table of Mason et al. [31] completed by those of Devoto [32].

Since the silver polarisability value is of the same order that the one of copper [33], we estimate the momentum-transfer cross section from those of copper [34–39]. At high energy we use the data of Mayol et al [34]. We obtain the average momentum cross sections $\bar{Q}_{ej}^{(1,1)}$ by integration with a 24 points Gauss-Legendre method and using the physical relations given in Ref. [40].

According to our knowledge no data exist for the collisions between e^- and diatomic molecule of silver Ag_2 , so we estimate it from the following relation:

$$\bar{Q}_{e\text{Ag}_2}^{(1,1)} = \pi^{2/3} \sqrt{2 \left(\frac{\bar{Q}_{e\text{Ag}}^{(1,1)}}{\pi} \right)^{3/2}}. \quad (13)$$

This formulation has been obtained from p.987 of Ref. [40] and has been used in Ref. [22] and recently in Ref. [41].

The time τ between two collisions can be estimated by $\tau = \frac{\lambda_{fe}}{\bar{v}_e}$ where \bar{v}_e is mean thermal velocity of electrons. With the assumption that the drift velocity which contributes to the electrons flux is low compared to the mean velocity of electrons from the Maxwellian distribution one can obtain:

$$\bar{v}_e = \sqrt{\frac{8kT_{tre}}{\pi m_e}}, \quad (14)$$

where m_e is the mass of one electron.

We assume that the electrons relax to a Maxwellian distribution with the temperature T_{trh} and that the heavy particles relax to a Maxwellian distribution with the temperature T_{tre} . Hence, by equalling the energy transmitted to heavy particles by electrons: $\frac{3}{2}k(T_{tre} - T_{trh}) \frac{2m_e}{m_h} \frac{1}{\tau}$ with the energy gained in the electrical field by electrons between two collisions: $e^2 \frac{E^2}{m_e} \tau$, we can deduce the ratio whose definition is $\theta = \frac{T_{tre}}{T_{trh}}$ as:

$$\theta^2 - \theta = \frac{\pi e^2}{24k^2} \frac{E^2}{T_{trh}^2} \frac{\bar{m}_h}{m_e} \lambda_{fe}^2, \quad (15)$$

with \bar{m}_h the mean value of mass balanced with the concentrations of heavy particles and E the value of electrical field. Since the ratio θ depends on chemical composition and the composition depends on the thermal non-equilibrium θ , we resolve the Eq. (15) by a dichotomy numerical method. For each step of heavy species temperature, the value of θ is calculated.

Following Ref. [18], we have to notice that the electron density has to be high enough to obtain Maxwellian distribution and Boltzmann distribution.

To approach a stationary state the loss of electrons has to be equal to the production of electrons. We neglect the other energy losses due to radiation and heat conduction. From Refs. [18] and [42], we can roughly estimate the minimal electronic density needed to satisfy these latter remarks. Thus, we obtain for electrons a concentration around $10^{16-5} \times 10^{17} \text{ m}^{-3}$. Furthermore, the thermal equilibrium is reached when the transfer rate of energy due to collisions between electrons and heavy particles is larger than the rate of energy gain in the applied field.

To determine the electrical conductivity, we consider a slice of electrons that moves to the anode. The interaction of the slice with the medium is due to the collisions between the electrons of the slice with ions and neutral particles. We introduce the drift mean free path:

$$\lambda_{f,\text{drift}} = \left\{ n_{\text{Ag}} \bar{Q}_{e\text{Ag}}^{(1,1)} + (n_{\text{Ag}^+}) \bar{Q}_{e\text{Ag}^+}^{(1,1)} + (n_{\text{Ag}^-}) \bar{Q}_{e\text{Ag}^-}^{(1,1)} + n_{\text{Ag}_2} \bar{Q}_{e\text{Ag}_2}^{(1,1)} \right\}^{-1}.$$

The electron conductivity is then written as:

$$\sigma = \frac{n_e e^2}{m_{e^-}} \frac{\lambda_{f,\text{drift}}}{\bar{v}_e}. \quad (16)$$

This can be compared to the electrical conductivity obtained with the third order approximation of the Chapman-Enskog method σ_{CE} [20–22].

