Transport Coefficients of Air - PMMA Mixtures Thermal Plasmas

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Abstract
The transport coefficients of Air - PMMA mixtures thermal plasmas is important to estimate the performances of cutting of the electrical arc in this gas by a circuit breaker. In this paper, Air - PMMA mixtures thermal plasmas dynamical viscosity, thermal and electrical conductivities coefficients are calculated in a temperature range from 5000K to 30000K. The calculations are made by supposing thermodynamic equilibrium at pressure of 1 bar to 10 bar. The results of the calculations show the influence of the initial proportion of PMMA but also that of the pressure on the mixture plasma transport coefficients. As the efficiency of the breaking of the electric current by the circuit breaker depends closely on the thermal and electrical characteristics of the extinguishing medium, this extinguishing medium should have a high thermal conductivity and an electrical conductivity varying rapidly with temperature. The plasma of the mixture constituted by 80% of air and 20% of PMMA presents at first sight best characteristics for the breaking of electric current. It has the highest thermal conductivity peak among the plasmas of the mixtures studied.

Keywords: electrical arc, thermal plasma, dynamical viscosity, thermal conductivity, electrical conductivity, circuit breaker

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1. Introduction

The electrical arc which is generally defined as a high current electrical discharge has a wide variety of applications these days. Due to the wide range of its applications, it has given rise to numerous research works both on experimental and theoretical level [1-36]. Among its applications, we can cite lighting, welding, cutting, waste treatment and cutting of electric current. Indeed, the interruption of the electric current in certain switchgear, in particular the circuit breaker, is done from the electrical arc. To cut the electrical current, the opening of the circuit breaker contacts creates an electric arc which interacts with the surrounding environment. If in most applications, the arc must be maintained for as long as possible, its rapid extinction is sought in breaking devices. In fact, they are designed to provide manual or automatic control of electrical circuits (contactors) as well as protection of installations against short circuits (circuit breaker).

Certain arc electric cutting techniques are based on the rapid elongation of the arc between the contacts and others, on a rolling of the arc between two insulating parts. Numerous theoretical [3,4,13,18,25,27-36] and experimental [3,10] studies have already been carried out on polymers. From studies carried out on laminated arcs with ablative walls [2,3], it appears that the PMMA polymer has interesting characteristics for breaking the electric current.

Our study is part of the interruption of the electric current by means of the electric arc used as energy dissipater by heat exchanges with the surrounding environment. As the electric current cutting technique in air and compressed air [37] is widely used in low and medium voltage circuit breakers, in this work, we want to study the influence of the PMMA polymer on air breaking performance. The breaking performance is partly linked to certain characteristics of the plasma formed in the circuit breaker at the time of breaking. This article is therefore devoted to the calculation of the transport coefficients of Air - PMMA mixtures thermal plasmas at thermodynamic equilibrium. In addition to pure air and pure PMMA, the mixtures concerned are: 80% Air - 20% PMMA; 50% Air - 50% PMMA; 20% Air - 80% PMMA. The temperature range goes from 5000K to 30000K for pressures of 1 bar; 2 bar; 5 bar; 8 bar and 10 bar. Transport properties such as dynamic viscosity, thermal and electrical conductivities are calculated using expressions deduced from Chapman Enskog theory. Determining any characteristic of a plasma begins with knowing the equilibrium composition of the plasma. The different chemical species that we have taken into account in the composition of plasmas are: e, C, H, N,
O, C₂, H₂, N₂, O₂, CH, CO, CN, OH, HN, NO, C⁺, H⁺, O⁺,
N⁺, CH⁺, CO⁺, CN⁺, OH⁺, HN⁺, NO⁺, C₂⁺, H₂⁺, N₂⁺, O₂⁺,
C₂⁺, H₂⁺, N₂⁺, O₂⁺, C₂⁺, N₂⁺ and O₂⁺ [28].

2. Transport Coefficients

The electrical and thermal conductivities and the
coefficient of dynamical viscosity are the transport
coefficients retained in this study. The theoretical study of
these coefficients is based on the resolution of the
Boltzmann equation by the Chapman-Enskog [38] method.
Devoto developed exact theoretical expressions which
allow the calculation of transport coefficients of gas
mixtures at v components. But for gases constituted by
numerous particles as ours, the calculations become
complicated from the third-order approximation of
Chapman-Enskog method. However, it is shown that we
can bring simplifications to the expressions of the
transport coefficients of mixture at ν components when
one of the chemical species has a very low mass with
regard to that of the other components. Indeed, electrons
have an unimportant mass with regard to that of the heavy
particles. Thus the transport properties of electrons and
heavy particles are independently treated.

