**Impact of pressure on air plasma contaminated with AgSnO2 Thermodynamic and Transport Analysis**

**Abstract**

The physico-chemical properties of the electric arc are decisive for the success or failure of the circuit breaker to cut the electric current. The effectiveness of the circuit breaker in cutting off the electric current is highly dependent on the thermal and electrical characteristics of the extinguishing medium. The present study theoretically evaluates the influence of pressure on the electrical current-breaking capacity of low-voltage air circuit breaker, through the thermodynamic properties and transport coefficients of air plasma contaminated with silver alloy and tin dioxide vapor. These physical quantities are determined at local thermodynamic equilibrium in a temperature range from 500 K to 30,000 K. We use the Gibbs free energy minimization method to determine the equilibrium composition and thermodynamic properties of the air-AgSnO2 mixture plasma. The analytical expressions required to determine the transport coefficients of the air-AgSnO2 mixture plasma are deduced from the Boltzmann equation using the approximate Chapman-Enskog method. Analysis of the results obtained shows that, for a given temperature, the numerical particle densities and mass density of the air-AgSnO2 mixture plasma increase as the pressure of the medium rises. The mass enthalpy, sound velocity, energy density, thermal flux density and electrical conductivity of the air-AgSnO2 mixture plasma decrease with increasing pressure. The peaks in the specific heat and thermal conductivity of the air-AgSnO2 mixture plasma are shifted towards higher temperatures as the medium pressure increases. For temperatures above 9,000 K, the dynamic viscosity of the air-AgSnO2 mixture plasma increases with increasing media pressure. As a result, the increased pressure in the medium can help extinguish the arc created when the electric current is cut off by the AgSnO2 air circuit breaker with electrical contact.

**Keywords**: circuit breaker, plasma, electric arc, thermodynamic properties, transport coefficients, pressure, AgSnO2 electrical contact.

**1. Introduction**

Switching devices such as circuit breakers play a very important role in the transport and distribution networks of electrical energy from the various production plants to the users. Indeed, the circuit breaker is the protection element by excellence which has the possibility of de-energizing an electrical circuit by instantly cutting off the current in the event of anomalies. The circuit breaker can prevent fires usually caused by these anomalies (Adjigkiga et al., 2022). The success or failure of the circuit breaker to cut off the electric current depends to a large extent on the physico-chemical properties of the arc created inside it. Improving the performance and optimizing the efficiency of air circuit breakers requires a good understanding of the physico-chemical phenomena involved in cutting off the electric current. These are influenced by electrode vapors and environmental pressure.

Studies carried out on electrical contacts such as those made of Cu, Ag, AgWC, have shown that the behavior of the electric arc changes according to the nature of the electrodes of the circuit breaker [1–6].

We have chosen to focus on silver-tin dioxide alloy (AgSnO2) because it is becoming increasingly popular for circuit-breaker electrical testing. In addition, it is highly resistant to arc erosion and has good anti-welding properties [7–10].

Studies have been carried out on tin dioxide (SnO2) sensors doped with noble metals such as Pd and Ni for the detection of a wide variety of toxic, combustible and industrial gases [11–13]. When the electric current is cut in a circuit breaker, an electric arc is created between its electrodes. This electric arc will generate a plasma which can be de-fined as a medium made up of a set of particles (atoms, molecules, electrons, radical ions) totally or partially ionized and electrically neutral (Kohio et al., 2020).

In this work, we are interested in the influence of pressure on the electrical current interrupting capacity of the low-voltage air circuit breaker through the thermodynamic properties and transport coefficients of the air-AgSnO2 mixture plasma. The pressure of the medium can also be used to assess arc extinguishing performance [14]. The effectiveness of the circuit breaker in cutting off the electric current is highly dependent on the thermal and electrical characteristics of the extinguishing medium. It is therefore advisable to select an extinguishing medium that simultaneously offers at least the following characteristics [15]:

* high thermal flux density;
* low energy density;
* high thermal conductivity;
* low electrical conductivity decreasing with temperature.

The paper is divided into an introduction, an analytical expressions section, a results section and a conclusion, with references.

**Methodology:**

**Analytical expressions**

We use the **Gibbs** free energy minimization method to determine the equilibrium composition and thermodynamic properties of the air-AgSnO2 mixture plasma [16, 17]. The analytical expressions required to determine the transport coefficients of the air-AgSnO2 mixture plasma are deduced from the **Boltzmann** equation using the approximate **Chapman-Enskog** method. In their work, **Colombo** et **al** [18–20] have shown that the simplified expressions of **Devoto** [21] can be used to calculate plasma transport coefficients.

