INFLUENCE OF COPPER VAPOURS ON THE RADIATIVE TRANSFER IN THERMAL AIR PLASMA

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ABSTRACT

In this contribution we investigated the influence of a copper vapour on the radiative transfer in the air thermal plasma at the pressure of 1 bar. We covered the entire spectrum ranging from pure air to pure copper vapour. The calculation of the radiative emission was done by calculating radiative flux divergence using discrete ordinates method (DOM). We also included net emission coefficients (NEC) for the comparison purposes. In simulations we used 24 independent directions based on available computational power. The spatial integration was carried over fixed spatial step. The fixed temperature profile was used describing steady state plasma. The computed data suggested large impact of the copper vapour on the arc radiative properties. The radiative energy transfer increased by the factor of 3 while changing from the pure air to the pure copper vapour and assuming the same temperature profile. Larger portion of energy was also reabsorbed close to the plasma arc wall.

1. INTRODUCTION

Understanding and evaluation of radiation transfer within thermal plasma plays important role for development of new circuit breakers and switching gears [1, 2]. Tackling the radiation processes exactly is however nearly impossible task as too many different processes has to be taken into account. The simplifications are needed. The usual approach is to neglect scattering and evaluate only absorption and transmission [3]. In this case the radiation transfer can be expressed by relatively simple equation

$$\vec{n}\vec{\nabla}I_\nu(\vec{r},\vec{n}) = \kappa_\nu\left(B_\nu - I_\nu\right). \qquad (1)$$

Here $I_\nu(\vec{r},\vec{n})$ represents specific intensity of radiation field in the point $\vec{r}$ going in direction $\vec{n}$. Variables B_ν and κ_ν represent blackbody radiation and absorption coefficient respectively. Solution of equation (1) gives information about the radiation transfer inside plasma.

Finding a solution to equation (1) is computationally very complex as it depends not just on radiation at point $\vec{r}$ but also on radiation from entire space. The second obstacle is represented by absorption coefficient which depends on temperature and generally has very complex shape. The first generally accepted method to approximately evaluate radiation inside plasma is attributed to Lowke [4]. He introduced the Net Emission Coefficients (NEC) describing radiation from a centre of a isothermic cylinder. Other methods such as Discrete Ordinance Method (DOM) or P1 approximation are also used [5].

The main focus lies on the plasma containing SF_6 as this gas in extensively used in high-voltage circuit breakers [6, 7, 8]. Slightly less intention is paid to radiative transfer in air and air with admixtures [9, 10, 11]. The admixtures in the air are usually caused by metal vapours produced by arc in a low voltage circuit breakers. In this work we focused on radiative transfer in air thermal plasma with copper vapour. Such mixture was already studied by Aubrecht et. al. in [12]. However only the concentration not exceeding 10 vol% was included and the radiative emission was evaluated using only net emission coefficients. We widened the Cu concentration range and used DOM to simulate the absorption in colder parts of the arc.

2. NUMERICAL MODEL AND INPUT PARAMETERS

The DOM method is based on solving equation (1) over several discrete directions in the domain with defined temperature profile (see Figure 1). The solution can be found in the form of

$$I_\nu(R) = \int_A^R \kappa_\nu(x) B_\nu(x) e^{-\int_A^x \kappa_\nu(\xi)\mathrm{d}\xi} \mathrm{d}x + $$
$$+ I_\nu(A) e^{-\int_A^R \kappa_n u(x)\mathrm{d}x}, \quad (2)$$

where the first term represents radiation and absorption inside the domain and the second term radiation intensity coming from outside of the domain. The second term is usually neglected. The number of unique directions and spatial discretization directly influence the accuracy of the results. Randraianandraina et. al. [7] showed that there is only small change in results when considering over 8 directions and over 100 spatial points. Given the computer power available we decided to use 24 unique directions. We opted for fixed spatial step rather than fixed number of spatial points however. This way we kept the same computation error for different directions. The shape of temperature profile was arbitrary chosen based on limiting condition of copper vaporization temperature and zero derivatives at the plasma center as is depicted in the Figure 1.

