Properties of thermal air plasma with admixing of copper and carbon

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Abstract. This paper deals with investigations of air plasma with admixing of copper and carbon. Model plasma source unit with real breaking arc was used for the simulation of real discharges, which can be occurred during sliding of Cu-C composite electrodes on copper wire at electromotive vehicles. The complex technique of plasma property studies is developed. From one hand, the radial profiles of temperature and electron density in plasma of electric arc discharge in air between Cu-C composite and copper electrodes in air flow were measured by optical spectroscopy techniques. From another hand, the radial profiles of electric conductivity of plasma mixture were calculated by solution of energy balance equation. It was assumed that the thermal conductivity of air plasma is not depending on copper or carbon vapor admixtures. The electron density is obtained from electric conductivity profiles by calculation in assumption of local thermodynamic equilibrium in plasma. Computed in such way radial profiles of electron density in plasma of electric arc discharge in air between copper electrodes were compared with experimentally measured profiles. It is concluded that developed techniques of plasma diagnostics can be reasonably used in investigations of thermal plasma with copper and carbon vapors.

1. Introduction

Usually copper wire and various types of inserts, which are fixed on the contact surface of the pantograph, are widely used in power supply circuits of electric transport. Graphite, coke, copper-graphite or copper alloys can be used as materials in producing of such inserts. Each of these types of inserts has some advantages and disadvantages [1].

In particular, in spite of good lubricating properties of graphite and coke inserts, they have a comparatively high electrical resistivity. So, deterioration of tribological parameters of copper trolley wire takes place due to annealing in a result of significant Joule heating [2]. Moreover, such inserts have a sufficiently low hardness, so their service life is reduced.

The metal contact inserts on a base of copper alloys are characterized by a significantly less resistivity and a longer life. However, as a result of their affinity with the copper wire, the last one is significantly abraded by such inserts. Additionally, it must be noted that cost of copper wire is significantly higher in comparison with the cost of inserts.

Therefore, design engineers of such inserts usually recommend a copper-graphite composite as an optimal material for their produce [1]. Such composite has good lubricating properties due to its...
graphite component. The additions of copper in these materials provide the much higher electrical conductivity in comparison with graphite inserts. To avoid an affinity of these composite inserts with a conducting wire, the copper content in such material is insignificant.

On the other hand, an electric arc between a conducting wire and a pantograph contact frequently occurs, which leads to a significant erosion of the material. This phenomenon is greatly enhanced when icing of contact wire takes place. Understanding of a mass transfer processes in discharge gap and knowledge of plasma parameters will help to optimize the techniques with the aim to reduce the erosion of contact and wire. So, it will be contribution to improvement of economic performance of contact material productions.

The aim of this work is a study of plasma properties of model electric arc ignited in air atmosphere between Cu-C composite or copper electrodes. This paper deals with experimental investigations of parameters of thermal plasma mixture and calculations of electrical conductivity as well as electron density in discharge column.

2. Experimental investigations

2.1. Arc discharge arrangement
The free burning electric arc was ignited in air between the end surfaces of Cu-C composite non-cooled vertically arranged electrodes. At the fabrication technology the copper content in this composition was controlled around 20% [3]. This copper content was additionally verified by mass spectroscopy studies. The peculiarities of surface condition and erosion rate of composite electrodes under influence of arc discharge and plasma composition as well will be study in detail by additional investigation using metallography and optical spectroscopic techniques. Nevertheless, it was strongly controlled that both electrodes were not significantly consumed during experimental investigations. Additionally arc discharge between non-cooled copper electrodes in air flow 6.4 slpm was studied.

The diameter of the rod electrodes was 6 mm, the discharge gap was 8 mm, arc current was 3.5 or 30 A. To avoid the metal droplet appearing, a pulsing high current mode was used: namely, the rectangular current pulse of 30A was put on the "duty" low-current (3.5 A) discharge. The high-current pulse duration was of 30ms. The registration of arc plasma emission was performed at 7 ms after current pulse rise when a steady-state mode of electric arc discharge was realized. We found in our previous investigation that in such steady-state mode of arc discharge in air between copper containing electrodes the local thermodynamic equilibrium (LTE) is realized [4].