The equilibrium composition of the plasmas studied, required to calculate the various quantities, is given by **Banouga** et **al** [16]. In the plasma mixtures of air, silver and tin dioxide studied, we took into account forty (40) chemical particles:

* The electron and the monatomic particles are in total seventeen (17):

e-, Ag, N, O, Sn, Ag-, N-, O-, Sn-, Ag+, N+, O+, Sn+, Ag2+, N2+, O2+, Sn2+ ;

* The diatomic particles are a total of eleven (11):

NO, N2, O2, SnO, Sn2, N2-, O2-, NO-, NO+, N2+, O2+ ;

* l the triatomic particles and more are in total twelve (12):

N2O5, N2O4, N2O3, NO3, NO2, N2O, N3, O3, SnO2, N2O+, NO3-, NO2-.

**2.1. Thermodynamic properties**

**2.1.1. Mass density (kg.m-3)**

The mass density measures the amount of matter contained in a given volume of plasma. The mass density is given by the following relationship [22–24]:

 (1)

Where  is the total number of chemical particles,  (kg) the mass and  (m-3) the numerical density of the particle .

**2.1.2. Mass enthalpy (J.kg-1)**

The change in enthalpy **** of a system at constant pressure is the amount of heat transferred from the outside to the system, or from the system to the outside. The mass enthalpy can be expressed by the following relationship [17, 25]:

 (2)

where  (J.mol-1) is the standard enthalpy of formation at reference pressure P0 (P0 = 105 Pa) and temperature 300 K.  (J.mol-1) is the specific molar enthalpy at reference pressure P0 of the particle .  and Xi are respectively the average molar mass and molar fraction of the particle .

**2.1.3. Specific heat at constant pressure (J.kg-1.K-1)**

The specific heat or mass heat is the amount of energy required by heat exchange to raise the temperature of a medium by one degree. It represents a system's capacity to store heat. The mass heat can be defined from the enthalpy variation [14, 26]:

  (3)

where  is the temperature step. For this approximation to give good results, the temperature step must be sufficiently small  [27]. In this work, we have taken 100 K as the temperature step.

**2.1.4. Sound velocity in plasma (m.s-1)**

The speed of sound is the speed at which small disturbances propagate in a fluid. It is defined by [17, 28]:

 (4)

where R (J.mol-1.K-1) is the perfect gas constant,  (kg.mol-1) the average molar mass, T (K) the temperature and  the ratio of heats of mass at constant pressure and constant volume.

**2.1.5. Energy density (J.m-3)**

The energy density characterizes the distribution of energy in the medium. It is expressed as a function of mass density and mass enthalpy [14, 17, 23, 28]:

 (5)

**2.1.6. Thermal flux density (W.m-2)**

The thermal flux density determines the plasma's ability to evacuate energy to the outside environment through the cut-off chamber's exhaust surfaces. It is linked to the energy density and speed of sound in the plasma [14, 17, 23, 28]:

 (6)

**2.2. Transport coefficients**

**2.2.1. Electrical conductivity (Ω-1.m-1)**

The electrical conductivity of a plasma is a measure of its ability to conduct electric current. As the mobility of ions is lower than that of electrons, the electrical conductivity of a plasma is essentially provided by electrons. From the 3rd order approximation of the **Chapman-Enskog** method, it can be expressed by the following relationship [29–32]:

 (7)

where k is **Boltzmann**'s constant, e (C) the elementary charge,  (kg) the electron mass and  (m-3) the electron numerical density. The terms  are expressed in terms of the numerical densities and mean effective cross-sections of particle collisions.

**2.2.2. Thermal conductivity (W.m-1.K-1)**

The thermal conductivity represents the ability of materials or gas mixtures to conduct heat. The total thermal conductivity can be written as the sum of [33–36]:

* the thermal conductivity of translation, due to the translation of heavy particles  and electrons ;
* reaction thermal conductivity , due to various chemical reactions;
* internal thermal conductivity , due to internal molecular energies.

Thus, we have:

 (8)

**2.2.3. Dynamic viscosity (kg.m-1.s-1)**

The dynamic viscosity of a plasma characterizes its resistance to flow. It is highly dependent on heavy particles. The dynamic viscosity can be expressed by the following relationship [37–39]:

 (9)

The matrix elements Hii and Hij are expressed in terms of molar masses Mi (kg.mol-1), collision integrals  (m2) and mole fractions Xi.

