International Journal of Engineering Research
Volume No.7, Issue No.4, pp : 43-47

ISSN:2319-6890 (online), 2347-5013(print)
1 March 2018

Impact of Aerosol on Transport Coefficients of Air Thermal Plasmas in Circuit Breakers

Wêpari Charles Yaguibou(1), Niessan Kohio(1), Abdoul Karim Kagone(1) and Zacharie Koalaga(1)
(1) LAME, Université Ouaga I Professeur Joseph KI-ZERBO, BP 7020, OUAGADOUGOU, BURKINA FASO
Corresponding Email: wyweparicharles@gmail.com

Abstract: In West Africa, aerosols come from the desert and biomass fires. They are mainly composed of oxides of silicon, calcium, iron, aluminium and carbon. The air circuit breakers may have abnormal behaviour and failures of cuts when they operate in an environment polluted by aerosols. This study focuses on the influence of aerosols on the transport properties of air plasma at atmospheric pressure and local thermodynamic equilibrium between 4000 K and 20000 K. Chapman-Enskog method is used to calculate the transport coefficients. The results show that the dynamical viscosities and the thermal conductivity decrease with aerosol rate. The electrical conductivity increases.

Keywords: **Plasma, Equilibrium composition, Transport coefficients**.

1. Introduction

West Africa is dominated by desert aerosols and biomass fires. The aerosol distribution of this region in the atmospheric column is strongly conditioned by the atmospheric dynamics that are present there [1-4]. Studies have shown that the chemical composition of aerosols in West Africa is mainly dominated by oxides of silicon, calcium, aluminium and iron [5-12]. In addition there are carbonaceous aerosols from biomass and human activities [13-14]. For example, air circuit breakers operating in an environment polluted by aerosols may have abnormal behaviour and electrical interruption failures [15], because they are open to the outside. So we can observe a deposition of dust in the circuit breaker. The aerosol contains the metal particulars. However, studies have shown that the presence of metal vapour strongly influences the arc properties, as a consequence of its influence on the thermodynamic, transport and radiative properties of the plasma [16-23]. Further, metal vapour conducts electricity at lower temperatures than oxygen and nitrogen, which allows current to flow over a wider area. Together these effects influence the arc voltage and can lead a failure of the cut. Consequently, we are certainly watching fires and the destruction of the circuit breaker. The objective of this study is to highlight the influence of aerosols on the transport properties of plasma.

2. Method and material

The initial step in the calculation of transport coefficients is the determination of equilibrium composition of the gas or gas mixture. This is done using the principle of minimization of the Gibbs free energy of the mixture [24-28]. For air-aerosol mixture, we take into account 24 monatomic species: C, O, N, Si, Al, Fe, C^+, O^+, N^+, Si^+, Al^+, Fe^+, C^-, O^-, N^-, Si^-, Al^-, Fe^-, C^{++}, O^{++}, N^{++}, Si^{++}, Al^{++}, Fe^{++}; and electrons; 23 diatomic species: C_2, O_2, N_2, Si_2, Al_2, Fe_2, CO, CN, SiC, AlC, NO, SiO, AlO, SiN, FeO, AlN, C_2^+, O_2^+, N_2^+, CO^+, CN^+, NO^+, AlO^+; and 3 polyatomic species: CO_2, C_3, CO_2^+. We have used the well-known ***Chapman-Enskog*** method of resolution of ***Boltzmann*** equation for the determination of transport coefficients. This method is based on ***Sonine*** polynomials development [29-31].

2.1. Electrical conductivity

Devoto developed at third order approximation an expression of the electrical conductivity of a partially ionized gas following equation [32]:

$$\sigma = \frac{3}{2} e^2 n_1^2 \left[\frac{2\pi}{m_e kT}\right]^{\frac{1}{2}} \frac{\begin{vmatrix} q^{11} & q^{12} \\ q^{21} & q^{22} \end{vmatrix}}{\begin{vmatrix} q^{00} & q^{01} & q^{02} \\ q^{10} & q^{11} & q^{12} \\ q^{20} & q^{21} & q^{22} \end{vmatrix}} \qquad (1)$$

n_1 is the density of electrons and m_e its mass. q^{ij} depend on numerical densities and on average effective sections of collision of particles.

