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THERMOPHYSICAL PROPERTIES OF AIR-PA66-CU PLASMAS FOR LOW-VOLTAGE DIRECT CURRENT SWITCHGEAR

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Abstract. This paper presents the thermophysical properties of an air-polyamide 66-copper mixture in thermal plasma. Equations based on mass action law, conservation of neutrality and perfect gas law are used to calculate particle number densities. Thermodynamic properties and transport coefficients were obtained from equilibrium compositions and computed using the Chapman-Enskog method. Radiative properties are described in terms of the total absorption coefficient and the net emission coefficient.

Keywords: Thermal plasmas properties, Transport coefficient, Net emission coefficient, Local thermodynamic equilibrium.

1. Introduction

Due to a wide range of applications, low-voltage direct current (LVDC) systems are attracting increasing attention from researchers and developers. A major challenge in designing these systems is the interruption of both nominal and fault currents. Mechanical switches offer an inexpensive solution to this challenge. During switching operation in mechanical LVDC-switches, an electrical arc occurs upon contact separation. This arc has to be extinguished for a successful current interruption. Hence, fundamental understanding of arc behavior is necessary for developing efficient LVDC switchgear. With arc core temperatures of more than 10,000 K, experimental measurements of arcs are challenging. Therefore, spatially and temporally resolved numerical arc models offer valuable insights in addition to experimental investigations. In order to develop realistic models, the thermophysical properties of the media involved are needed. This paper presents the properties of an air-polyamid 66-copper mixture.

2. Composition and thermodynamic properties

The plasma is supposed to be a gaseous medium in equilibrium. The number densities of particles are obtained by the resolution of a set of equations based on the mass action law, the conservation of the neutrality and perfect gas law [1], using the energies for the various species given in JANAF tables and taking into account virial and Debye-Hückel corrections. For Air-PA66-Cu mixtures, we considered different species distributed in the following way:

- 58 neutral species: C, H, O, N, Cu, C₂, O₂, H₂, N₂, Cu₂, NO, NH, OH, CH, CO, CN, CuH, CuO, C₃, H₂O, C₂H, CO₂, CH₂, CN₂ (CNN and NCN), C₂N, C₂O, HO₂, NH₂, NO₂, N₂O, O₃, N₃, HNO, CHO, CHN, CNO, CH₃, CH₄, C₂H₂, C₂H₄, C₂N₂, C₄, NH₃, C₃O₂, H₂N₂, H₂O₂, H₄N₂, NO₃, HCON,

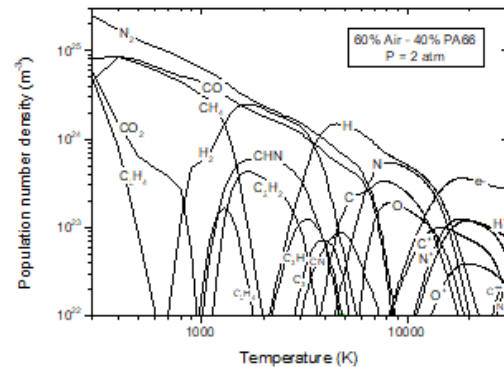


Figure 1. Composition of [60]Air-[40]PA66 plasma at $P=2$ atm (mass proportion).

CH₂O, C₂H₄O, HNO₃, HNO₂Cis, HNO₂trans, N₂O₃, N₂O₄, N₂O₅.

- 38 charged species: electrons, H⁺, H⁻, C⁺, C²⁺, C³⁺, C⁻, O⁺, O²⁺, O³⁺, O⁻, N⁺, N²⁺, N³⁺, Cu⁺, Cu⁺⁺, Cu⁺⁺⁺, Cu⁻, H₂⁺, H₂⁻, N₂⁺, O₂⁺, NO⁺, NH⁺, OH⁺, OH⁻, CH⁺, CH⁻, CO⁺, CN⁺, CN⁻, C₂⁺, C₂⁻, O₂⁻, C₃⁻, CO₂⁻, NO₂⁻, N₂O⁺, CHO⁺.

