

Effect of radiation intensity pulsations of plasma on its temperature

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Abstract. Effect of radiation intensity pulsations of non-stationary plasma on its radial temperature is studied. Consequence of these pulsations on accuracy of the measurement of plasma optical characteristics is discussed. The case of the plasma is stationary in space whereas temperature makes pulsations obeyed both harmonious and random laws in each its points is also investigated.

1. Introduction

It is well-known fact that both electroarc and high-frequency plasmas are not stationary [1-2]. The electric current and voltage, as well as speed and luminance of a stream of plasma are subjects of oscillation. There are many reasons causing instability of arc arrangement in space, such as interacting of arc with intrinsic magnetic field, circumambient convection, strong electric fields, turbulent flow fluctuations and others. It has been proven that both oscillations of luminance intensity of a stream on the plasmatron exit and voltage of arc display a random character, and an analytical relation between them has been derived [3]. Investigating the dependence of pulsations in a plasma stream – of plasma stream turbulence, fine-scale shunting, lateral oscillations of a positive column (and some other reasons) resulted in the fact that temperature oscillations submit to normal distribution [1]. In [4], pulsations of speed, electric current and voltage, and an optical signal in a stream of direct current arc plasma were studied. It was proven that fluctuation of these parameters attains 10-20 % of its stationary values. In [5-8], the research of space oscillations of an electric arc in plasmatron with fixed arc length resulted in the fact that the space displacement of arc can alterate considerably the temperature of plasma and its radial distribution. High-frequency argon plasma can be also non-stationary. Anisotropic plasma's hydrodynamic-type instability produced by interacting of plasma kernel with a flow of blown in cold gas is the principal cause of instability. In [9], it was studied the dependence of temperature into the plasma axis of ICP-AES (Inductively Coupled Plasma Atomic Emission Spectrometry) of the inductive frequency and it was shown that frequency increasing leads to temperature decrease on the discharge axis. Besides, it was shown that the space pulsations in ICP-AES plasma are not significant by comparison to that of arc plasma, whereas time oscillations can be essential.

2. Plasma model.

Let's axisymmetric plasma, which is stationary in space, plus the temperature exhibits simultaneously two kinds of oscillations, harmonic and random, in each its points about average temperature T_c .

Harmonious temperature oscillations can be expressed by:



$$T = T_c + a \cdot \cos(\omega t), \quad (1)$$

where ω – the cyclic frequency and a – the amplitude value of temperature oscillations. The distribution function of the temperature difference $T - T_c$ related to equation (1) can be presented as:

$$\varphi_2(T - T_c) = \frac{1}{\pi \sqrt{a^2 - (T - T_c)^2}}. \quad (2)$$

The distribution function of random temperature oscillations is taken as Gauss distribution function, which can be written by:

$$\varphi_1(T - T_c) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(T - T_c)^2}{2\sigma^2}}, \quad (3)$$

where σ is the root-mean-square deviation of temperature.

By accounting for expressions (2) and (3) and replacing $\xi = (T - T_c)$, the generalized distribution function takes the form:

$$\varphi(\xi) = \int_{-a}^a \varphi_1(\zeta - \xi) \varphi_2(\zeta) d\zeta = \frac{1}{\sigma \sqrt{2\pi^3}} \int_{-a}^a \frac{\exp(-\frac{(\zeta - \xi)^2}{2\sigma^2})}{\sqrt{a^2 - \zeta^2}} d\zeta. \quad (4)$$

During the integration prescribed by the function (4) the limits of the quantities a and ξ has been taken from 1000 K up to 4000 K in this study. In figure 3, we are presenting the graphs of the function $\varphi(\xi)$ drawn for $\sigma = 2000$ K and $a = 1000$ K (1), 2000 K (2), 3000 K (3) и 4000 K (4).

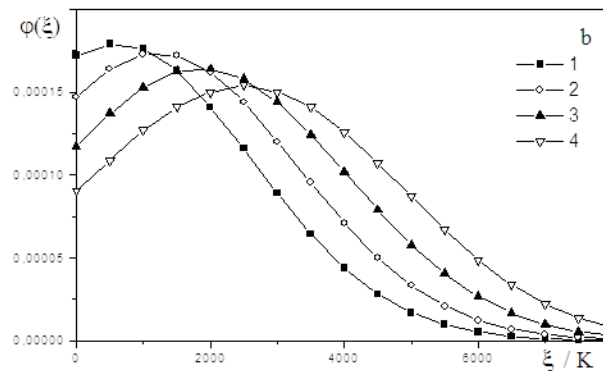


Figure 1.

It is seen from the graphs presented in figure 1 that the maximal values of distribution functions are displaced to right side from average temperature by rising a for a given σ .

3. Radial radiation intensity and temperature

The oscillations of temperature followed the distribution function (4) act to radiation intensity and the radial temperature. Radiation intensity relates to temperature by relationship [12]:

$$\varepsilon_v(T) = \frac{1}{4\pi} A_{ij} n_0(T) \frac{g_i}{Z_a(T)} e^{-\frac{E_i}{kT}} h\nu, \quad (5)$$

where $Z_a(T) = \sum_i g_i e^{-\frac{E_i}{kT}}$ – the statistic sum, A_{ij} – the probability of atom transition from i -th energy state with energy E_i to j -th energy state with energy E_j , g_i – the weight of i -th state.