2.2. *Thermal Conductivity*

The total thermal conductivity λ_{tot} plasma has been calculated by adding the different contributions:

$$\lambda_{tot} = \lambda_{tr}^h + \lambda_{tr}^e + \lambda_{int} + \lambda_{reac} \qquad (1)$$

where the members on the right-hand side of the equation represent in the order:

- The translational contribution of heavy particles. It is given at second approximation by:

$$\lambda_{tr}^h = 4 \frac{\begin{vmatrix} L_{11} & \cdots & L_{1v} & X_1 \\ \cdots & L_{ii} & \cdots & \cdots \\ L_{v1} & \cdots & L_{vv} & X_v \\ X_1 & \cdots & X_v & 0 \end{vmatrix}}{\begin{vmatrix} L_{11} & \cdots & L_{1v} \\ \cdots & L_{ii} & \cdots \\ L_{v1} & \cdots & L_{vv} \end{vmatrix}} \qquad (1)$$

the coefficients L_{ij} are given by ***Muckenfuss***.

- The translational contribution of electrons at third approximation is obtain by [32-33]:

$$\lambda_{tr}^e = \frac{75}{8} n_1^2 \sqrt{\frac{2\pi RT}{M_1}} \frac{q^{22}}{q^{11}q^{22} - (q^{12})^2} \qquad (1)$$

n_1 is the electrons density and M_1 its molar mass.

- The internal conductivity which is due to the effect of internal degrees of freedom is taken into account with the Eucken correction [34-35]:

$$\lambda_{int} = \sum_{i=1}^{N} \frac{(\lambda_{int})_i}{\sum_{j=1}^{N} \frac{D_{ii}(1)}{D_{ij}(1)} \frac{x_j}{x_i}} \qquad (1)$$

- The reactive thermal conductivity which is described by [33-36]:

DOI : 10.5958/2319-6890.2018.00094.6

$$\lambda_{reac} = -\frac{1}{RT^2}\frac{\begin{vmatrix} A_{11} & \cdots & A_{1\vartheta} & \Delta H_1 \\ \vdots & \ddots & \vdots & \vdots \\ A_{\vartheta 1} & \cdots & A_{\vartheta\vartheta} & \Delta H_\vartheta \\ \Delta H_1 & \dots & \Delta H_\vartheta & 0 \end{vmatrix}}{\begin{vmatrix} A_{11} & \dots & A_{1\vartheta} \\ \vdots & \ddots & \vdots \\ A_{\vartheta 1} & \dots & A_{\vartheta\vartheta} \end{vmatrix}} \qquad (1)$$

ϑ is the number of reactions

2.3. Viscosity

The viscosity can be considered as mainly due to the heavy chemical species because of the mass ratio between electrons and heavy chemical species. We used the following formulation [36-37]:

$$\eta = -\frac{\begin{vmatrix} H_{11} & \cdots & H_{1v} & X_1 \\ \dots & H_{ii} & \dots & \dots \\ H_{v1} & \cdots & H_{vv} & X_v \\ X_1 & \dots & X_v & 0 \end{vmatrix}}{\begin{vmatrix} H_{11} & \dots & H_{1v} \\ \dots & H_{ii} & \dots \\ H_{v1} & \dots & H_{vv} \end{vmatrix}} \qquad (1)$$

where $\boldsymbol{H_{ij}}$ are functions of collision integrals, molar mass and molar fraction.

2.4. Collision integrals

In thermal plasmas, the calculation of the transport coefficients is based on a specific and rather complicated method of solution of the ***Boltzmann*** equation, known as the ***Chapman–Enskog*** method which was presented in exhaustive detail by ***Hirschfelder and al*** [16]. The transport coefficients are approximated using ***Sonine*** polynomials and require the knowledge of the particle number densities and the collision integrals $\Omega_{ij}^{(l,s)}$ which characterize the interaction between two particles *i* and *j* [16]:

$$\Omega_{ij}^{(l,s)} = \left(\frac{kT}{2\pi\mu_{ij}}\right)^{1/2} \int_0^\infty exp\left(-\gamma_{ij}^2\right)\gamma_{ij}^{2s+3} Q_{ij}^{(l)}(\varepsilon)\, d\gamma_{ij} \qquad (1)$$

