Spectral studies of inductively coupled plasma characteristics of low pressure discharges for two configurations of vacuum chambers

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Abstract. In this work, we carried out comparative studies of the electron temperature in Inductive coupled radio frequency (ICRF) for two configurations of discharge chambers – cylindrical and flat, considered as prototypes of ICP technological modules of the installation in the argon pressure range from 10 to 50 Pa. The study used optical emission spectrometry of the plasma. As a result, the dependences of the electron temperature on pressure and power were obtained. It is shown that with increasing pressure, different dynamics of the electron temperature is observed for the cylindrical and plane geometry of the inductor.

1. Introduction
Optical emission spectroscopy (OES) is a set of methods [1, 2] for determining such plasma parameters as electron density [3–6], electron temperature [3, 4, 6–10], the form of electron energy distribution functions (EEDF) [11-13]. The study of discharges by OES methods allows one to determine the main characteristics of the plasma without causing disturbances in it. This is convenient not only for fundamental research, but also for industrial applications, since access to industrial reactors is often limited, the compact implementation of the diagnostic method using an optical fiber is an additional advantage of this method. Electron temperature is one of the main parameters of a partially ionized plasma. Determination of \( T_e \) in plasma, in the processes of deposition of functional coatings and modification of materials, is an important task for predicting the properties and parameters of coatings, and for choosing the optimal operating modes of technological units.

The aim of the research is to study the dynamics of the electron temperature in ICRF discharges (13.56 MHz) for two configurations of discharge chambers - cylindrical and flat, in the argon pressure ranges from 10 to 50 Pa and the power supplied to the inductor from 0.1 to 1.0 kW.

2. Experimental setup, results and discussion
The work carried out comparative studies of two schemes for the execution of induction discharges - cylindrical (Figure 1) and flat (Figure 2), considered as prototypes of technological modules of the installation for creating an ICP. Photographs of the combustion process of an RFI discharge at various inductor geometries are shown in Figures 3 and 4. The cylindrical ICP source is a quartz water-cooled tube with an inner diameter of 27 mm and a length of 250 mm with an inductor with an inner diameter
and height of 60 mm, 2.5 turns. The flat ICP scheme is made using a silicate glass flask with an inner diameter of 150 mm, placed on the outside of the bottom of a flat coil with an outer diameter of 80 mm, 2.5 turns.

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**Figure 1.** Diagram of a cylindrical ICP source.  
**Figure 2.** Schematic of a flat ICP source.

Plasma radiation is focused through collimator optics and transmitted to the optical system of the spectrometer. The spectrum decomposed into wavelengths is converted into a digital signal, which is transmitted to a PC (laptop) and processed using special software. The research uses the Ocean Optics USB4000-VIS-NIR spectrometer with Plasus PL-25-12-00 collimator optics, the spectral measurement range is 345 - 1041 nm with a resolution of 1.5 nm.

The measured spectra were normalized with respect to the exposure time, the spectra were recorded at equal distances from the radiation source towards the core of the ICP discharge glow. In the studies for both discharge circuits, uniform means of creating a vacuum were used - an assembly based on AVZ-20 and NVD-600 (DVN-150), pressure measurements - a capacitive membrane sensor MKS 627B, working gases supply - RRG-10-360 and HF power supply - AE Cesar 1330 (VCG) and AE VarioMatch 5000 (SU). The intensity of the brightest lines is higher in the case of cylindrical ICP.

The electron temperature $T_e$ was estimated using the method of relative spectral line intensities [14]. The calculations were carried out under the assumption of a Boltzmann distribution of atoms over excited states and a Maxwellian electron energy distribution function. Ionization is determined by the Saha formula. These assumptions are fulfilled in the plasma of an ICRF discharge [15]. If the main excitation processes are determined by inelastic collisions of electrons with atoms, the ratio of the intensities of the spectral lines has the form

$$\frac{I_j}{I_l} = \frac{g_j A_j \lambda_j}{g_l A_l \lambda_j} e^{-\frac{E_j-E_l}{kT_e}},$$

where $g_j$ and $g_l$ are the statistical weights of the upper levels, $A_j$ and $A_l$ are the transition probabilities, $\lambda_j$ and $\lambda_l$ are the wavelengths, $E_j$ and $E_l$ are the energies of the upper levels, $k$ is the Boltzmann constant, and $T_e$ is the electron temperature. In the calculations, we used the intensities of two argon lines with wavelengths of 738.4 nm and 763.5 nm [16], which appear during transitions between electronic levels $3s^23p^5(3P^o_{1/2})4p^3[3/2]$, $3s^23p^5(3P^o_{3/2})4s^2[3/2]^0$ for $\lambda_j = 738.4$ nm and $3s^23p^5(3P^o_{3/2})4p^3[3/2]$, $3s^23p^5(3P^o_{3/2})4s^2[3/2]^0$ for $\lambda_l = 763.5$ nm. Thus, knowing the transition probabilities of the corresponding spectral lines and experimentally measuring the ratio of their intensities, we can determine the electron temperature $T_e$ from (1) by the formula

$$kT_e = \frac{E_j - E_l}{\ln \left( \frac{I_j g_j A_j \lambda_j}{I_l g_l A_l \lambda_l} \right)},$$

where $E_j$ and $E_l$ are the energies of the upper levels, $A_j$ and $A_l$ are the transition probabilities, $\lambda_j$ and $\lambda_l$ are the wavelengths.
where $h$ is Planck's constant, $A_j$ and $A_l$ are the transition probabilities, $E_j$ and $E_l$ are the energies of the upper levels [17].