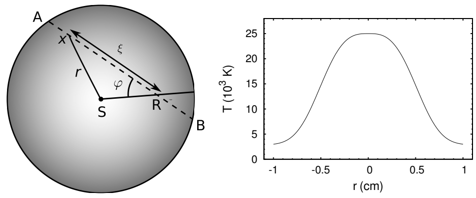

Fig. 1: Schematics description of calculation domain and temperature profile.

The plasma radiation properties are determined by absorption coefficients. To calculate these coefficients the concentration of each species inside plasma has to be known for each temperature within temperature profile. The calculated concentrations of major species considered in our modelling are shown in the Figures 2 and 3 for pure air and air with 20 mass% of copper vapour respectively. The air in our calculations was composed of only N_2, O_2, Ar and their products in percentages correcponding to ambient air. For calculation we assumed the thermal equilibrium inside plasma and uniform pressure of 1 bar.

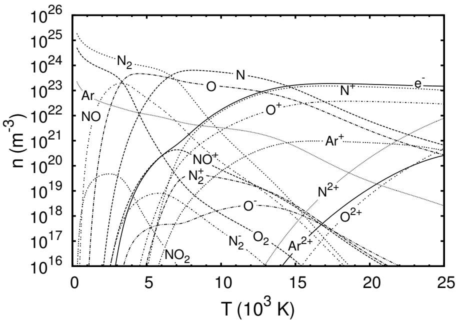

Fig. 2: Concentration of major species in the air at the pressure of 1 bar.

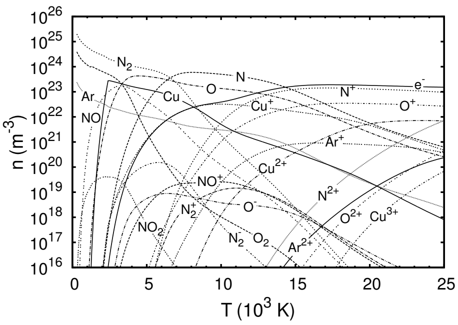

Fig. 3: Concentration of major species in the air with 20 mass% Cu vapour admixture at the pressure of 1 bar.

The main difference between the presented is observed in electron and ion concentrations. From temperature 2 000 K to 10 000 K the dominant ion becomes Cu^+. The sharp drop in Cu concentration at low temperature is caused by condensation of Cu at 2400 K.

Based on this concentration profiles we calculated the absorption coefficients. The representative results for a few temperatures are depicted in the Figures 4 and 5 for air and air with 20 mass% of copper vapour respectively. These results are resembling those presented in [12].

The important change is observed in frequency range spanning from 1×10^{15} Hz to 2×10^{15} Hz where a large quantity of intensive copper lines is located. Incidentally this is also the range where Planck function has its maximum for selected temperature range. Higher emission and absorption thus can be expected with copper vapour addition to the air.

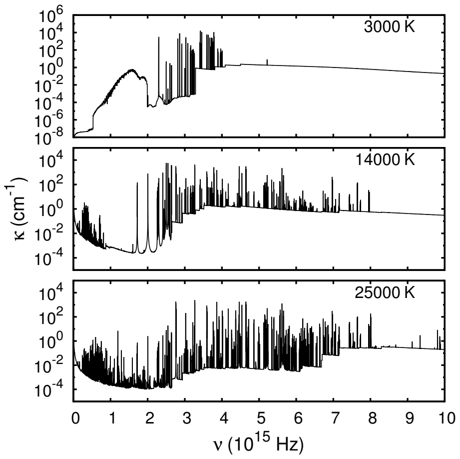

Fig. 4: Absorption coefficient of air as the function of radiation frequency and temperature. Note the different scale in the lowest temperature subfigure.