We present in Figure 1 the composition of [60]Air-[40]PA66 thermal plasma, showing the evolution of the main species with temperature at $P=2$ atm.

The condensed phases probably play a major role at low T , but they are not taken into account here. As consequences, properties of C_p , and thermal conductivities are probably imprecise at low T ($T < 3$ kK). With the equilibrium compositions, it is possible to calculate the thermodynamic properties (i.e. mass density ρ , specific enthalpy h , specific entropy s and specific heat at constant pressure C_p). As example, the specific heat at constant pressure C_p ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) is given in Figure 2 at different pressures for the mixture [40]Air-[60]Cu. At low temperature and 1 atm,

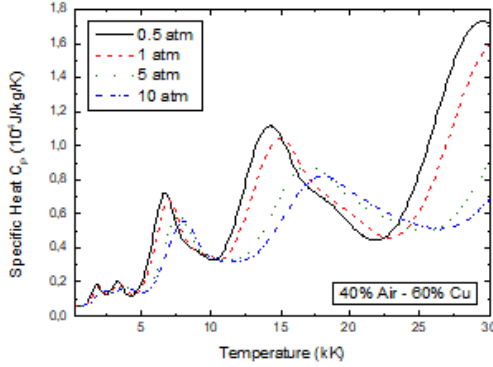


Figure 2. Evolution of CP of [40]Air-[60]Cu at different pressures and low temperatures (mass proportions).

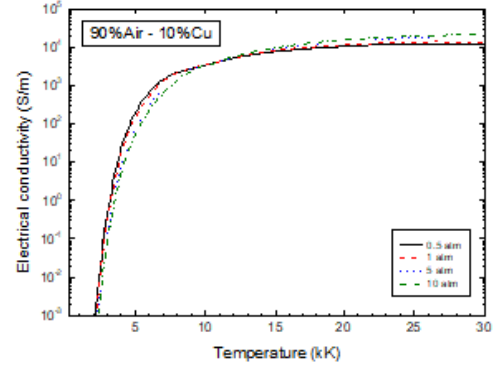


Figure 3. Evolution of the electrical conductivity for different pressures and [90]Air-[10]Cu mixture (mass proportions).

59 there are several peaks which are due to dissociation
 60 of molecules and ionization of atomic species. For
 61 a given Air-PA66-Cu mixture and depending n the
 62 concentration of each gas, we can observe some peaks
 63 at: 1.5 kK for C_2H_4 and CH_4 polyatomic molecules,
 64 2.5 kK for Cu_2 , 3.7 kK and 5 kK for H_2 , C_2 , C_3 , CN
 65 and C_2H , 4 kK for O_2 , and 7 kK for N_2 . Then we
 66 have first ionization of Cu (around 8 kK), and O, C,
 67 N, H (around 15 kK). Finally, we have the second
 68 ionization of Cu (15 kK), and O, N, C around 3 kK.
 69 The ionization energy of neutral oxygen and nitrogen
 70 are 13.61 eV and 14.53 eV respectively, 35.1 eV and
 71 29.60 eV for O^+ and N^+ ions, ionization energy of
 72 neutral copper is 7.72 eV and 20.29 eV for Cu^+ , ion-
 73 ization energy of neutral C is 11.26 eV, neutral H is
 74 13.59 eV, and 24.38 eV for C^+ . The pressure increase
 75 tends to shift the peaks to higher temperatures and
 76 to decrease their amplitude. See [2] for more details.

77 The corrections to thermodynamic properties of
 78 ideal plasmas have been determined in the framework
 79 of the Debye-Hückel theory. Besides the Debye-Hückel
 80 correction, we also included the Virial correction even
 81 if its influence is very low for the pressures considered
 82 in this study.