With $\gamma_{ij} = (\varepsilon/kT)^{1/2}$ which is the relative velocity, μ_{ij} the reduced mass and $\boldsymbol{\varepsilon}$ the kinetic energy. $Q_{ij}^{(l)}(\varepsilon)$ is the transport cross section which depends on the differential cross-sections and consequently on the interaction potential [16, 34, 36]. The collision integrals calculation is made by considering four categories of interaction: Neutral-neutral interaction; neutral-ion interaction; electron-neutral interaction and charged-charged interaction. We present the calculation of the collision integrals by using intermolecular potentials.

2.4.1. Neutral - neutral interactions

Many types of potential have been suggested to describe the interaction between two neutral particles. We summarize the values of the Lennard-Jones parameters used in the case of the interaction between two neutral simple combining rules:

$$\begin{cases} \varepsilon_{ij} = \left(\varepsilon_i \varepsilon_j\right)^{1/2} \\ \boldsymbol{\sigma_{ij}} = \dfrac{\mathbf{1}}{\mathbf{2}}\left(\boldsymbol{\sigma_i} + \boldsymbol{\sigma_j}\right) \end{cases} \qquad (1)$$

When the parameters of ***Lennard-Jones*** **(12-6)** potentials are determined, the average cross sections are determined from Neufeld table [38]:

$$\bar{\Omega}_{ij}^{(l,s)} = r_0^2 \left[\frac{A}{T^{*B}} + \frac{C}{exp\,(DT)} + \frac{E}{exp\,(FT)} + \frac{G}{exp\,(HT)} + RT^{*B} sin(ST^{*W}\right.$$

where A, B, C,D, F,G,H,S,P,W are defined by Neufeld [38]

We use the values published by ***Capitelli*** and ***Giordano*** on interactions of particles of air [39]. Si-Si interaction is given by ***Pascal*** [40].

2.4.2. Neutral-ion interaction and Electrons - neutral interactions

For collision interactions are obtain by data of [36, 40, 43]. For the other collisions between neutral and charged particles, we considered them as elastic and that the charge particle engenders a dipole in the neutral particles during the collision. ***Kihara and al*** give the following formulation [42]:

$$\bar{\Omega}_{ij}^{(l,s)} = \left(\frac{Z^2 e^2 \xi}{2\pi\varepsilon_0 kT}\right)^{\frac{1}{2}} \left(\frac{\Gamma\left(s+\frac{3}{2}\right)}{\frac{(s+1)!}{2}} \frac{A_{(4)}^{(l)}}{\frac{2l+1-(-1)^l}{2(l+1)}}\right) \qquad (11)$$

where $A_{(4)}^{(1)} = 0{,}6547$ et $A_{(4)}^{(2)} = 0.3852$ et $A_{(4)}^{(3)} = 0{,}7166$, Z is the charge number of the particle, $\boldsymbol{\varepsilon_0}$ is permittivity of the vacuum and $\boldsymbol{k}$ Boltzmann constant. The polarizabilities α of neutral particle that we use in our calculation are given in [16, 36, 37, 41]. Electron-neutral collision integrals are given by [34, 36, 39, 43, 40].

2.4.3. Charged-charged interaction

Using the expression from transport sections efficacies of ***Liboff*** [44]; ***Devoto*** established the following formulas [45]:

$$\begin{cases} \bar{\Omega}_{ij}^{(1,s)} = \left[\dfrac{4}{s(s+1)}\right] b_0^2 \left[ln\,\dfrac{2\lambda_D}{b_0} - \dfrac{1}{2} - 2\bar{\gamma} + \Psi(s)\right] \\ \bar{\Omega}_{ij}^{(2,s)} = \left[\dfrac{12}{s(s+1)}\right] b_0^2 \left[ln\,\dfrac{2\lambda_D}{b_0} - 1 - 2\bar{\gamma} + \Psi(s)\right] \end{cases} \qquad (12)$$

Where $b_0 = \frac{Z_i Z_j e^2}{2kT}$, $\Psi(s) = \sum_{n=1}^{s-1}\frac{1}{n}$, $\Psi(1) = 0$, $\lambda_d = \left(\frac{kT}{4\pi n_1 e^2}\right)^{1/2}$, $\bar{\gamma} = 0{,}5772$. The Debye length taken in to account the presence of electrons and ions is given by [46].