2.1. Thermal Conductivity Coefficient

The following relation gives the total thermal
conductivity of the plasma:

\[ \lambda = \lambda_{n_e}^c + \lambda_{n_e}^h + \lambda_{int} + \lambda_R \]  

(1)

\[ \lambda_{n_e}^c \] and \[ \lambda_{n_e}^h \] are respectively the translation thermal
conductivities of electrons and heavy particles. \[ \lambda_{int} \] is the
internal thermal conductivity bound to the existence of
freedom degrees due to the molecules vibrations and the
rotations. \[ \lambda_R \] is the thermal conductivity due to the
reactions of ionization, recombination and dissociation.

\[ \lambda_{n_e}^c = 75n_e^2k \left( \frac{2\pi kT}{m_e} \right)^{1/2} \frac{1}{q^{11}(q^{12})^2 / q^{22}} \]  

(2)

\[ \lambda_{n_e}^h = 4n_e^2k \left( \frac{2\pi kT}{m_e} \right)^{1/2} \frac{1}{q^{11}(q^{12})^2 / q^{22}} \]  

(3)

Where \( x_i \) is the molar fraction of the particle i. The term
\( L_{ij} \) is a function of the heavy particles collision integrals,
masses molars and the plasma composition [38]. Because
of the existence of chemical reactions in the plasma, the
transfer of energy can be made under the shape of
chemical enthalpy. The thermal conductivity of reaction
reports processes not elastics in the plasma. It is defined at
the first order approximation by:

\[ \lambda_R = \frac{-1}{RT^2} \begin{vmatrix} 0 & \Delta H_1 & \ldots & \Delta H_\mu \\ \Delta H_1 & A_{11} & \ldots & A_{1\mu} \\ \vdots & \vdots & \ddots & \vdots \\ \Delta H_\mu & A_{\mu1} & \ldots & A_{\mu\mu} \end{vmatrix} \]  

(4)

where \( \Delta H_i \) represents the variation of enthalpy due to the
\( i^{th} \) chemical reaction. R is the constant of perfect gases.
The transfer of energy in internal movements (rotation and
vibration) of molecules is expressed by the internal
conductivity. By extension of the theory of Eucken for a
pure gas, we have:

\[ \lambda_{int} = \sum_{i=1}^{\nu} \left( \frac{\lambda_{int}^i}{x_i} \right) \]  

(5)

\( \lambda_{int}^i \) is the internal thermal conductivity of the \( i^{th} \)
component.

\[ \Xi_{ij} \] are defined by the relation:

\[ \Xi_{ij} = \frac{3}{16\sqrt{\pi}} \left( \frac{kT}{P_m^{1/2}} \right) \left( \frac{M_i + M_j}{2M_i M_j} \right)^{1/2} \]  

(6)

2.2. Electrical Conductivity Coefficient

By neglecting the contribution of the ions, Devoto
obtained a simplified theoretical expression for the
calculation of the electrical conductivity coefficient:

\[ \sigma = \frac{3}{2} n_e^2 \left( \frac{2\pi}{m_e kT} \right)^{1/2} \begin{vmatrix} q^{11} & q^{12} \\ q^{12} & q^{22} \end{vmatrix} \]  

(7)

\( n_e \) is the electrons numerical density and \( m_e \) the mass of the
electron.

\( q^0 \) depends on numerical densities and on average
effective sections of particles collision.
2.3. Dynamical Viscosity Coefficient

The transport of the impulse in the plasma is characterized by the coefficient of dynamical viscosity. It is independent from properties of electrons because of their low mass. A good approximation of this coefficient is obtained by:

$$\eta = \sum_{i=2}^{\nu} \frac{x_i^2}{\eta_i} + 1.385 \sum_{j=2}^{\nu} \frac{x_i x_j}{P_i M_i \Xi_{ij}^{(2,2)}}$$  \hspace{1cm} (8)

where \(m_i\) and \(x_i\) are respectively the mass and the molar fraction of the species \(i\); \(\eta_i\) is the coefficient of viscosity of a pure gas defined by Hirschfelder like:

$$\eta_i = \frac{5}{16 \sqrt{\pi}} \frac{(M_i kT)^{1/2}}{\Omega_{ij}^{(2,2)}}$$  \hspace{1cm} (9)

3. Collision Integrals

Determining the transport coefficients requires knowledge of the collision integrals between the particles present in the plasma. The values of these transport coefficients therefore depend closely on the values of the collision integrals corresponding to the different interactions present in the plasma. The calculation of the plasma transport coefficients can only be carried out once the equilibrium composition of the medium has been determined.