83 3. Transport coefficients

84 In order to study theoretically the plasma's behaviour
 85 with numerical arc models, it is necessary to calcu-
 86 late the transport coefficients like viscosity, electrical
 87 conductivity and thermal conductivity. Their calcula-
 88 tion is based on the Chapman-Enskog method [3] and
 89 adapted to partially ionized gases. The expressions
 90 used to obtain the transport properties as functions
 91 of temperature, pressure and number densities are
 92 given in [2]. According to the method, the transport
 93 properties are governed by elastic collisions between
 94 all the species which are represented through effective
 95 collision integrals [3]. The choice of the potentials and
 96 the use of the collision integrals can strongly influence
 97 the transport coefficients. Consequently, the biblio-

98 graphical study of the interaction potentials and the
 99 calculation of the corresponding integrals constitute
 100 the most important and most complex part of the
 101 general calculation of transport coefficients.

102 Most of the collision integrals are issued from previ-
 103 ous works done on pure air, CF_3 -Air, Ar- H_2 -Cu or
 104 Air-metal, Ar- H_2 , Ar- O_2 and CO- H_2 [2, 4-9]. Other
 105 neutral-neutral collisions were all treated using the
 106 Lennard-Jones potential and the associated paramete-
 107 rs [10], the other collisions neutrals-charged particle
 108 were derived from the polarization potential. The
 109 collision integrals for the electron-neutral interactions
 110 e-H, e- C_2 , e- H_2 , e-CH, e-CO, e-CN, e-NH, e-OH, e-
 111 CO $_2$, e- H_2O , e- N_2O , e-NH $_3$ and e-CH $_4$ were issued
 112 from Andre And-2 and the missing integral collisions
 113 have been estimated according the ion-neutral colli-
 114 sions with a polarization potential and polarizabilities.
 115 All the charged-charged se interactions were described
 116 by a screened Coulomb potential [3]. Concerning the
 117 definition of the Debye length, more details are given
 118 in [2]. Here, we took both electrons and ions for the
 119 Debye length calculation.

120 The expression of the transport coefficients can be
 121 found in [2]. As example, the Figure 3 shows typical
 122 evolutions of electrical conductivity for different pres-
 123 sures. At low temperature, this coefficient increases as
 124 the pressure decreases whereas the opposite effect is
 125 observed at high temperature. This behaviour can be
 126 explained by analysing the evolutions of the electron
 127 number density and the electron mobility. Despite the
 128 fact that the electron density is continuously growing
 129 with pressure for a given temperature, the curves of
 130 electrical conductivity crossed around 14.5 kK since for
 131 this temperature the main elastic collisions involving
 132 electrons (responsible for their mobility) change: at
 133 low temperature they are mainly electron-neutral colli-
 134 sions whereas at high temperature electron-charged
 135 particles collisions are predominant. See [2] for more
 136 details on the influence of pressure and/or mixtures
 137 on this coefficient.

4. Radiative properties

The detailed description of the elementary processes responsible for emission and absorption were described in [11]. A rigorous calculation would consist in resolving the RTE equation for all wavelengths of the spectrum and for all directions. For a practical problem, the calculation time would be extremely long. Some methods have therefore been developed in order to simplify the spectral or geometrical dependencies of the radiation while keeping a good accuracy. For a detailed description of the different existing methods, the reader will find references into the general work of Cressault [12]. One of the frequently applied methods in the numerical models destined to thermal plasmas is the NEC [11] which takes into account emission and absorption of radiation in isothermal conditions. At the center of the sphere of radius R_p , the NEC is written:

$$\varepsilon_N(R_p, T, P) = \int_0^{\infty} L_{\lambda}^0(T) K'_{\lambda}(T, P) \exp(-K'_{\lambda} R_p) d\lambda \quad (1)$$