3. Results

3.1. Test of calculation program

The results of our calculation program are tested in comparison with values of dry air of **Kagone**'s works [30, 46]. In figures 1, and 2, we compare respectively the total thermal conductivity and the dynamical viscosity of this study with those of **Kagone**. All the figures show that our results and those of **Kagone** are in good agreement. However, the total thermal conductivity presents a difference at low temperature (T <8000 K). The Electrical conductivity is given in table 1. Electrical conductivity is high in low temperature while It is slightly weak at high temperatures compared to **Kagone**'s data. Dynamical viscosity data are significantly higher than that of **Kagone** for temperatures below 12000 K. Those differences can be due to the data used in the calculation of the chemical composition and the computation of collision integrals. We used approximate methods of calculation the missing data and have to consider the influence of electronically excited states.

DOI : 10.5958/2319-6890.2018.00094.6

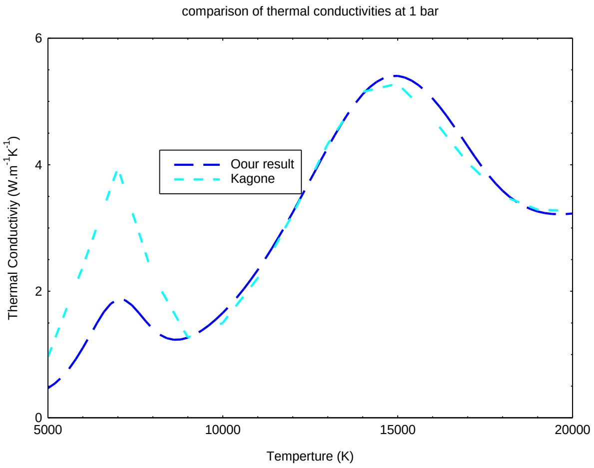

Figure 1: Comparison of total thermal conductivity data of air plasma at atmospheric

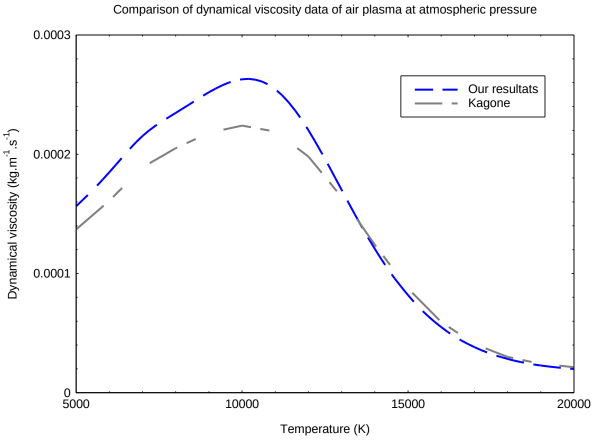

Figure 2: Comparison of dynamical viscosity data of air plasma at atmospheric pressure.

Temperatures (K)	Kagone	Results	Uncertainty ($\Omega^{-1}m^{-1}$)
5000	20.6	24.4601	15.78
8000	983	1001.77	1.87
10000	3200	2997.6	6.75
12000	5460	4899.23	11.45
15000	8460	7505.41	12.72
20000	11700	10966.9	6.68

Tableau 1: Comparison of results of electrical conductivity with that of **Kagone**.

3.2. Influence of aerosol's rate on transport coefficients

3.2.1. Thermal conductivity

The curves evolution of total thermal conductivity of the different mixtures is similar. Each curve exhibits two peaks: the first peak around 7000 K and a second one around 15000 K. The first peak essentially corresponds to the dissociations of molecules at low temperature (N_2, O_2, C_2, CO CO_2, AlC, SiO, SiN, CN, C_3), and the ionization of Si, Fe and Al; because they have lower ionization energies than C, N and O. The second corresponds to the ionization of the C, O, N, Si^+, Al^+ and Fe^+. The thermal conductivity decreases when the aerosol's rate increases. Finally, this study shows that small proportions of aerosol barely change this coefficient. The shape of thermal conductivity curve gives important information on the performance of the gas used for the electrical arc extinction. The more the reaction thermal conductivity is high, the more the electrical arc extinct is fast. So, the shape of the curve shows that the increase of aerosol in the mixture is bad for the extinction of the electric arc.