A more detail description of experimental setup and measurement procedure one can find in [5,6].

2.2. Experimental techniques

2.2.1. Temperature measurement. Boltzmann plot method was applied for plasma temperature determination. The one-pass tomographic recording of the spatial distribution of spectral line intensities was used in the first techniques [7]. Monochromator MDR-12 with 3000-pixels CCD linear image sensor (B/W) Sony ILX526A accomplished fast scanning of spatial distribution of radial intensity. Due to the instability of the discharge, statistical averaging of the recorded spatial distributions of the radiation characteristics was carried out.

In alternative techniques the diagnostics with simultaneous registration of spectral and spatial distribution of emission intensity was used. Spectra registration was performed by digital camera on CCD matrix in a grating spectrometer in such approach [6].

Selection of Cu I spectral lines and analysis of their spectroscopic data was previously carried out in [8]. So, copper spectral lines 510.5, 515.3, 521.8, 570.0 and 578.2 were used for plasma diagnostics in present work.
2.2.2. Electron density measurement. Radial profiles of electron density were obtained from half-
width of spectral line Cu I 515.3 nm in assumption of dominating quadratic Stark effect. The spectral
device combined with Fabry-Perot interferometer in etalon mode was used for registration of spectral
line profiles at 30 A [9]. A special program graphical user interface in such experimental techniques
was used.

Unfortunately, such Fabry-Perot interferometer can’t be used for half-width determination in a case
of 3.5 A current. So, electron density in this case was calculated by algorithm based on previously
obtained plasma parameters, namely: temperature distributions for 3.5 and 30 A, electron density for
30 A, intensities ratio of Cu I spectral lines. Comprehensive description of the algorithm is described
in paper [8].

3. Results and discussions

3.1. Results of temperature measurements
Radial temperature profiles T(r) of electric arc discharges are shown in figure 1. Experimentally
obtained data (Exp) and error bars are approximated by Gaussian curves T, T SUP and T INF accordingly.
Measurements were carried out in middle section of arc column.

![Figure 1. Experimentally obtained data (Exp) and approximation curves of temperature radial
profiles T, T SUP and T INF in middle section of discharge gap of electric arcs between Cu-C
electrodes at current 3.5 A in air (a) and copper electrodes in air flow at currents 3.5 A (b) and
30 A (c).](image)

3.2. Calculation of plasma parameters

3.2.1. Transport properties of arc discharge plasma. The real thermal and electrical conductivity
radial profiles of air-copper plasma mixtures were calculated in detail in our previous investigations
[10]. Electric arc between copper electrodes in air flow at current 3.5 A was studied. It was found that
the copper admixture almost has no influence on the thermal conductivity of such plasma mixture in experimental temperature range 3000 K<T<6000 K (see figure 2). It is well known, in contrast to this parameter, the electric conductivity is very sensitive to the metal admixture in plasma.

So, the electrical conductivity $\sigma$ of air plasma with admixing of copper can be calculated by solution of energy balance equation (1). In this approach the thermal conductivity $\lambda$ of air without any admixtures was used. The electric field $E$ of arc plasma column was measured additionally by discharge length $L$ varying (see figure 3).

$$\sigma E^2 + \frac{1}{r} \left[ \frac{d}{dr} \left( r \lambda \frac{dT}{dr} \right) \right] = 0 .$$  \hspace{1cm} (1)

![Figure 2. Radial profiles of thermal (a) and electrical (b) conductivity of plasma in arc discharge in air flow with copper admixture (filled) and without it (open).](image)

It must be noted that in equation (1) radiation losses term is neglected. Our preliminary estimation of radiation losses, caused by emission of copper spectral lines, showed that influence of this mechanism is insignificant for the temperatures up to 8500 K. Additionally we can note that just similar conclusion was made in paper [11], where author showed that radiation losses is negligible in the current range up to 30 A.