**3. Results and discussions**

In this section, we present the results of the thermodynamic properties and transport coefficients of the air-AgSnO2 mixture plasma for different pressure values. They are determined at local thermodynamic equilibrium (LTE) over a temperature range from 500 K to 30,000 K. We have selected five pressure values for this purpose, namely P = 1 atm, P = 5 atm, P = 10 atm, P = 15 atm and P = 20 atm. We have chosen to present only the results for plasmas of 99% air and 1% AgSnO2 alloy vapor, in order to reduce the volume of results presented, especially as the thermodynamic properties and transport coefficients of the air-AgSnO2 plasma mixtures we have studied show similar behavior with respect to the pressure value [16, 17]. The AgSnO2 alloy electrical contact material used in this study consists of 4% SnO2 and 96% Ag. In fact, metal oxides of the SnO2 type (3.3 to 14% maximum) are intended to reduce the risk of welding in the cutting device. However, their addition in large quantities increases the duration of the electric arc, thus aggravating the erosion of electrical contacts [6, 7, 17]. We considered mass percentages.

F**igures** **1** and **2** respectively show the evolution of the numerical particle densities, as a function of temperature and at local thermodynamic equilibrium, for plasmas of 99% air - 1% AgSnO2 alloy vapor at pressures of 1 atm and 15 atm.

Looking at the various results in **figures** **1** and **2**, we see that the numerical particle densities of the various plasma particles increase as the pressure of the medium increases for the same given temperature. For example, at 15,000 K, under a pressure of 1 atm, the numerical densities of Ag; Sn; O and N particles in the 99% air - 1% AgSnO2 alloy vapor plasma are respectively 9.9761x1017 m-3; 1.6290x1018 m-3; 5.4367x1022 m-3 and 1.4953x1023 m-3. And at 15,000 K, under a pressure of 15 atm, the numerical densities of Ag; Sn; O and N particles in the 99% air - 1% AgSnO2 alloy vapor plasma are respectively 8.2952x1019 m-3; 1.3988x1020 m-3; 1.2362x1024 m-3 and 4.0260x1024 m-3. Indeed, as the pressure of the mixture increases, the collision rate is higher and, consequently, the speed of dissociation and ionization reactions increases. This may explain the increase in particle number density as the pressure of the medium increases.



**Figure 1**. Evolution of the numerical particle densities of 99% air - 1% AgSnO2 plasma at 1 atm pressure, as a function of temperature and at ETL



**Figure 2**. Evolution of the numerical particle densities of 99% air - 1% AgSnO2 plasma at 15 atm pressure, as a function of temperature and at ETL

F**igure 3** shows the evolution of the mass density of the plasma mixture of 99% air - 1% AgSnO2 alloy vapor, as a function of temperature and at local thermodynamic equilibrium, for different pressure values. We find that, for a given temperature, the mass density increases slightly with increasing mixture pressure. For example, at 5,000 K, under a pressure of 1 atm, the 99% air - 1% vapor plasma of the AgSnO2 alloy has a mass density of 0.0607 kg.m-3, and under a pressure of 20 atm, it has 0.0641 kg.m-3, an increase of 5%. The increase in mass density as pressure rises can be explained, on the one hand, by the fact that the gas becomes denser. When a gas is at high pressure, it becomes denser and the gas particles move closer together. On the other hand, the increase in mass density as pressure rises can be explained by the shifting of the equilibria of the various dissociation and ionization reactions to higher temperatures.



**Figure 3**. Influence of pressure on the mass density of 99% air - 1% AgSnO2 plasma, at ETL.

F**igure 4** shows the evolution of the plasma mass enthalpy of the 99% air - 1% AgSnO2 alloy vapour mixture, as a function of temperature and at local thermodynamic equilibrium, for different pressure values. We note that plasma enthalpy of mass decreases with increasing pressure. For example, at 8,000 K, under a pressure of 1 atm, the plasma of 99% air - 1% AgSnO2 alloy vapor has a mass enthalpy 3.6214x107 J.kg-1, and at a pressure of 20 atm, it has 2.2868x107 J.kg-1, a decrease of 36%. This decrease in enthalpy of mass can be explained by the increase in mass density in the mixture, as the pressure of the medium increases.



**Figure 4**. Influence of pressure on the mass enthalpy of 99% air - 1% AgSnO2 plasma at ETL.

F**igure 5** shows the evolution of the plasma-specific heat of a 99% air - 1% AgSnO2 alloy vapor mixture, as a function of temperature and at local thermodynamic equilibrium, for different pressure values. We note a shift in the plasma-specific heat peaks towards higher temperatures and a slight decrease in their values with increasing pressure. The various dissociation and ionization reactions are responsible for these variations in specific heat. Indeed, as pressure increases, the various dissociation and ionization reactions take place at higher temperatures.



**Figure 5**. Influence of pressure on the specific heat of 99% air - 1% AgSnO2 plasma at ETL.

F**igure 6** shows the evolution of the sound velocity in the plasma of the 99% air - 1% AgSnO2 alloy vapor mixture, as a function of temperature and at local thermodynamic equilibrium, for different pressure values. The speed of sound in the plasma decreases with increasing pressure, for a given temperature. Indeed, when a gas is at high pressure, it becomes denser and the gas particles move closer together. This explains the decrease in the speed of sound in plasma.