The knowledge of the collision integral is determining for the calculation of the transport coefficients. It is thus important to choose the types of interaction which are appropriate with the nature of the particles populating studied plasma. The calculation of the collision integrals is made by considering four categories of interaction: Neutral - neutral interaction; neutral - ion interaction; electron - neutral interaction and charged - charged interaction.

3.1. Neutral - Neutral Interaction

Two methods were applied for the determination of the collision integrals: the method of smoothing of the published results and the method of the reduced temperatures.

**Interaction N-N:** We used the values published by Capitelli et al [3] from the Morse potential.

**Interaction N-N_{2} and N_{2}-N_{2}:** These interactions are represented by a repulsive exponential potential. The corresponding collision integrals are proposed by Capitelli et al [3].

**Interaction H-H, H-H_{2} and H_{2}-H_{2}:** We retained the results of Vanderslice et al [3] but for the collision integral \(\Omega^{(2,2)}\) of the H-H interaction, we chose the values proposed by Belov [3]. This author considers an interval of much wider temperature covering our temperature range.

**Interaction O-O, O-O_{2} and O_{2}-O_{2}:** We used the values obtained by Mexmain [3] who made a detailed study of these interactions. By the method of the reduced temperatures, we use the reduced collision integrals published by Hirschfelder [38] according to the reduced temperature \(T^*\). For other interactions between not polar neutral species, the used potential is the one of Lennard-Jones.

The reduced temperature is given by:

$$T^* = \frac{k}{\varepsilon} T$$  \hspace{1cm} (10)

$$\frac{\varepsilon}{k} = 0.77 \frac{3}{2} T_b$$  \hspace{1cm} (11)

where \(T_b\) is the boiling point of the particle, \(\varepsilon\) is the maximum of attractive energy for an interaction between similar species.

3.2. Electron - Neutral Interaction

We used the collision integrals published by Spencer et al [3] for e - H, e - O, e - H_{2}, e - O_{2}, e - N_{2}, e - CO, e - OH and e - NO interactions and the method of the stiff spheres for the interactions e - C_{2}, e - CH, e - CN and e - HN. For the interaction e - N, we retained the values proposed by Capitelli et al [3]. The collision integrals of e - C interaction are calculated by Robinson et al [3].

3.3. Neutral - Ion Interaction

It is the collision integrals calculated by Capitelli et al [3] that we used for the interactions H - H_{+}; N - N_{+} and those calculated by Eymard [3] for the interaction N_{2} - N_{2}^{+}. For the interactions O - O_{+} and O_{2} - O_{2}^{+}, we used the values calculated by Mexmain [3]. Other neutral - ion interactions were considered purely elastic and the corresponding integrals of collision was determined from Maxwell's potential.

3.4. Charged - Charged Interaction

We used the collision integrals of charged - charged particles calculated by Devoto [3].

In general, the collision integrals published in the references cited previously is given for \(\Omega_{ij}^{(1,1)}\) and \(\Omega_{ij}^{(2,2)}\). Thus to obtain the others we used the formula of recurrence established by Hirschfelder [38]:

$$\Omega_{ij}^{(l,s+1)} = \Omega_{ij}^{(l,s)} + \frac{T}{s+2} \frac{\partial \Omega_{ij}^{(l,s)}}{\partial T}. \hspace{1cm} (12)$$

4. Results and Discussion

In this part we present the results of the calculations of the transport coefficients of the studied mixtures plasmas. An analysis of the influence of the PMMA percentage in the mixture as well as that of the pressure on the plasma transport coefficients is made.

