Determination of the temperature field of a spherical arc

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Abstract. The work is devoted to mathematical modeling of the plasma temperature field. To do this, it was represented as a conducting sphere under boundary conditions of the third kind. The simulation of the thermal process is based on the numerical integration of the heat equation. This takes into account the change in the thermal conductivity of the plasma and convective heat transfer. Also, based on the obtained result, an analysis of the behavior of the temperature field was carried out.

1 Introduction

Plasma is a state of matter in which free electrons, positively charged atoms or ions and neutral atoms or molecules are present in the substance.

In the simplest case, plasma can be represented as an ionized gas. Depending on the degree of ionization of atoms, plasma is conditionally divided into cold and hot. Cold plasma is a state of ionized gas in which the number of positively charged ions is negligible. Obviously, a large amount of energy is required to detach a large number of electrons from a multi-electron atom. In this sense, highly ionized plasma can be called hot [1-3].

Plasma is the most common state of matter in nature. Stars are giant regions of hot, that is, highly ionized plasma. The outer surface of the earth's atmosphere is surrounded by a plasma shell called the ionosphere. Plasma occurs in all types of gas discharges.

Low-temperature plasma finds wide practical application in devices used in current control circuits of space and ground-based nuclear power plants. Recently, a large number of theoretical papers have been published on modeling discharges in inert gases describing the contraction of a positive discharge column. Plasma is a state of matter in which free electrons, positively charged atoms or ions and neutral atoms or molecules are present in the substance [4-6]. Therefore, plasma is defined as a collection of charged and neutral particles.

In the simplest case, plasma can be represented as an ionized gas. But the gas is specific: it may contain charged particles that vary greatly in mass. Depending on the degree of ionization of atoms, plasma is conditionally divided into cold and hot. Cold plasma is a state of ionized gas in which the number of positively charged ions is negligible. Obviously, a large amount of energy is required to detach a large number of

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electrons from a multi-electron atom. In this sense, a strongly ionized plasma can be called hot. To describe its properties today, various models are often used. Several papers have been devoted to the calculation of temperature fields under various conditions. In this case, the temperature dependence of the thermal conductivity of the plasma is often not taken into account [7-9].

2 Main Part

We will consider the arc itself as a spherical continuous conductive ball with a specific electrical conductivity σ, in which all the electrical energy supplied to the unit volume is diverted due to thermal conductivity to the cooled walls of the sphere with radius R. The plasma energy balance is described by the thermal conductivity equation, which in a spherical system has the form [10]

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\lambda\frac{dT}{dr}\right) = -\sigma E^2 \quad (1)$$

where: λ is the coefficient of thermal conductivity, E is the electric field strength.
The following boundary conditions were taken into account: at r = R T = Tc, where Tc is the wall temperature, the absence of heat flow in the center due to symmetry

$$\left.\frac{dT}{dr}\right|_{r=0} = 0 \quad (2)$$

and a given warm flow on the plasma surface

$$\left.\frac{dT}{dr}\right|_{r=r_0} = -\frac{W}{2\pi\lambda r_0} \quad (3)$$

where: r_0 is the radius of the conductive channel; W is the power invested in the discharge per unit of its length.

As is known, the thermal conductivity of plasma is caused by the movement of particles. Electrons play a major role in the transfer of heat from hot plasma sites to cold ones. They have great speed due to thermal motion. If there is a temperature difference in a certain area, then electrons with high energies go in one direction, and with lower ones – in the other. In this case, the dependence of thermal conductivity on temperature has the form [11]

$$\lambda = \frac{10^{-21}}{Q}\sqrt{\frac{T}{A}} \quad (4)$$

where: A is the atomic mass of the gas, Q is the effective collision cross section equal to

$$Q = \sqrt{2}\pi d^2 \quad (5)$$

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The arc itself is represented by two regions: conducting at $0 < r < r_0$ and non-conducting ($\sigma = 0$) at $r_0 < r < R$. In the conducting region, in accordance with the accepted assumptions, the thermal potential σ is constant.