3 Composition, electrical conductivity versus temperature

In Fig. 1(a), we represent the composition of a silver gas and plasma versus temperature at thermal equilibrium and pressures of 1 atm and 10 atm and in Fig. 1(b) the composition is given for a non-thermal equilibrium parameter θ of 2 at 1 atm. In our previous paper [11] we have shown that the vaporisation of liquid silver appears around 2400 K for 1 atm and 2900 K for 10 atm. So, we plot the composition in a scale between 2400 K and 9 000 K. In these figures we remark that the concentration of monatomic silver is higher for higher pressure in the considered temperature range. This is due to the fact that the monatomic silver is the main chemical species in the considered temperature range and then following the Dalton law (10) its concentration is higher for higher pressures. The electron concentrations have a similar behaviour with a higher concentration about a ratio of 2.5 for pressure of 10 atm than for pressure of 1 atm. When a thermal non-equilibrium is taken into account (Fig. 1(b)) the composition is different; we have an ionisation of silver and ionisation of silver ions at lower heavy species temperature. So the electrons' concentration is higher for lower heavy species temperature.

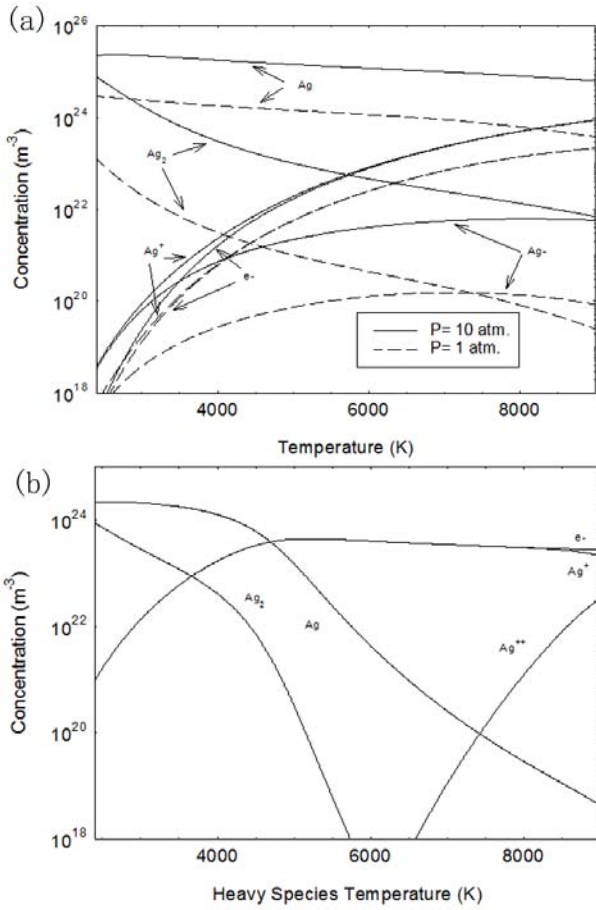


Fig.1 (a) Composition of silver plasma versus temperature for two pressures $P=1$ atm (dashed lines) and $P=10$ atm (solid lines) at thermal equilibrium, (b) Composition of silver plasma versus temperature for a pressure of 1 atm and thermal non-equilibrium parameter $\theta = \frac{T_{ire}}{T_{trh}} = 2$

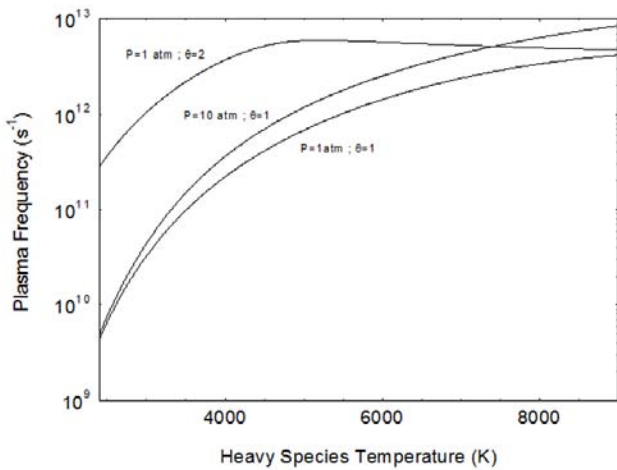


Fig.2 Plasma frequency of silver plasma versus heavy species temperature for two pressures (1 atm and 10 atm) at and out of thermal equilibrium ($\theta=1$ and $\theta=2$)