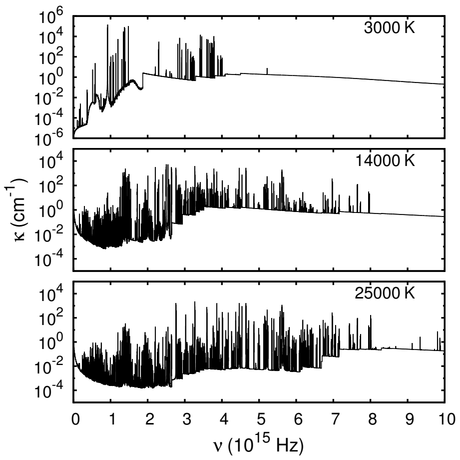

Fig. 5: Absorption coefficient of air with 20 mass% copper vapour admixture as the function of radiation frequency and temperature. Note the different scale in the lowest temperature subfigure.

3. RESULTS AND DISCUSSION

The radiative transfer inside plasma is best described by the divergence of radiation flux $\vec{\nabla}.\vec{F}$. This quantity represents the difference between the emitted and absorbed radiation. The radiation flux itself is defined as integral over all directional angles of the radiation intensity. This puts the divergence of the radiation flux in the centre of arc cylinder in relation with net emission coefficient ε_N as

$$\vec{\nabla}.\vec{F} \approx 4\pi\varepsilon_N. \qquad (3)$$

In our results we included the factor 4π into the divergence of radiation flux for easier comparison of both quantities.

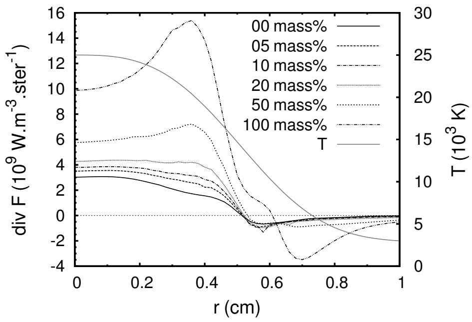

Fig. 6: Divergence of radiation flux across the arc diameter. The data are calculated for several volumetric concentrations of copper vapour admixture.

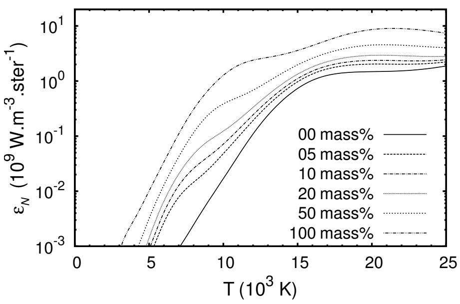

Fig. 7: Net Emission Coefficients of cylindrical arc plasma with the radius $R = 1\,cm$. The data are calculated for several volumetric concentrations of copper vapour admixture.

The expected behaviour of the divergence of the flux was indeed confirmed as can be seen in the Figure 6. With increasing concentration of copper vapours the radiation from the plasma center increases. The same behaviour is predicted by the net emission coefficients in the Figure 7. The discrepancy factor of approximately 2 between net emission coefficients and divergence of radiation flux can be explained by different temperature profiles. Net emission coefficient calculates the isothermic cylinder whereas divergence of radiation flux evaluates the temperature profile. The emission from the outer regions of plasma is higher in case of isothermic cylinder thus effectively reducing the net emission coefficient. Better agreement could be achieved by using reduced plasma radius when calculating net emission coefficients.

One more notable effect is observed in the Figure 6. It is the transition of the absorption region closer to the wall with increasing copper vapour concentration. This effect is especially visible when changing the concentration from 50 mass% to pure copper vapour. This effect can be attributed to the existence of absorption lines in absorption coefficient of copper at low temperature (see the Figure 5) whereas no such lines are present in case of air (see 4). As the copper vapour concentration increases the importance of these lines increases as well attributing to the low temperature absorption.

4. CONCLUSION

We calculated the divergence of radiation flux in the arc plasma in air with increasing copper vapour concentration. Increasing copper vapour concentration with fixed temperature profile leads to increased emission in the central parts of the arc and higher absorption close to the outer wall. In real situation the power input would probably be constant. As the result one can expect the plasma to cool down as the concentration of metal vapour increases. Also the thermal stress to the arcing chamber wall would increase as more energy will be transferred via radiation.

5. ACKNOWLEDGEMENT

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