In the no conducting zone, the energy equation (1) will take the form

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\lambda\frac{dT}{dr}\right)=0 \tag{6}$$

or

$$\frac{d}{dr}\left(r^2\lambda\frac{dT}{dr}\right)=0 \tag{7}$$

where from

$$r^2\lambda\frac{dT}{dr}=C \tag{8}$$

Substituting equation (4) into equation (8)

$$r^2\sqrt{T}\frac{dT}{dr}=C_1 \tag{9}$$

Let's separate the variables

$$\sqrt{T}dT=\frac{C_1}{r^2}dr \tag{10}$$

We integrate both parts, taking into account the fact that the plasma temperature is much higher than the temperature on its surface, taking T_c=0

$$\int_T^0\sqrt{T}dT=\int_r^R\frac{C_1}{r^2}dr \tag{11}$$

where from

$$-\sqrt{T^3}=-\frac{C_2}{Rr}\left(R-r\right) \tag{12}$$

by $r = r_0$ $T = T_0$

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$$C_2 = \sqrt{T_0{}^3}\,\frac{Rr_0}{R - r_0} \tag{13}$$

Thus, we obtain a functional dependence for the temperature field in the non-conducting zone

$$T = T_0\left(\frac{r}{r_0}\frac{R - r}{R - r_0}\right)^{2/3} \tag{14}$$

From here we find the density of the heat flux on the plasma surface

$$\left.\frac{dT}{dr}\right|_{r=r_0} = -\frac{2T_0}{3r_0}\frac{R - 2r_0}{R - r_0} \tag{15}$$

Equating (15) and (3), we obtain a formula for calculating the input power

$$W = \frac{4}{3}\pi\lambda T_0\frac{R - 2r_0}{R - r_0} \tag{16}$$

where from

$$T_0 = \frac{3}{4}\frac{W}{\pi\lambda}\frac{R - r_0}{R - 2r_0} \tag{17}$$

As follows from formula (14), the plasma temperature field decreases in the direction from the center. This is due to the process of heat transfer to the environment on the surface of the plasma itself. Using formula (17), one can find the temperature of the plasma in its center.

Below is a graph of changes in the temperature field of a spherical plasma (fig. 1).

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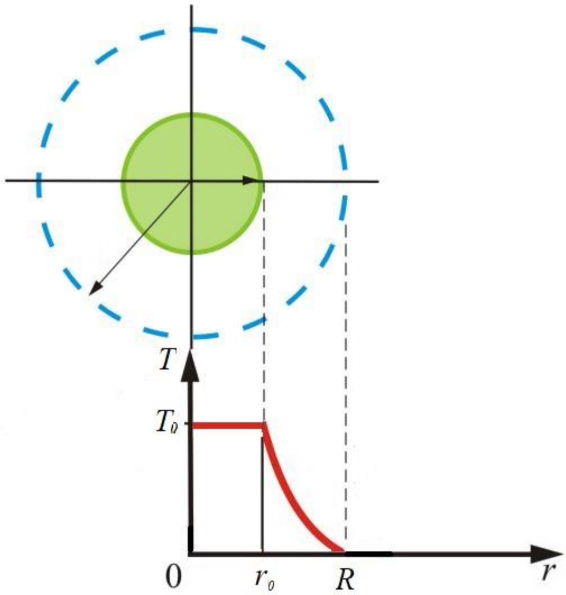

Fig. 1. Temperature distribution over the radius of the sphere

3 Conclusions

The article was devoted to the study of spherical plasma. When finding a solution to the problem, the dependence of the thermal conductivity of the plasma on temperature is taken into account. The law of temperature change in the cross-section of the arc was obtained, as well as formulas for finding the density of the supplied flow and the temperature of the plasma in its center. The result obtained can be used to study the properties of ball lightning.

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