In Fig. 2, we have plotted the plasma frequency for two pressures at thermal equilibrium and for a non-thermal equilibrium parameter θ of 2 at 1 atm. The plasma frequency values obviously follow the electronic

concentration, see Eq. (1). The plasma frequency is higher for higher temperature and higher for higher parameter θ for a given heavy species temperature. The plasma frequency values vary between Gigahertz to Terahertz in the considered temperature range.

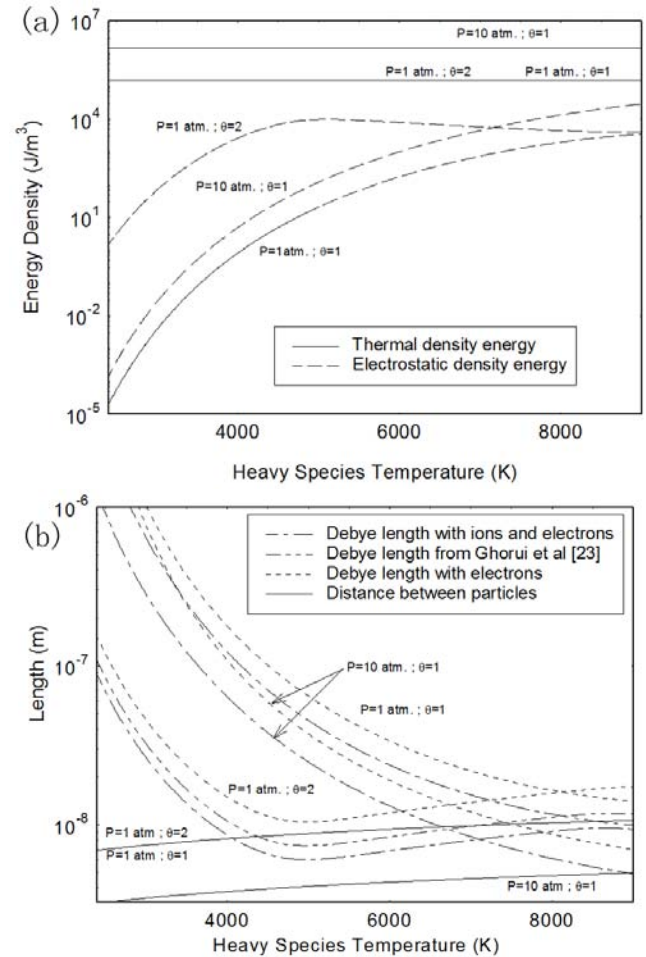


Fig.3 (a) Electrostatic energy density and thermal energy density of silver plasma versus heavy species temperature at thermal equilibrium for two pressures and out of thermal equilibrium at atmospheric pressure, (b) Debye length (dashed lines) and distance between particles (solid lines) of silver plasma versus heavy species temperature at thermal equilibrium $\theta=1$ for two pressures and out of thermal equilibrium $\theta=2$ at atmospheric pressure and for various considered Debye length formulations

In Fig. 3(a) and (b) we have plotted the values contained in the two criteria (2) and (3) with the Debye length calculated with Eq. (4) versus heavy species temperature. Since the chemical species follow the Dalton law (10), one can observe that the second member of Eq. (2) depends on the pressure. So we obtain approximately (only the variation due to the pressure correction in Debye-Hückel approximation Δp (10)) for the thermal energy density, the same value for thermal equilibrium and non-thermal equilibrium. The electrostatic density energy increases when the

thermal non-equilibrium parameter increases. As a matter of fact when the thermal non-equilibrium increases, the electrons and ions concentrations increase. Consequently, the density of charged particles increases and then the electrostatic density energy increases. For the considered temperature and pressure the criterion of plasma ideality (2) is satisfied. In Fig. 3(b), the distance between particles and the Debye length is plotted. We remark that the Debye length is higher than the distance between particles for two cases, namely at atmospheric pressure and at ten times the atmospheric pressure at thermal equilibrium but not for the case out of thermal equilibrium $\theta=2$ with the Debye length Eqs. (5) and (6). Nevertheless, taking the coefficients $\sqrt[3]{4\pi}$ the condition (3) is satisfied. A featured result is that the thermal non-equilibrium parameter can lead to a non-satisfied condition of (3) leading to the plasma to be out of Debye-Hückel approximation in our considered temperature range.