Figure 1 shows the evolution of thermal conductivity \(\lambda\) of plasma as a function of the PMMA percentage in the mixture, at a pressure of 1 bar. With the exception of pure air, we observe few differences between the values of the thermal conductivity of the various mixtures plasmas. The
peaks of $\lambda$ observed, at $T = 7000K$, correspond to the dissociation of the particles CO and N$_2$. The peaks due to the dissociation of the other diatomic particles of the plasmas of the Air - PMMA mixtures, are located at temperatures below 5000K. The thermal conductivity highest peak at $T = 7000K$ is that of pure air plasma.

Figure 1. Evolution of the plasma thermal conductivity as a function of the PMMA percentage in the mixture, at a pressure of 1 bar

For high temperatures, ie for $T \geq 20000K$, the plasmas are almost completely ionized. The thermal conductivity is mainly due to the translational thermal conductivity of the electrons. The equilibrium composition of the different plasmas shows that they all have almost the same electron numerical density, for high temperatures [28]. This explains the similarity of the thermal conductivity evolution of the various mixtures plasmas beyond 20000K. The influence of the ionization of simple atoms C, H, O and N, appears from temperatures between 13000K and 16000K. In this temperature range, it is the 80% Air - 20% PMMA mixture plasma which gives the most significant thermal conductivity peak. The thermal reaction conductivity constitutes the main component of the total thermal conductivity, for temperatures corresponding to the dissociation and ionization temperatures of the various particles. The thermal conductivity $\lambda$ plays a very important role on the arc time constant $\tau$. Consequently, the shape of the curve $\lambda (T)$ gives information on the quality of the mixture considered for cutting the electric arcs. The importance of this thermal conductivity manifests itself particularly through its reaction component $\lambda_R$. From the study of several gases, Hertz [3] proposes an empirical relation linking the arc time constant $\tau$ to the maximum of the plasma thermal reaction conductivity coefficient: $\tau \lambda_R^{\text{max}} = C\tau$. This relation clearly shows the primordial role that the thermal conductivity of reaction plays in the speed of extinction of arcs. If the peak of $\lambda_R$ is high, then the extinction time of the arc is short.

To show the influence of pressure, we have only presented results for the case of the plasma of the 50% Air -50% PMMA mixture to give the most significant results. The remarks made on the influence of pressure on the thermal conductivity of this plasma are valid for the other plasmas. In Figure 2, we have represented the curves, as a function of the temperature, of the 50% Air - 50% PMMA mixture plasma thermal conductivity for the different values of the pressure. The direction of the arrows in the figure indicates the increasing direction of pressure.

It is noted that when the pressure increases, the peaks of the thermal conductivity $\lambda$ move towards the high temperatures. The translation of the peaks is linked to the displacements of the chemical reaction equilibria that we observed and explained when studying the composition of the plasma. This translation of the ionization and dissociation peaks is accompanied by a slight increase in the value of the thermal conductivity.

Figure 2. The curves of the 50% Air - 50% PMMA mixture plasma thermal conductivity as a function of the pressure value

The evolution of the electrical conductivity of the mixtures plasmas studied is shown in Figure 3. For the high temperatures, the various mixtures plasmas have almost identical electrical conductivities. At these temperatures, all plasmas are almost completely ionized, and have the same electron numerical density. The electrical conductivity then becomes independent of the nature of the mixture considered.

Figure 3. Evolution of the plasma electrical conductivity as a function of the PMMA percentage in the mixture, at a pressure of 1 bar

In the temperature range of 7000K to 13000K, the air plasma has the weakest electrical characteristic. From 13000K to 22000K, it has an electrical conductivity slightly higher than that of other plasmas. Beyond 22000K
its electrical conductivity is significantly lower than that of all other plasmas. On the other hand, the electrical properties of 80% Air - 20% PMMA, 50% Air - 50% PMMA and 20% Air - 80% PMMA mixtures plasmas are identical over almost the entire temperature range.

To show the influence of pressure, we have only presented results for the case of the plasma of the 50% Air - 50% PMMA mixture to give the most significant results. The remarks made on the influence of pressure on the electrical conductivity of this plasma are valid for the other plasmas studied. Figure 4 gives the curves, as a function of the temperature, of the electrical conductivity of 50% Air - 50% PMMA mixture plasma for the different values of the pressure. In this figure, the arrow indicates the increasing direction of pressure.

