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THERMOPHYSICAL PROPERTIES OF AIR-PA66-COPPER PLASMAS FOR LOW-VOLTAGE DIRECT CURRENT SWITCHES

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Abstract. This paper presents the thermophysical properties of an air-PA66-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-switches. 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-PA66-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-copper mixtures, we considered different species distributed in the following way:

- ☐ 58 neutral species: C, H, O, N, Cu, C_2, O_2, H_2, N_2, Cu_2, NO, NH, OH, CH, CO, CN, CuH, CuO, C_3, H_2O, C_2H, CO_2, CH_2, CN_2 (CNN and NCN), C_2N, C_2O, HO_2, NH_2, NO_2, N_2O, O_3, N_3, HNO, CHO, CHN, CNO, CH_3, CH_4, C_2H_2, C_2H_4, C_2N_2, C_4, NH_3, C_3O_2, H_2N_2, H_2O_2, H_4N_2, NO_3, HCON, CH_2O, C_2H_4O, HNO_3, HNO_2Cis, HNO_2trans, N_2O_3, N_2O_4, N_2O_5.
- ☐ 38 charged species: electrons, H^+, H^-, C^+, C^{2+}, C^{3+}, C^-, O^+, O^{2+}, O^{3+}, O^-, N^+, N^{2+}, N^{3+}, Cu^+, Cu^{++}, Cu^{+++}, Cu^-, H_2^+, H_2^- , N_2^+, O_2^+, NO^+, NH^+, OH^+, OH^-, CH^+, CH^-, CO^+, CN^+, CN^-, C_2^+, C_2^-, O_2^-, C_3^-, CO_2^-, NO_2^-, N_2O^+, CHO^+.

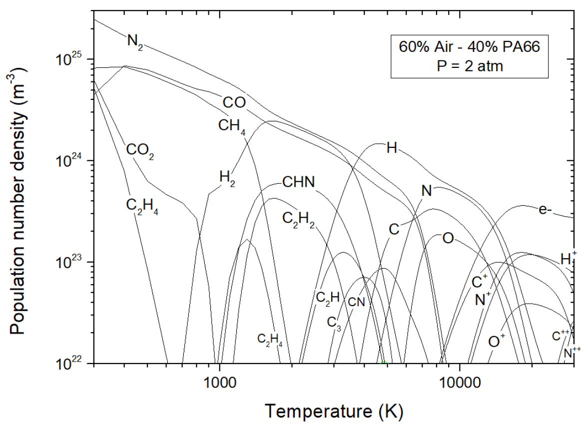

Figure 1. Composition of 60% Air – 40% PA66 plasma at $P = 2$ atm (mass proportion).

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 (J.kg^{-1}.K^{-1}) is given in Figure 2 at different pressures for the mixture

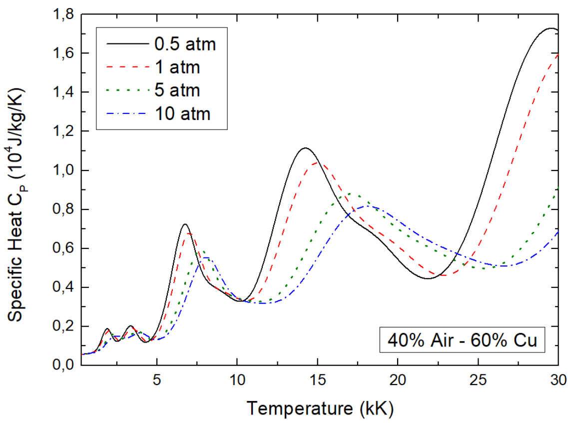

Figure 2. Evolution of C_P of 40% Air – 60% Cu at different pressures and low temperatures (mass proportions).

40% Air – 60% Cu. At low temperature and 1 atm, there are several peaks which are due to dissociation of molecules and ionization of atomic species. For a given air-PA66-copper mixture and depending on the concentration of each gas, we can observe some peaks at: 1.5 kK for C_2H_4 and CH_4 polyatomic molecules, 2.5 kK for Cu_2, 3.7 kK and 5 kK for H_2, C_2, C_3, CN and C_2H, 4 kK for O_2, and 7 kK for N_2. Then we have first ionization of Cu (around 8 kK), and O, C, N, H (around 15 kK). Finally, we have the second ionization of Cu (15 kK), and O, N, C around 3 kK. The ionization energy of neutral oxygen and nitrogen are 13.61 eV and 14.53 eV respectively, 35.1 eV and 29.60 eV for O^+ and N^+ ions, ionization energy of neutral copper is 7.72 eV and 20.29 eV for Cu^+, ionization energy of neutral C is 11.26 eV, neutral H is 13.59 eV, and 24.38 eV for C^+. The pressure increase tends to shift the peaks to higher temperatures and to decrease their amplitude. See [2] for more details. The corrections to thermodynamic properties of ideal plasmas have been determined in the framework of the Debye-Hückel theory. Besides the Debye-Hückel correction, we also included the Virial correction even if its influence is very low for the pressures considered in this study.