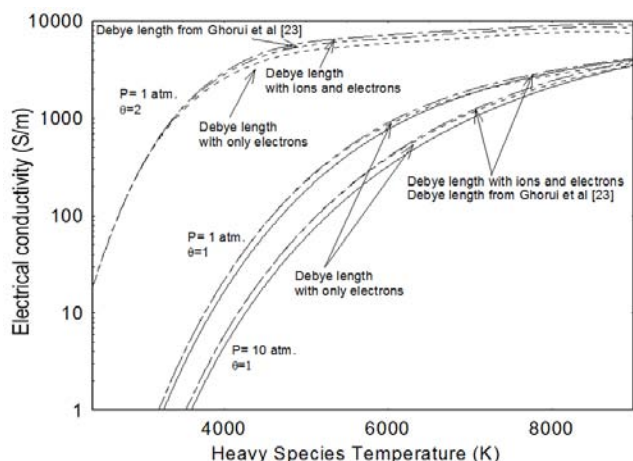


Fig.4 Electrical conductivity (S/m) calculated with the Chapman-Enskog method at the third order approximation (solid lines) and from the electrons mobility (dashed lines) at thermal equilibrium $\theta=1$ for two pressures and out of thermal equilibrium $\theta=2$ at atmospheric pressure and for various considered Debye length formulations

With the composition results (Fig. 1), we have calculated in Fig. 4 the electrical conductivity with the classical method used in the case of gas, namely Chapman-Enskog at the third order approximation [20–22], and with the described method with electron mobility (17) with the three Debye lengths (4), (5) and (6). At thermal equilibrium, the results are quite similar within 2% and the main difference can be found between the third approximation of Chapman-Enskog and from value found from the mean free path of electrons within 15%. We can notice that electrical conductivity is higher for higher thermal non-equilibrium at a given heavy temperature because the electronic concentration is higher. According to Le Chatelier’s law [43], the increase of the pressure opposes changes to the original state of equilibrium, so the ionisation appears at a

higher temperature for a higher pressure, the electrical conductivity is lower for higher pressure.

4 Evaluation of thermal non-equilibrium and estimation of electrical conductivity versus electrical field

The electrical field during fuse operation can reach an upper value around 10^4 V/m. So we consider five characteristic electrical fields ($E=5\times 10^2$ V/m, 10^3 V/m, 5×10^3 V/m, 10^4 V/m at 1 atm and 10^5 V/m at 10 atm) that can appear during fuse arc period [8,9]. The electrons get energy from electrical field and partially transfer it to the heavy particles by collisions. So two temperatures can exist, one for the electrons the other for the heavy species. Before we can get an estimation of the thermal non-equilibrium θ we have to estimate the validity of the criteria of the model. In Fig. 5(a), the electrostatic energy density and the thermal energy density are plotted versus heavy species temperature $T_h = T_{trh}$ for two electrical fields 10^4 V/m at 1 atm and 10^5 V/m at 10 atm. The electrostatic energy density is lower than the thermal energy density in the temperature range and for considered electrical fields. The thermal criterion concerning the electrostatic energy density and the thermal energy density (2) and consequently the Gibbs free energy utilization [19] is satisfied in our temperature range and in our electrical field range.

In Fig. 5(b), we have plotted the Debye length for the three Eqs. (4)–(6) and the mean distance between particles. The criterion (3) concerning the Debye-Hückel approximation is satisfied for the considered electrical fields, pressures and temperatures range taking the ratio of $\sqrt[3]{4\pi}$ of Eq. (3) into account.