It is found that the plasma becomes less conductive when the pressure increases at low temperatures (T ≤ 12000K). The increase in pressure leads to an increase in the concentrations of molecular species. Collisions e- heavy particles are then more important and more frequent. This causes the electrons to brake, and leads to a decrease in the electrical conductivity. From 13000K, an inversion of this evolution of the electrical conductivity is observed; it increases when the pressure increases. At high temperatures, all molecular species are dissociated. Collisions e-heavy particles become negligible. As at these temperatures the plasma is characterized by a high electronic density, this leads to high electrical conductivity values. Furthermore, we note that the influence of pressure on electrical conductivity is identical for all the plasmas studied.

The evolution of the dynamic viscosity of the five plasmas of the mixtures, as a function of the temperature, is given in Figure 5. This figure shows that the most viscous plasmas are those containing a high percentage of oxygen and a low percentage of hydrogen and carbon. The arrow shows the increasing direction of the PMMA percentage in the mixture which gave rise to plasma. Pure air plasma has the highest dynamic viscosity and pure PMMA plasma the lowest dynamic viscosity. Air plasma is characterized by the presence of heavy particles, especially NO at relatively high temperatures, and this is what contributes to making it fairly viscous. But this presence of the NO species also leads to an increase in the electron density, at low temperature. For all plasmas, there is a similar variation in dynamic viscosity as a function of temperature. It increases at first time to reach its peak between 10000K and 120000K, then decreases rapidly in a second time between 12000K and 20000K and finally tends towards a limit value between 20000K and 30000K.

To show the influence of pressure, we have only presented results for the case of the plasma of the 50% Air - 50% PMMA mixture to give the most significant results. The influence of pressure on the dynamical viscosity of this plasma are valid for the other plasmas. Figure 6 shows the evolution of the dynamic viscosity of the 50% Air - 50% PMMA mixture plasma, as a function of the temperature for the different pressure values. At low temperature, the dynamic viscosity is independent of the pressure. From T = 9000K, we notice that the maximum of the dynamic viscosity moves towards high temperatures when the pressure increases. This evolution of the dynamic viscosity with pressure is explained by the fact that heavy particles disappear at higher temperatures when the pressure is high.

The evolution of the dynamic viscosity of the five plasmas of the mixtures, as a function of the temperature, is given in Figure 5. This figure shows that the most viscous plasmas are those containing a high percentage of oxygen and a low percentage of hydrogen and carbon. The arrow shows the increasing direction of the PMMA percentage in the mixture which gave rise to plasma. Pure air plasma has the highest dynamic viscosity and pure PMMA plasma the lowest dynamic viscosity. Air plasma is characterized by the presence of heavy particles, especially NO at relatively high temperatures, and this is what contributes to making it fairly viscous. But this presence of the NO species also leads to an increase in the

5. Conclusion

In this work, Air - PMMA mixtures thermal plasmas dynamical viscosity, thermal and electrical conductivities
are calculated in a temperature range from 5000K to 30000K. The calculations are made by supposing thermodynamic equilibrium at pressure of 1 bar to 10 bar. The calculations of these transport coefficients is based on the resolution of the Boltzmann equation by the Chapman-Enskog method. The results obtained show that the dynamic viscosity of the plasma varies similarly as a function of temperature whatever the percentage of PMMA in the mixture. It increases at first time to reach its peak between 10000K and 120000K, then decreases rapidly in a second time between 12000K and 200000K and finally tends towards a limit value between 20000K and 30000K. Pure air plasma has the highest dynamic viscosity and pure PMMA plasma the lowest dynamic viscosity. At low temperature, the dynamic viscosity of the plasma is independent of the pressure. But, from \( T = 9000K \), we notice that its peak moves towards high temperatures when the pressure increases.

For high temperatures, the various mixtures plasmas have almost identical electrical conductivities. In the temperature range of 7000K to 13000K, the air plasma has the weakest electrical characteristic. But from 13000K to 22000K, it has an electrical conductivity slightly higher than that of other plasmas. On the other hand, the electrical properties of 80% Air - 20% PMMA, 50% Air - 50% PMMA and 20% Air - 80% PMMA mixtures plasmas are identical over almost the entire temperature range. It is found that the plasma becomes less electrically conductive when the pressure increases at low temperatures \( (T \leq 12000K) \).

From 13000K, an inversion of this evolution of the electrical conductivity is observed; it increases when the pressure increases. The shape of the thermal conductivity curve \( \lambda (T) \) gives information on the quality of the mixture considered for breaking electric arcs.