The statistical weights of the upper levels, the transition probabilities, the energies of the upper levels, and other corresponding constants are taken from the Atomic Spectra Database Lines Data NIST [18] and are presented in Table 1.
Table 1

| \( \lambda, \text{nm} \) | \( A, \text{cm}^{-1} \) | \( g \) | \( E, \text{eV} \) |
|---------------------|----------------|------|--------|
| 738.4               | \( 8.5 \times 10^6 \) | 5    | 13.30  |
| 763.5               | \( 24.5 \times 10^6 \) | 5    | 13.17  |

For two schemes of the studied discharges, according to formula (2), the dependences of the electron temperature \( T_e \) on the pressure and power of the RF signal in the ranges of 10-50 Pa and 0.1-1.0 kW, respectively, are plotted. The curves are shown in Figures 5, 6. There is a decrease in the electron temperature with an increase in the electric power. This is typical for gas discharges at a pressure of 10 Pa and is a consequence of two-stage ionization, which, with an increase in the electron density, requires a lower electron temperature to provide the required ionization rate [19]. The measurement results are in qualitative agreement with the experimental data of other authors [19].

Figure 6 shows that with increasing pressure, a different dynamics of the electron temperature is observed for the cylindrical and flat geometry of the inductor. The structure and magnitude of the electromagnetic field depend on the geometry and distance between the inductor and the grounded electrode. In the case of a cylindrical inductor, the spectral characteristics of the jet were recorded; the decrease in the electron temperature is due to an increase in the frequency of collisions between atoms and electrons with increasing pressure and, accordingly, a more efficient transfer of energy from the electron gas to neutral particles. In the case of a flat inductor, the distance between the electrodes is less, the spectral characteristics were recorded in the region with a higher concentration of the electromagnetic field due to the presence of the potential component of the field, inversely proportional to the distance between the electrodes. Thus, for the cases of flat and cylindrical inductors, the electron distribution function is different. In the case of a flat inductor, the electron energy exceeds the maximum of the elastic collision cross section, the electrons spend less energy in collisions with the neutral plasma component, and an increase in the electron temperature is observed.

Figure 5. Dependence of \( T_e \) on RF power at a pressure of 10 Pa, curves – approximation.
3. Conclusions

It follows from the results obtained that the cylindrical ICP has a higher electron temperature at 10 Pa, which is explained by the higher values of the magnetic field induction associated with the geometry of the inductor in comparison with the flat circuit, as well as higher values of the local pressure in the flow plasma flow. At the same time, a flat ICP source allows one to create a more voluminous plasma, which is explained by the large dimensions of the space for the discharge burning; accordingly, the diffusion and death factor of charged particles on the chamber walls is much lower.

A decrease in the electron temperature with an increase in the electric power is a consequence of two-stage ionization, which, with an increase in the electron density, requires a lower electron temperature to ensure the required ionization rate.

For a cylindrical inductor, with increasing pressure, a decrease in the electron temperature is due to an increase in the frequency of collisions between atoms and electrons. In the case of a flat inductor, where the distance between the electrodes is smaller, the spectral characteristics were recorded in the region with a larger potential component of the electromagnetic field as compared to the circuit for a cylindrical inductor. Thus, the shape of the electron distribution function, in the case of a flat inductor, differs from the case with a cylindrical circuit. The energy of electrons exceeds the maximum of the cross section for elastic collisions, electrons spend less energy in collisions with the neutral component of the plasma, and an increase in the electron temperature is observed.

From the point of view of the efficiency of using the input power into an ICP discharge, a cylindrical scheme is preferable for processing bulk materials passing along a plasma and for processes associated with gas-phase changes, for example, as a source of dissociation of molecules and creating a flux of atomic radicals for CVD processes or reactive deposition of thin films. It is also worth noting that the cylindrical ICP scheme is a more efficient source of heating the working gas, which can be used in the processes of ion-assisted heat treatment of local areas of various materials. The flat scheme of excitation of a gas discharge is widely used in the processes of plasma-chemical etching of elements of microelectronics and optics, due to the possibility of obtaining dense plasma uniformly distributed over the area. The results obtained for various methods of excitation of an...
inductive discharge make it possible to take into account the peculiarities of a particular scheme of execution when they are applicable in various technological problems.

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