In Fig. 5(c), the drift and thermal velocities are plotted versus heavy species temperature. We notice that the approximation of Maxwellian distribution (7) is satisfied since the drift velocity is lower than the thermal velocity. Consequently, we can fix a limit of validity of 10^4 V/m at atmospheric pressure and 10^5 V/m at 10 atm.

In Fig. 6, we have plotted the thermal non-equilibrium parameter θ for several electrical fields. Obviously one can observe that the thermal equilibrium is higher for higher electrical field and the thermal equilibrium is reached for electrical field lower than 10^3 V/m in considered heavy species temperature range. The thermal equilibrium ratio is around the same value for the various considered Debye length Eqs. (4), (5) and (6).

In Fig. 7, using Eq. (17) we have plotted the electrical conductivity for several electrical fields and two pressures. The ratio between electrical conductivity obtained with various considered Debye

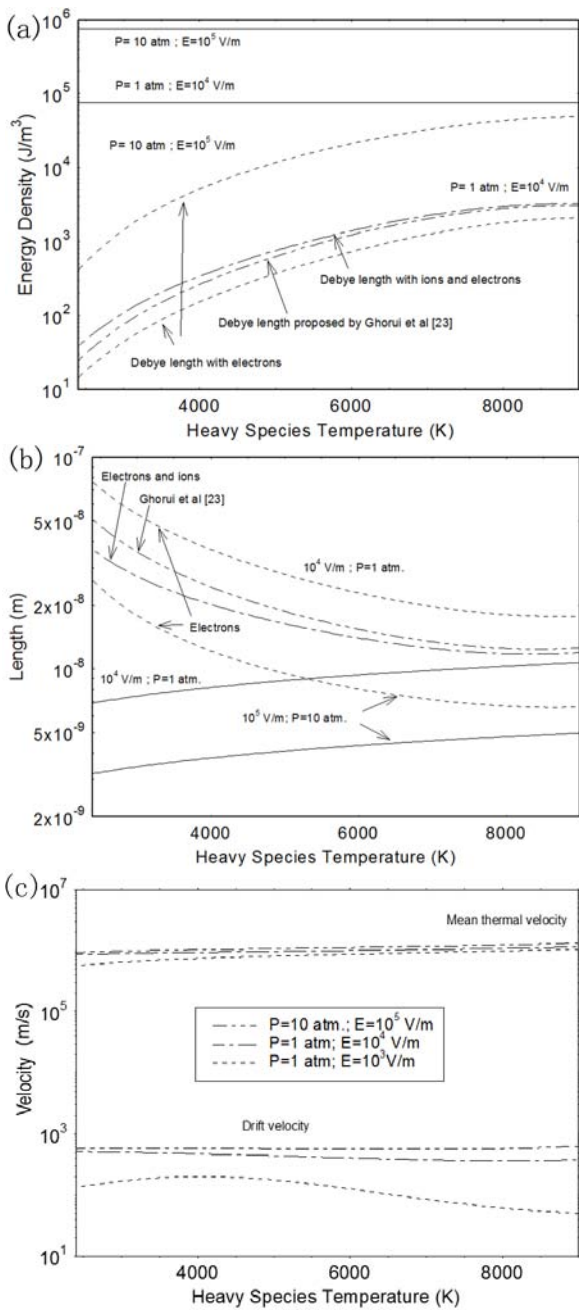


Fig.5 (a) Electrostatic energy density (dashed lines) and thermal energy density (solid lines) of a silver plasma versus heavy species temperature for several electrical fields and two pressures (1 atm and 10 atm), (b) Debye length (dashed lines) and mean distance between particles (solid lines) versus heavy species temperature in a silver plasma for several electrical fields and two pressures (1 atm and 10 atm), (c) Drift and thermal velocity versus heavy species temperature for several electrical fields and two pressures (1 atm and 10 atm)

length Eqs. (4), (5) and (6) can reach 1.3. We can observe that for the same pressure the electrical conductivity at 10^4 V/m (non-thermal equilibrium) at low temperature can reach a value higher of several decades than the one obtained at 10^3 V/m (closed to the thermal equilibrium). As a matter of fact, when the

electrical field increases the non-equilibrium parameter θ (Fig. 6) increases and then the ionisation increases for a given heavy species temperature. For higher pressure the electrical conductivity is lower for a given electrical field. So we find around the same values for electrical conductivity at pressure of 10 atm with an electrical field of 10^5 V/m than the values obtained at pressure of 1 atm with electrical field of 10^4 V/m. As a matter of fact, and as we have shown in section 2, when the pressure increases the ionisation appears at a higher temperature.