It is noted that when the pressure increases, the peaks of the thermal conductivity \( \lambda \) move towards the high temperatures. This translation of the peaks is accompanied by an increase of the value of the thermal conductivity. In all the temperature range considered, it is the 80% Air - 20% PMMA mixture plasma which has the highest thermal conductivity peak. This mixture could therefore have performances for the cut of the electric current superior to those of pure air and pure PMMA with regard to its thermal conductivity in the temperature range going from 13000K to 16000K. However, other properties of the plasma such as thermodynamic properties and other parameters should be the subject of further studies to complement this study.

References

[1] A. Bultel, A. Favre, V. Morel, D. Benredjem, W.- Ü. L. Tehchang-Brillet, J.-F. Wyart, P. Teulet, I. F. Schneider, “Caractérisation spectroscopique d’un arc stabilisé dans l’argon pollué par de l’eau et du cuivre,” JITEPE vol.3:n:2-4, 2019.
[2] B. Cheminat, “Influence de l’ablation des parois sur les caractéristiques d’un arc électrique lumineux,” Revue Phys. Appl. 24 277-284, 1989.
[3] Z. Koalaga, “Contribution à l’étude expérimentale et théorique des plasmas d’arc électriques lumineux.” Thèse de doctorat d’université, Clermont-Fd, 1991.
[4] V. V. Noussov, B. Hage, B. Jusselin and C. Fèvet, “Simulation of the Thermal Radiation Effect of an Arc on Polymer Walls in Low-Voltage Circuit Breakers”, Technical Physics, Vol. 52, No. 5, pp. 651-659, 2007.
[5] P. André, W. Bussière, E. Duffour, L. Brunet and J.M. Lombard, “Effects of dielectric on arc plasma pressure and ablation measurement in high - power apparatus”, IEEE transactions on magnetic, vol.39, N°:1, January 2003.
[6] T. Tmenova, F. Valensi, A. Veklich, Y. Cressault, V. Boretskij, K. Lopariko, Y. Aftandilyants, “Étude d’un arc impulsionnel immergé à l’aide de deux dispositifs expérimentaux,” JITEPE vol.3:n:1, 2017.
[7] Z. Leforest, J.-J. Gonzalez, P. Fenton, “Etudes expérimentale et numérique d’un arc électrique dans l’eau,” JITEPE vol.3:n:2-2, 2017.
[8] M. Abbouai, P. André, A. Augeard, “Modèle enthalpique de Stefan pour l’étude du pied d’arc cathodique” JITEPE vol.4:n:1, 18, 2017.
[9] Y. Abdo, V. Rohani, F. Cauneau, L. Fulcheri, “Nouvelles perspectives dans l’étude de la dynamique des arcs AC et DC soumis à des champs transversaux.” JITEPE vol.3:n:4, 2017.
[10] B. Cheminat et P. Andanson, “Etude expérimentale d’une décharge d’arc électrique contaminée par des vapeurs d’isolants”, Revue Phys. Appl. 21, 187-193, 1986.
[11] F. Baudoin1, J-J. Gonzaleze2 and P. Checchin, “Study of the curvature of the electrical arc in low voltage breaking devices: influence of the external magnetic field”, J. Phys. D: Appl. Phys. 38, 3778-3791, 2005.
[12] M. Buffo, J. Andrea, N. Dumoulin, E. Guillard, J.-P. Martin, S. Saadate, “Simulation de l’arc électrique à l’ouverture d’un contacter” JITEPE vol.3:n:1, 4, 2017.
[13] M. Abbouai and B. Cheminat, “Détermination de caractéristiques d’un arc électrique plasma contaminated by vapors from insulators”, JITIES Transactions on Plasma Science, vol.16:n:1, February 1991.
[14] F. Valensi, M. Razafinimanana, A. Gleizes, L. Felberbaum, T. Lamara, T. Morand, “Etude expérimentale d’un arc impulsionnel entre des contacts Ag et Ag-C.” JITEPE vol.3:n:1-5, 2017.
[15] P. André, M. Abbouai, “Déséquilibre thermique dans un plasma d’air ensemencé d’aluminium.” JITEPE vol.3:n:2-3, 2017.
[16] M. Kabler-Riederger, P. Joyceger, G. Dépauleda, J.-M. Baucherie, D. Hong, “Banc d’essai pour la mesure de l’échauffement du point de contact”. JITEPE vol.5:n:2-8, 2019.
[17] J. Rossignol, S. Clain and M. Abbouai, “The modelling of the cathode sheath of an electrical arc in vacuum,” J. Phys. D: Appl. Phys. 36, 1495-1503, 2003.
[18] Z. Koalaga, “Influence of the choice of internal temperatures on the composition of CHxHyOzNt plasmas out of thermodynamic equilibrium: Application to CH2 plasma”, Physics of Plasmas. Volume 9, Number 11. November 2002.
[19] N. Kohio, A. K. Kagoné, Z. Koalaga, F. Zougmoré, D. Njomo, “Calculation of transport coefficients of air - water vapor mixtures thermal plasmas used in circuit breakers ” International Journal of Engineering Research, 3: 711-715, 2014.
[20] F. Bendjabbari, P. André, M. Benbakkar, D. Rochette, S. Flazi, D. Vacher, “Plasma Formed in Argon, Acid Nitric and Water Used in Industrial ICP Torches”, Plasma Science and Technology, Vol.14, No.8, Aug. 2012.
[21] A. Harry Solo, P. Fenton, J-J. Gonzalez, “Compositions chimiques et propriétés thermodynamiques à l’ETL d’un mélange air-CH4” JITEPE vol.5:n:2-2, 2019.
[22] P. André, N. Kohio, A. K. Kagoné, Z. Koalaga and F. Zougmoré, “Contribution à l’étude de la conductivité thermique d’un plasma d’air” JITEPE vol.5:n:2-3, 2019.
[23] P. André, A. K. Kagoné, Z. Koalaga, N. Kohio and F. Zougmoré, “Contribution à l’étude de la conductivité thermique d’un plasma d’air” JITEPE; vol. 5, n2, 3, 2019.
[24] W. C. Yaguibou, E. Korsaga, A. Kagoné, N. Kohio, Z. Koalaga, F. Zougmoré, “Coefficients de transport des plasmas Al2O3 - air dans un disjoncteur électrique”. Journal de physique de la SOAPHYS ; J : P Soaphys, 1, 2019.
[25] P. André, “Composition and thermodynamic properties of ablated vapours of PMMA, PA6-6, PETP, POM and PE”, J. Phys. D: Appl. Phys. 29, 1963-1972, 1996.
[26] N. Kohio, A. K. Kagoné, W. C. Yaguibou, Z. Koalaga, F. Zougmoré, “Water Vapor Influence on Thermodynamic Properties of Air-water Vapor Mixtures Plasmas at Low Temperatures” International Journal of Physics, Vol. 7, No. 3, 66-72, 2019.
[27] E. Duffour, P. Maillfreyt, “Structure and thermodynamic properties from molecular dynamics simulations of the polyethylene crystal”, Polymer 43, 6341-6349, 2002.