**Figure 6**. Influence of pressure on the sound velocity of 99% air - 1% AgSnO2 plasma at ETL.

F**igure 7** shows the evolution of the energy density of the 99% air - 1% AgSnO2 alloy vapor plasma, as a function of temperature and local thermodynamic equilibrium, for different pressure values. We see that the energy density decreases with increasing medium pressure.



**Figure 7**. Influence of pressure on the energy density of 99% air - 1% AgSnO2 plasma at ETL.

F**igure 8** shows the evolution of the thermal flux density of the 99% air - 1% AgSnO2 alloy vapor plasma mixture, as a function of temperature and at local thermodynamic equilibrium, for different pressure values. We note that the thermal flux density decreases as the pressure of the medium increases.



**Figure 8**. Influence of pressure on the thermal flux density of 99% air - 1% AgSnO2 plasma at ETL.

F**igure 9** shows the evolution of the electrical conductivity of the 99% air - 1% AgSnO2 alloy vapor plasma, as a function of temperature and at local thermodynamic equilibrium, for different pressure values. We observe that electrical conductivity decreases slightly with increasing pressure, for temperatures below 14,000 K. For example, at 11,000 K under a pressure of 1 atm, the 99% air - 1% vapor plasma of AgSnO2 alloy has an electrical conductivity of 4996 Ω-1.m-1, and it has a value of 3406 Ω-1.m-1, under a pressure of 20 atm, a decrease of 31%. This decrease in electrical conductivity can be explained by shifting chemical equilibria. In fact, the increase in pressure in the mixture causes dissociation and ionization phenomena to shift to higher temperatures.



**Figure 9**. Influence of pressure on the electrical conductivity of 99% air - 1% AgSnO2 plasma at ETL.

F**igure 10** shows the evolution of the thermal conductivity of the 99% air - 1% AgSnO2 alloy vapor plasma, as a function of temperature and at local thermodynamic equilibrium, for different pressure values. We find that increasing pressure leads to a shift in thermal conductivity peaks towards higher temperatures. In fact, increasing pressure causes dissociation and ionization phenomena to shift to higher temperatures. As thermal conductivity is strongly linked to the various chemical reactions, the shift in its peaks under the action of the medium's pressure can be explained by the displacement of chemical equilibria.



**Figure 10**. Influence of pressure on the thermal conductivity of 99% air - 1% AgSnO2 plasma at ETL.

Figure 11 shows the evolution of the dynamic viscosity of the 99% air - 1% AgSnO2 alloy vapor plasma mixture, as a function of temperature and at local thermodynamic equilibrium, for different pressure values. For temperatures below 9,000 K, we observe that the dynamic viscosity hardly varies as the pressure of the medium increases. And for temperatures above 9,000 K, the dynamic viscosity increases with increasing pressure in the mixture. For example, at 15,000 K, under a pressure of 1 atm, the plasma of a mixture of 99% air - 1% AgSnO2 alloy vapor has a dynamic viscosity of 1.4885x10-4 kg.m-1.s-1, and a value of 2.6641x10-4 kg.m-1.s-1, under a pressure of 20 atm, an increase of 78%. This increase of the dynamic viscosity can be explained by the displacement of chemical equilibria under the action of pressure.



**Figure 11**. Influence of pressure on the dynamic viscosity of 99% air - 1% AgSnO2 plasma at ETL.

**4. Conclusion**

We have theoretically evaluated the influence of pressure on the thermodynamic properties and transport coefficients of air plasma contaminated with silver-tin dioxide alloy (AgSnO2) vapor, over a temperature range from 500 K to 30,000 K, at local thermodynamic equilibrium.

The results obtained show that, for a given temperature, the numerical particle densities and mass density of the air-AgSnO2 mixture plasma increase as the medium pressure rises. The mass enthalpy, sound velocity, energy density, thermal flux density and electrical conductivity of the air-AgSnO2 mixture plasma decrease with increasing pressure. The specific heat and thermal conductivity peaks of the air-AgSnO2 mixture plasma are shifted to higher temperatures as the medium pressure increases. At temperatures above 9,000 K, the dynamic viscosity of the air-AgSnO2 plasma increases as the pressure rises.

By comparing the characteristics of a good extinguishing medium with those of the air plasma contaminated by electrical contact vapors in the AgSnO2 alloy, under the influence of pressure, we note that increasing the pressure of the medium can be favorable to extinguishing the electric arc created when the electric current is cut off by the AgSnO2 electrical contact air circuit breaker.

However, a study of the radiation of the air-AgSnO2 mixture plasma at different pressure values might be necessary to better appreciate the influence of pressure on the extinction of the electric arc created.

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