So, radial distribution of electrical conductivity can be calculated in the following manner:

$$\sigma(r) = - \frac{1}{rE^2} \left[ \frac{d}{dr} \left( r \lambda \frac{dT}{dr} \right) \right] .$$  \hspace{1cm} (2)
Figure 3. Voltage drop on discharge gap of electric arcs between Cu-C electrodes in air at current 3.5 A (a) and between copper electrodes in air flow at currents 3.5 A (b) and 30 A (c).

In figure 4 electrical conductivity radial profiles of electric arc plasma are shown. Calculated data (from equation (2)) was approximated by Gaussian curves according to three different temperature profiles $T$, $T_{\text{Sup}}$ and $T_{\text{Inf}}$. The procedure of approximation was carried out under strong requirements of true value of experimental discharge current.

Figure 4. Radial profiles of electrical conductivity calculated from equation (2) and approximation curves $\sigma_T$, $\sigma_{T\text{Sup}}$ and $\sigma_{T\text{Inf}}$ in discharge gap of electric arcs between Cu-C electrodes at current 3.5 A in air (a) and between copper electrodes in air flow at currents 3.5 A (b) and 30 A (c).

At the next step of investigation the radial profiles of electron density in arc discharge were obtained from calculated profiles of electrical conductivity.

3.2.2. *Electron density calculation.* Since the mobility of electron is much higher than the ion mobility, the ion current in plasma can be neglected. Then plasma electrical conductivity can be written as:
\[ \sigma(r) = eN_e(r)\mu_e(r), \]  
(3)

where \( e \) is the elementary electrical charge, \( N_e(r) \) – electron density distribution, \( \mu_e \) – electron mobility, which can be expressed in terms of the frequency of electron collisions with other particles:

\[ \mu_e(r) = \frac{e}{m_e \nu_e(r)}, \]  
(4)

where \( m_e \) is the mass of electron, \( \nu_e \) – electron frequency collisions with particles of all sorts, which can be written as:

\[ \nu_e(r) = \sum_p \nu_{e-p}(r), \]  
(5)

\[ \nu_{e-p}(r) = N_p(r)u_eQ_{e-p}, \]  
(6)

where \( \nu_{e-p} \) is the frequency of electron collisions with particles of sort "p", \( N_p(r) \) – the radial distribution of particle density of sort "p" and \( u_eQ_{e-p} \) – the product of the average electron velocity and collision cross section for particles of sort "p". It was assumed that plasma is in LTE, so Maxwell distribution was used in calculation of the average value \( u_e \) in equation (6).

Thus, electron densities can be obtained from equations (3) – (6). Peculiarities of necessary calculation of plasma composition and the cross sections determination are discussed in detail in paper [10].
In figure 5 radial profiles of electron densities in electric arc plasma column are shown. Simulations were carried out on the base of calculated electrical conductivities according to three different temperature profiles $T$, $T_{\text{Sup}}$ and $T_{\text{Inf}}$. In case of electric arcs between copper electrodes in air flow at currents 3.5 A and 30 A experimentally measured radial profiles of electron density in plasma between copper electrodes in air flow are additionally shown in figure 5 (b,c) [12].

One can conclude that agreement between experimental and calculated data is more or less acceptable. Unfortunately, experimental validation of electron densities in electric arc between composite Cu-C electrodes was complicated due to the strong continuum radiation. Nevertheless, calculated radial profiles of electron density in electric arc between these electrodes seem to be quite reasonable. At the next step of investigation another kind of experimental techniques must be used to obtain such profiles.

**Conclusions**

The complex technique of plasma property studies is suggested. From one hand, the radial profiles of temperature and electron density in plasma of electric arc discharge in air between Cu-C composite and copper electrodes in air flow were measured by optical spectroscopy techniques. From another hand, the radial profiles of plasma electric conductivity were calculated by solution of energy balance equation. The electron density was obtained from the electric conductivity profiles by calculation in LTE assumption and taking into account that thermal conductivity is not affected by electrode material admixtures.

The good agreement between experimental and calculated in such way plasma electron densities in electric arc discharge between copper electrodes in air flow is found. So such approach can be recommended for low temperature thermal plasma diagnostics.

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