Taking into account the distribution function (4) average radiation intensity can be calculated by the formula:

$$\bar{\varepsilon}(T_c) = \int \varepsilon(T) \varphi(T - T_c) dT \quad (6)$$

We calculated radiation intensity for a chosen spectral line Ar I 415.8 nm. The dependence of radiation intensity of the temperature for this line was given in [6]. Integration (6) was performed for the temperature region $T_c = 4000 \text{ K} - 16000 \text{ K}$, the oscillation amplitudes were taken equal to $a = 500 \text{ K} - 4000 \text{ K}$ and root-mean-square deviations – $\sigma = 500 \text{ K} - 4000 \text{ K}$.

The results of integrating (6) testify that the real values of $\varepsilon(T)$ differ from those averaged $\bar{\varepsilon}(T)$. This difference depends on the amplitude of temperature oscillation a , root-mean-square pulsations σ , and the temperature region. When a is constant, this difference increases with growing σ . However, in the temperatures region of $12000 \text{ K} - 13000 \text{ K}$, this difference is insignificant. At constant σ , with growing a this difference also increases, and for chosen line Ar I 415.8 nm difference between $\bar{\varepsilon}(T)$ and $\varepsilon(T)$ is maximal in the vicinity of temperature 8000 K and it is minimal in the vicinity of $12500 \text{ K} - 13000 \text{ K}$.

Spectroscopic determination of the temperature of axisymmetric plasma was performing by experimental founding the lateral intensity distribution of the arc, then, the radial radiation intensity was deriving by means of Abel's integral transformation [13] and, finally, the temperature distribution upon arc radius was determined by using temperature dependence of the radiation intensity (5).

To determine the radial temperature, we are choosing lateral intensity distribution on arc in the form:

$$I(x) = I(0) \exp(-\alpha x^2), \quad (7)$$

where $I(0)$ – the value of radiation intensity on the arc axis and α – a factor. Substituting (7) in Abel's integral equation gives us the radial distribution $\varepsilon_v(r')$, where $r' = r/R$ – relative radius of plasma flow.

The radial radiation intensity and the radial temperatures have been calculated by taking constant values of σ and variable amplitude a , which were equal successfully 1000 K , 2000 K , 3000 K and 4000 K , then – for constant a and variable σ equal successfully 1000 K , 2000 K , 3000 K and 4000 K .

Calculation of temperature distribution on arc radius has been performed for three temperatures of arc axis equal to $T_0 = 8000 \text{ K}$, 10000 K and 12000 K and for the range of σ and a equal to $1000 \text{ K} - 4000 \text{ K}$

by taking into consideration the values of radial intensity and dependences of radiation intensity of temperature.

The results of calculating the radial temperatures T for the axis temperature 10000 K are drawn in figure 2. The curves of dependences $T(r')$ for $\sigma = 1000$ K and $a = 1000$ K (2), 2000 K (3) and 3000 K (4) are presented in figure 2-a, and for $a = 1000$ K and $\sigma = 1000$ K (2), 2000 K (3) and 3000 K (4) – in figure 2-b. The curves labeled by the number 1 correspond to the radial temperatures at the absence of oscillations.

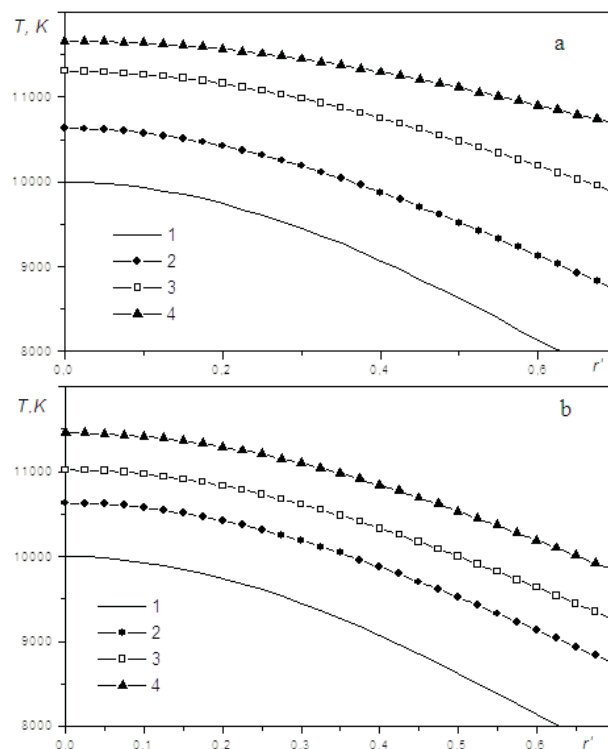


Figure 2

We can see in figure 2 that pulsations result in temperature growing on entire profile. Effect of pulsations depends on σ and a . By growing σ difference between the true and observed profiles increases and can attain 1500 K at arc axis and 3000 K at periphery. Growing of oscillation amplitude a also results in increase of difference between the true and observed profiles.

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