where K'_{λ} (m^{-1}) is the monochromatic absorption coefficient K_{λ} (m^{-1}) corrected by the induced emission and correlated with the local emission coefficient by Kirchhoff's law. In this expression the variations with frequency/wavelength of the corrected absorption coefficient K' can be very complicated and due to the exponential term, self-absorption of radiation in the emitting regions is rather well estimated. We know that a strong absorption takes place within the first mm of plasma which is a very general property of thermal plasma radiation. In spite of the strong approximation of isothermal plasma, this NEC gives acceptable values for the radiative balance in the hottest regions of thermal plasmas [11]. Indeed, the local emission depends on the local temperature, whereas the main self-absorption occurs in the very near surroundings of the emission point as it will be pointed in the results. The main difficulty of this method consists not only of the calculation of the spectral absorption coefficient which strongly varies according to the wavelength and temperature, but also of the calculation of the radiation lines including their absorption. Therefore, various physical phenomena must be considered: the radiation of the atomic continuum (radiative recombination, Bremsstrahlung and radiative attachment), the radiation of molecular continuum (photo-dissociation, photo-ionization and photo-attachment) and the radiation of the atomic lines (by taking into account the absorption phenomena), and the radiation of molecular lines. An example of total absorption coefficient for [50]Air-[50]Cu mixture at 3 atm is given in Figure 4 at 10 kK and 15 kK.

For the calculation of the NEC, we used the "line-by-line" method. See works from [12] for more details. It is well-known that NEC increases with the temperature and with the pressure, and decreases with the

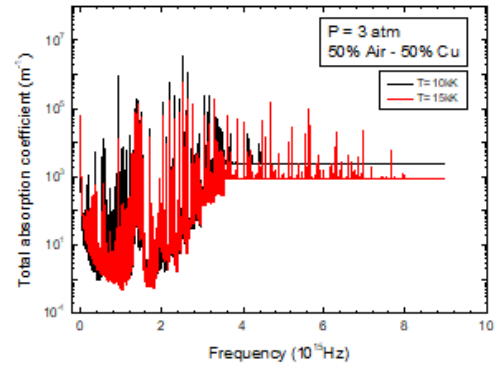


Figure 4. Total absorption coefficient [50]Air-[50]Cu mixture at 3 atm, 10 kK and 15 kK.

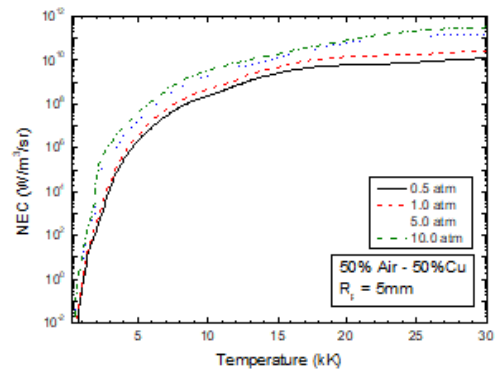


Figure 5. Influence of the pressure on the NEC for [50]Air-[50]Cu mixture and $R_p=5$ mm.

plasma thickness. In this paper, we proposed Figure 5 to show the influence of the pressure for [50]Air-[50]Cu mixture and $R_p=5$ mm.

5. Conclusion

This paper presents the thermophysical properties of an Air-PA66-Cu mixture in thermal plasma. The number densities of the particles were calculated using a set of equations based on the mass action law, conservation of neutrality and perfect gas law. The thermodynamic properties, including mass density, specific enthalpy, specific entropy and specific heat at constant pressure, were obtained from the equilibrium compositions, while the transport coefficients, namely the viscosity, electrical conductivity and thermal conductivity, were computed using the Chapman-Enskog method adapted to partially ionized gases. Furthermore, radiative properties in terms of the total absorption coefficient and the NEC were calculated as well. Overall, this paper provides valuable insight into the behaviour and properties of thermal Air-PA66-Cu plasmas. The calculated data set will serve as a basis for numerical arc simulations of LVDC switchgear in future publications.

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