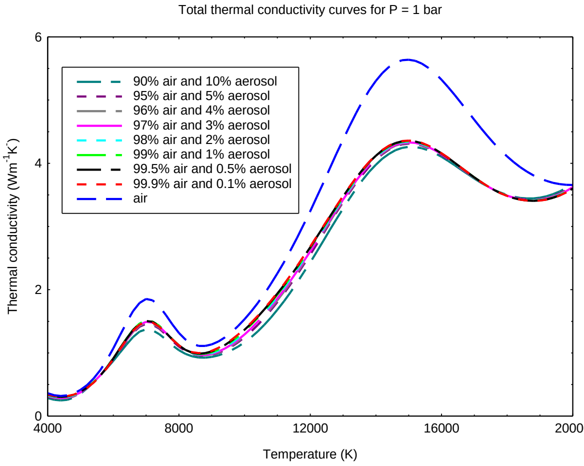

Figure 3: The curves of total thermal conductivity of the different mixtures.

3.2.2. The electrical conductivity

The electrical conductivity increases with temperature because the density of electrons increases when the temperature increases in the medium. For temperatures below 10000 K, a low quantity of aerosol leads to an important increase of the electoral conductivity for temperatures less than 1000 K. The electron density varies fastly with the ionization phenomena. The electrical conductivity is proportional to the square of the electron density in this temperature range. When the mixture contains species that have low ionization energies (this is the case for metals), the density of electrons increases with the dust's rate (T< 10000 K).

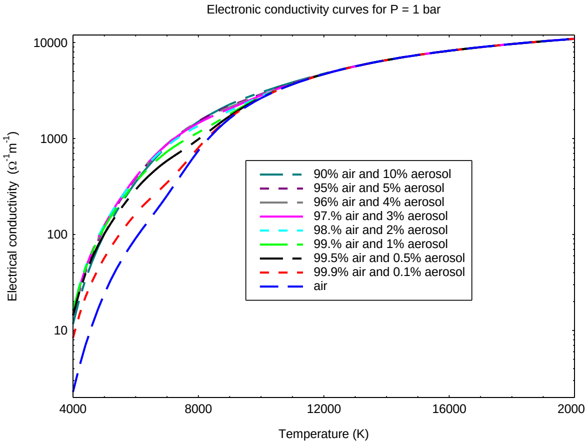

Figure 4: Electrical conductivity.

3.2.3. Dynamical viscosity

For all these plasmas, the maximum dynamical viscosity is between 9000K and 11000K. The viscosity decreases with the increase of the temperature when the ions become more important in the plasma (T>11000K). This drop is explained not only by the decrease in binary diffusion terms but also by the dominance of columbic forces linked to the interactions between charged particles whose values are much higher. We observe that the viscosity of the different mixtures is lower than that of dry air at low temperature. This phenomenon could be explained by the fact that the constituent elements of aerosols are essentially silicon, carbon, aluminium, and iron which have a low ionization potential compared to respect to oxygen and nitrogen. This weakness of the ionization energies causes ionizations at low temperatures, hence a faster transition to ionized plasma. We also note that the viscosity decreases with rate of aerosol.

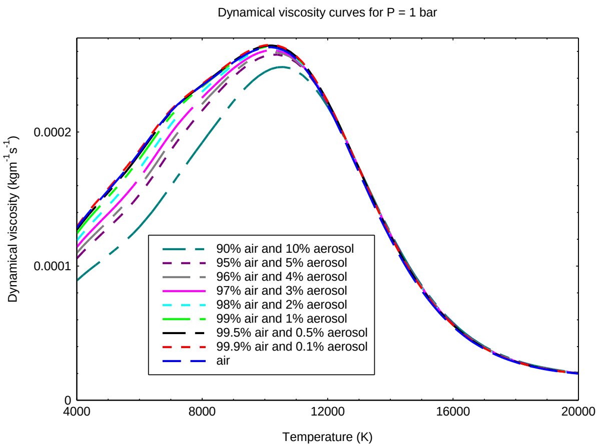

Figure 5: Dynamical viscosity

4. Conclusion

The results of calculation show that dynamical viscosities and thermal conductivities decrease with aerosol percentage. But a very small aerosol proportion in the mixture strongly increases the electrical conductivity. So aerosol can be bad for a good performance of the circuit breaker that works in a polluted environment. The Increase the aerosol rate may negatively influence and degrade circuit breaker performance. Therefore, the circuit breaker must be cleaned and protected against dust.