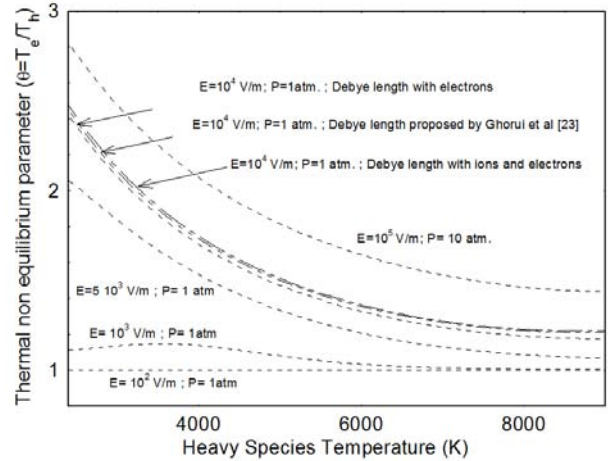


Fig.6 Thermal non-equilibrium ratios versus heavy species temperature for several electrical fields and two pressures (1 atm and 10 atm)

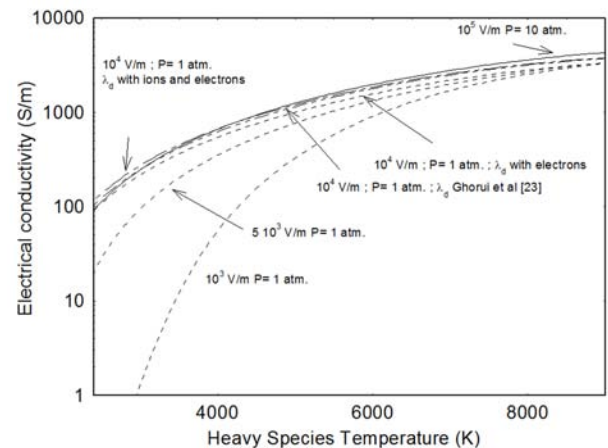


Fig.7 Electrical conductivity of a silver plasma versus heavy species temperature for several electrical fields and two pressures (1 atm and 10 atm)

5 Conclusion

The calculation of electrical conductivity in the presence of the high electrical field of pure silver plasma is required before we can understand the fuse behaviour during its work. To our knowledge, no such needed data are available. In a first step we have described the physical model to obtain the thermal non-equilibrium parameter and the electrical conductivity.

In a second step, we have tested the physical validity assumptions about the Maxwellian distribution, the plasma ideality, the Debye-Hückel approximation and the quasi electrical neutrality in such conditions. We have shown that our model can be considered as valid for pressure 1 atm and electrical field lower than 10^4 V/m and lower than 5×10^5 V/m for 10 atm. The formulation of Debye length needed notably to describe the interaction between charged particles is debatable. We have made the calculation taking the three main kinds of Debye length equations. We have shown that the thermal non-equilibrium parameter is not too sensitive to the Debye length equations unlike the electrical conductivity as mentioned in Ref. [23]. The thermal non-equilibrium parameter and electrical conductivity have been estimated for several electrical fields and pressures. In the fuse application the electrical field varies during time, due to both the distance between electrodes varying in time (burn-back) and to the applied electrical potential. The frequency of the latter has to be lower than the plasma frequency that has been already calculated in this paper. This work has to be pursued for higher plasma density leading to metallic plasma^[16] and for other kinds of electrodes^[44]. The theoretical study has also to be pursued with an evaluation of the electrical conductivity obtained from measurements at the same time of the current, the voltage, a speed camera (the electrical field and the plasma volume) and temperatures from spectroscopic measurements.

Acknowledgments

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