3. Transport coefficients

In order to study theoretically the plasma's behaviour with numerical arc models, it is necessary to calculate the transport coefficients like viscosity, electrical conductivity and thermal conductivity. Their calculation is based on the Chapman-Enskog method [3] and adapted to partially ionized gases. The expressions used to obtain the transport properties as functions of temperature, pressure and number densities are given in [2]. According to the method, the transport properties are governed by elastic collisions between all the species which are represented through effective collision integrals [3]. The choice of the potentials and the use of the collision integrals can strongly influence the transport coefficients. Consequently, the bibliographical study of the interaction potentials and the calculation of the corresponding integrals constitute the most important and most complex part of the general calculation of transport coefficients.

Most of the collision integrals are issued from previous works done on pure air, CF_3-Air, Ar-H_2-Cu or Air-metal, Ar-H_2, Ar-O_2 and CO-H_2 [2, 4–9]. Other neutral-neutral collisions were all treated using the Lennard-Jones potential and the associated parameters [10], the other collisions neutrals-charged particle were derived from the polarization potential. The collision integrals for the electron-neutral interactions e-H, e-C_2, e-H_2, e-CH, e-CO, e-CN, e-NH, e-OH, e-CO_2, e-H_2O, e-N_2O, e-NH_3 and e-CH_4 were issued from Andre [11] and the missing integral collisions have been estimated according the ion-neutral collisions with a polarization potential and polarizabilities. All the charged-charged interactions were described by a screened Coulomb potential [3]. Concerning the definition of the Debye length, more details are given in [2]. Here, we took both electrons and ions for the Debye length calculation.

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

4. Radiative properties

The detailed description of the elementary processes responsible for emission and absorption were described in [12]. A rigorous calculation would consist in resolving the radiative transfer 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 [13]. One of the frequently applied methods in the numerical models destined to thermal plasmas is the net emission coefficient (NEC) [12] which takes into account emission and absorption of radiation in isothermal conditions. At the center of the sphere of

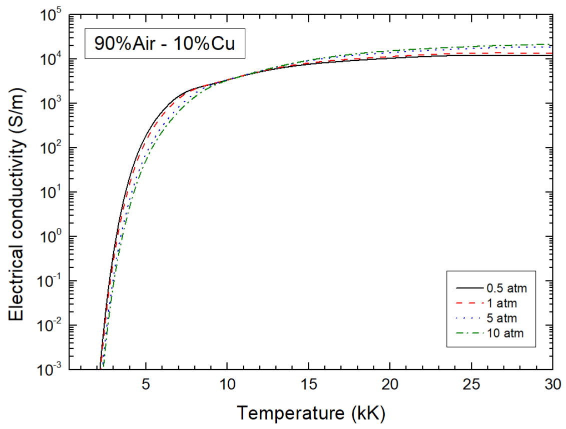

Figure 3. Evolution of the electrical conductivity for different pressures and 90% Air – 10% Cu mixture (mass proportions).

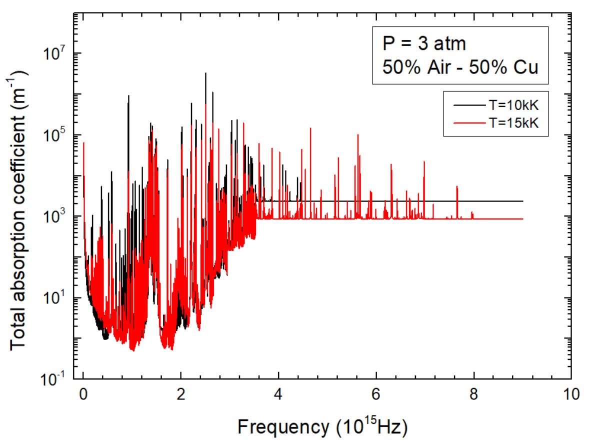

Figure 4. Total absorption coefficient 50% Air – 50% Cu mixture at 3 atm, 10 kK and 15 kK.

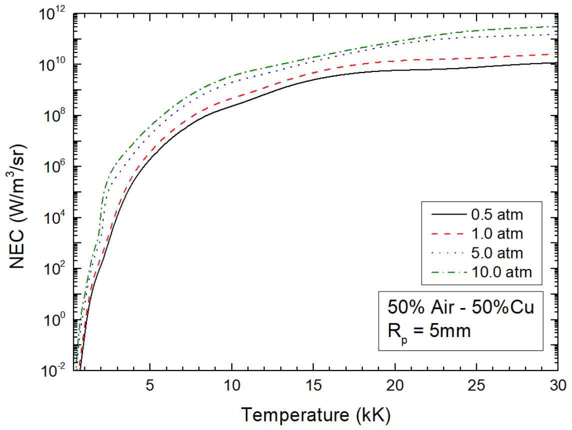

Figure 5. Influence of the pressure on the NEC for 50% Air – 50% Cu mixture and $R_p = 5$ mm.

radius R_p, the NEC is written:

$$\varepsilon_N(R_\mathrm{p}, T, P) = \int_0^\infty L^0_\lambda(T) K'_\lambda(T, P) \exp(-K'_\lambda R_\mathrm{p})\,\mathrm{d}\lambda \tag{1}$$

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 [12]. 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 [13] for more details.

It is well-known that NEC increases with the temperature and with the pressure, and decreases with the plasma thickness. In this paper, we proposed Figure 5 to show the influence of the pressure for 50% Air – 50% Cu mixture and $R_\mathrm{p} = 5$ mm.

5. Conclusion

This paper presents the thermophysical properties of an air-PA66-copper 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-copper plasmas. The calculated data set will serve as a basis for numerical arc simulations of LVDC-switches in future publications.

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