5. References

i. *M. Legrand, Etude des aérosols sahariens au-dessus de l'Afrique à l'aide du canal à 10 microns de METEOSAT: Visualisation, interprétation et modélisation, Thèse de doctorat de l'Université des Sciences et Techniques de Lille Flandres Artois, France (1990).*

ii. *F. Malavelle, Effets direct et semi-direct des aérosols en Afrique de l'ouest pendant la saison sèche, Thèse de doctorat de l'Université Toulouse III Paul Sabatier (UT3 Paul Sabatier), France (2011).*

iii. *O. Pancrati, Télédétection de l'aérosol désertique depuis le sol par le radiomètre infrarouge thermique multibande, Thèse de doctorat de l'Université des Sciences et Technologies de Lille, France, (2003). (HYPERLINK "http://www-loa.univ-lille1.fr/Actualites/THESES/these_ovidiu.pdf" http://www-loa.univ-lille1.fr/Actualites/THESES/these_ovidiu.pdf).*

iv. *C. Lemaître, Détermination du chauffage radiatif des aérosols désertiques au-dessus de l'Afrique de l'Ouest et de leur impact sur la dynamique atmosphérique à l'aides d'observations satellitaires au cours de la campagne AMMA, Thèse de doctorat des sciences de l'environnement, Université Paris VI, France, (2011).*

v. *H. A. Bouh, F. Benyaich, M. Bounakhla, Y. Noack, M. Tahri, F. Zahry, J. Mater, Variations Saisonnières des particules atmosphériques et ses composants chimiques dans la Ville de Meknès, Environ. JMESCN 4(1) 49-62; ISSN : 2028-2508 (2013).*

vi. *G J. Y. Antenne, Le phénomène des brumes sèches au Sénégal, en 1984-1985, Bulletin n° 7 de l'ORSTOM et du centre de météorologie spatiale, Sénégal, (1985).*

vii. *C. Tobias et C. Megie, Les lithométéores au Tchad Premiers résultats concernant la nature, la composition et l'importance des aérosols transportés par voie atmosphérique dans la région de N'Djamena (Tchad), Cah. O.R.S.T.O.M, sk. Pbdol., vol. XVIII, no 1, 71-81, (1980-1981).*

viii. *L. Herrmann, K.E. Bleich, Sterk & K. Stahr, Dépôt des poussières sur le sol en Afrique de l'Ouest : Propriétés et source des poussières et influence sur les propriés des sols et sites", Résumé de travaux, Université de Hohenheim, Institut pour la science du sol et Ecologie (310)*

ix. *D. Orange, J. Y. Gac and M. I. Diallo, Constituent composition of Harmattan dus and geochimical balance of atmospheric deposition in continental west Africa, Papers for IAHS proceedings/ IAHS Symposium H2-Tracers in Hydrology, (1993).*

x. *D. Orange, et J. Y. Gac, Bilan géochimique des apports atmosphériques en domaines sahélienne et soudano-guinéen d'Afrique de l'ouest (bassin s supérieurs du Sénégal et de la Gambie), Géodynamique 5 : 51-65, (1990).*

xi. *E.H.T. Doumbia, "Caractérisation physico-chimique de la pollution atmosphérique urbaine en Afrique de l'Ouest et étude de l'impact sur la santé, Thèse de doctorat de l'Université Toulouse III - Paul Sabatier, France, (2012).*

xii. *V. Michaud, Etude des propriétés hygroscopiques des aérosols Atmosphériques, thèse de doctorat de l'Université Blaise Pascal, Clermont-Ferrand, N° 627, France, (2009).*