[28] A. K. Kagoné, N. Kohio, W. C. Yaguibou, Z. Koalaga, F. Zougmoré, “Calculation of the Chemical Composition of Air - PMMA Mixtures Thermal Plasmas” American Journal of Physical Chemistry. Vol. 9, No. 2, pp. 27-35, 2020.

[29] P. André, M-A. Courty, A. K. Kagoné, Z. Koalaga, N. Kohio, F. Zougmoré, “Calcul de la composition chimique dans un plasma issu de mélanges de PTFE, d’air, de cuivre et de vapeur d’eau dans le cadre d’appareillages de coupure électrique à air.” JITIPEE; vol. 2, no1, 3, 2016.

[30] W. C. Yaguibou, N. Kohio, A. K. Kagoné, Z. Koalaga et F. Zougmoré, “Influence des aérosols sur la composition à l’équilibre d’un plasma d’air.” JITIPEE ; vol. 4, no1, 5, 2018.

[31] P. André and Z. Koalaga, “Composition of a thermal plasma formed from PTFE with copper in non-oxidant atmosphere. Part II: Comparison of a test case with nitrogen”, High Temperature Material Processes 14, 3, 289, 2010.

[32] P. André, L. Brunet, E. Duffour, and J.M. Lombard, “Composition, pressure and thermodynamic properties calculated in plasma formed in insulator vapours of PC and POM at fixed volume”, Eur. Phys. J. AP 17, 53-64, 2002.

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