xiii. *P. Flament, K. Deboudt, H. Cahier, B. Chatement, X. Meriaux, Mineral dust and carbonaceous aerosols in West Africa: Source assessment and haracterization, Atmospheric Environment 45, 3742-3749, (2011).*

xiv. *El Hadji T Doumbia, Physico-chemical characterization of urban atmospheric pollution in West Africa and health impact study, Thèse de doctorat de l'Université Toulouse III - Paul Sabatier, France, (2012).*

xv. *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 DOI : 10.18145/jitipee.v2i1.128.g70, (2016).*

xvi. *Y Cressault, A B Murphy, Ph Teulet, A Gleizes and M Schnick, Thermal plasma properties for Ar–Cu, Ar–Fe and Ar–Al mixtures used in welding plasmas processes: II. Transport coefficients at atmospheric pressure, J. Phys. D: Appl. Phys. 46 (2013) 415207 (27pp), doi:10.1088/0022-3727/46/41/415207*

xvii. *M. Abbaoui, B. Cheminat, Determination of the characteristics of an electric arc plasma contamitated by vapors from insulators, IEEE transactions on plasma science, vol : 19, N° 1, (1991).*

xviii. *M. Abbaoui, B. Cheminat and P Andanson, Influence de la nature du métal sur la conductivité d'un plasma argon-metal, J. Phys. D: Appl. Phys. 18 (1985) L159-Ll65.*

xix. *P. Andanson, A. Lefort, J. Roche, Erosion des contacts électriques sous l'effet d'un arc électrique de forte intensité, J. Phys D: Appl. Phys., Vol. 12,(1979).*

xx. *C. Baudry, A. Vardelle, G. Mariaux, M. Abbaoui, A. Lefort, Numerical modeling of a DC non-transferred plasma torch: movement of the arc anode attachement and resulting anode erosion, High Temperature Material Processes 9 (2005) 1-15, (Begell House Inc, http://begellhouse.com Downloaded 2006-3-21 from IP 195.221.123.70 by Prof. LEFORT ANDRE).*

xxi. *B. Cheminat et P. Andanson, La conduction dans la colonne d'un arc electrique contamine par des vapeurs de cuivre, J. Phys. D: Appl. Phys. 18 (1985) 2183-2192.*

xxii. *B. Cheminat, R. Gadaud et P. Andanson, Vaporisation of a silver anode in an electric arc colum, J. Phys. D: Appl. Phys. 20 (1987) 444-452.*

xxiii. *H Ouajji, B Cheminat, P Andanson, Model of an electric arc column in the presence of copper vapor, J. Phys. D: Appl. Phys. 20 (1987) 63-38.*

xxiv. *P. André, "Etude de la composition et des propriétés thermodynamiques des plasmas thermiques à l'équilibre et hors d'équilibre thermodynamique", Thèse de doctorat de l'Université Blaise PASCAL, Clermont-Ferrand II, France, (1995).*

xxv. *P André, M. Abbaoui, R. Bessege, Comparison Between Gibbs Free Energy Minimization and Mass Action Law for Multitemperature Plasma with Application to nitrogen, Plasma chemistry and Plasma Processing, Vol. 17, No, 2, 1997 ; 207-217.*

xxvi. *P. André and Z. Koalaga, Composition of a thermal plasma formed from PTFE with copper in non-oxidant atmosphere. High Temperature Material Processes14, 3 (2010) 279.*

xxvii. *N. Kohio, A. K. Kagoné, Z. Koalaga, F. Zougmoré, Composition of Air-Water Vapor Mixtures at Low Temperatures, I.J.A.R.S.E.T, Vol. 1, Issue 5 (2014) , ISSN: 2350-0328.*

xxviii. *S. Cayet, M. Dudeck, Equilibre chimique dans des mélanges gazeux en déséquilibre thermique, Journal de Physique III, EDP Sciences, 6 (3), pp.403-420.<10.1051/jp3:1996130>. <jpa-00249465>.*

xxix. *Z. Koalaga. Contribution à l'étude expérimentale et théorique des plasmas d'arcs électriques laminés, Thèse d'Université Clermont Ferrand II, France. 1991.*

xxx. *A. K. Kagone, Caractérisation théorique de plasmas thermiques d'arc électrique de mélanges d'air et de vapeur d'eau : application au disjoncteur basse et moyenne tension, Thèse de doctorat, Université de Ouagadougou, Burkina Faso, (2012).*

xxxi. *P. Krenek; Thermophysical properties of H2O- Ar plasmas at temperature 400-50000 K and pressure 0.1 MPa, Plasma chem plasma process (2008) 28: 107-122.*

xxxii. *R. S. Devoto, Simplified Expressions for the Transport Properties of Ionized Monatomic Gases, Phys. Fluids 10, 2105 (1967), doi: 10.1063/1.1762005.*

xxxiii. *M. Capitelli, Transport proprieties of partially ionized gases, Journal de Physique Colloques, 1977, 38 (C3), pp.C3-227-C3-237. <10.1051/jphyscol:1977325>. <jpa-00217113>.*

xxxiv. *M. Capitelli, D. Bruno, A. Laricchiuta, Fundamental Aspects of Plasma Chemical Physics Transport, Springer Series on Atomic, Optical and Plasma Physics 74*

xxxv. *A K Kagoné, Z Koalaga and F Zougmoré, Calculation of air-water vapor mixtures thermal plasmas transport coefficients, IOP Conf. Series: Materials Science and Engineering 29 (2012) 012004doi:10.1088/1757-899X/29/1/012004.*

xxxvi. *P. Andre, L. Brunet, W. Bussière, J. Caillard, J.M. Lombard, and J.P. Picard, Transport coefficients of plasmas consisting of insulator vapours Application to PE, POM, PMMA PA66 and PC, Eur. Phys. J. Appl. Phys. 25, 169–182 (2004) DOI: 10.1051/epjap:2004007.*

xxxvii. *KOHIO Niéssan, KAGONÉ Abdoul Karim, KOALAGA Zacharie, ZOUGMORÉ François , NJOMO Donatien, Calculation of transport coefficients of air-water vapor mixtures thermal plasmas used in circuit breakers, I.J.E.R, Volume No.3, Issue No.12, pp : 711-715; 2014.*

xxxviii. *P. D. Neufeld, A. R. Janzen, and R. A. Aziz, Empirical Equations to Calculate 16 of the Transport Collision Integrals Ω(l,s)* for the Lennard Jones (12–6) Potential, J. Chem. Phys. 57, 1100 (1972); doi: 10.1063/1.1678363.*

xxxix. *M. Capitelli and D. Giordano, Collision Integrals of high-temperature air species, Journal of thermophysics and heat transfer, Vol. 14, N° 2, April-june 2000.*

xl. *Pascal Andre A. William Bussiere A. David Rochette ,Transport Coefficients of Ag–SiO2 Plasmas, Plasma Chem Plasma Process (2007) 27:381–403 DOI 10.1007/s11090-007-9086-y.*

xli. *xxxxi. A. Sanon and J. M Baronnet, Transport Coefficients of Ar/C/H/O/N Systems Thermal Plasma at Atmospheric Pressure, IOP Conf. Series: Materials Science and Engineering 29 (2012) 012003 doi:10.1088/1757-899X/29/1/012003.*

xlii. *xxxxii. Taro Kihara, Marion H. Taylor, and Joseph O. Hirschfelder, Transport Properties for Gases Assuming Inverse Power Intermolecular Potentials, 3, 715 (1960); doi: 10.1063/1.1706115.*

xliii. *xxxxiii. Gorse C, Capitelli M, Collision integrals of high temperature hydrogen species, Atomic and plasma-material interaction data for fusion (APID series) vol 9:75–82, (2001).*

xliv. *xxxxiv. Richard L. Liboff, Transport Coefficients Determined Using the Shielded Coulomb Potential, Physics of Fluids (1958-1988) 2, 40 (1959); doi: 10.1063/1.1724389,http://dx.doi.org/10.1063/1.1724389.*

xlv. *xxxxv. R. S. Devoto, Transport Coefficients of Partially Ionized Argon, Phys. Fluids 10, 354 (1967); doi: 10.1063/1.1762115*

xlvi. *xxxxvi. E. A. Mason, R. J. Munn, and Francis J. Smith, Transport Coefficients of Ionized Gases, Physics of Fluids (1958-1988) 10, 1827 (1967); doi: 10.1063/1.1762365.*