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Research

DISTRIBUTION OF TEMPERATURE FIELD IN PLASMA FLOW OF HIGH FREQUENCY UNIPOLAR TORCH PLASMATRON

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ABSTRACT

The phenomena that cause the experimentally recorded by the dispersed phase temperature distribution in the high-frequency torch (RF) discharge are discussed in this article. The results of calculation of the weight average temperature of the argon-graphite plasma, obtained by solving Elenbaas-Heller equation for the plasma column of cylindrical shape, with varying frequency and voltage on high-voltage electrode were given. Calculation of the temperature of the dispersed phase based on mathematical modelling of the data was conducted. The difference between the plasma gas temperature and the dispersed phase temperature was condensed shown. Assessment of energy losses, leading to an increase in the temperature of the soot during its condensation and reduction of the plasma column temperature was shown. It has been shown that, given the heat loss in argon plasma-graphite is possible to estimate the plasma temperature via temperature of dispersed particles.

INTRODUCTION

Low temperature plasma is widely used in the preparation and processing of powders, welding and cutting metals, decomposition of high-molecular compounds, etching of various materials, as well as the synthesis of chemical compounds. In plasma chemical reactions take place at a high rate, and non-equilibrium plasma systems promotes chemical reactions, impossible under normal conditions.

We have studied the isotopic effect in the oxidation of carbon in the plasma processes (Myshkin and Khan, 2015): CO content increases from 1.1% to 1.7% in the products of incomplete oxidation of carbon plasma in a magnetic field.

The plasma technologies are important during processing, time and temperature of the beginning of hardening process of plasma products. The treatment time at given flow rate of plasma gas, determined by the length and temperature field within the reactor. Therefore, for assessing the contribution to the isotope effect as the thermal diffusion and other processes, it is necessary to know the temperature distribution along the axis of the plasma reactor.

High-frequency torch discharge on the properties of is the single-electrode discharge E-type, which is formed based on capacitive coupling of the torch-to-earth. To analyze the electrical parameters of the RF torch discharge use the model in the form of an electrical circuit Neumann (Neyman, 1965).

The scientific literature is insufficient data about the distribution of temperature field in the plasma channel of RF torch discharge. Therefore the purpose of this work is the definition of the factors influencing the distribution of the temperature field of a given length in the plasma chemical reactor.

RESULTS

Experimental installation for testing plasma technologies based on RF torch discharge was described in the work (Myshkin and Khan, 2015).

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RF torch discharge was created with graphite electrode inside the plasma chemical reactor using a sine wave oscillator frequency of 27.12 MHz and a power of 4 kW. The length of the plasma channel in argon in a long quartz tube exceeds 50 cm with the use of such a generator. In this case on the walls of the plasma chemical reactor soot formed due to intensive evaporation of a graphite electrode and a small amount of oxidant molecules to form CO (CO_2) in its gaseous state.

Since a direct measurement of the weight average temperature of the plasma gas is difficult, then assessed the disperse phase temperature, formed by the condensation of carbon vapour. During registration of the spectrum of the plasma channel projected a predetermined area on the entrance slit of the monochromator MSDD1000 company SOLAR. When using a diffraction grating with a number of strokes 1200 lines/mm at the monochromator output plane portion formed of the analyzed spectrum 16 nm wide.

The emission spectrum was recorded over the entire length of torch discharge bounded by quartz tube 45 cm in length. Optical spectrum at the same time contains the flow of Planck's radiation and the line of atomic particles. The radiation intensity at the maximum of the Planck curve is reduced ten-fold axis of the plasma channel with a cross section of 2.5 cm to 12.5 cm section. Later Planck radiation flux varies slightly. The temperature of the dispersed phase *T*, generated in the evaporation of the graphite electrode and condensation of the carbon atoms calculated from the Wien's displacement law.

Fig. 1 shows a graph of the temperature distribution of the disperse phase along the axis of the plasma channel, which was determined from the Planck curve.

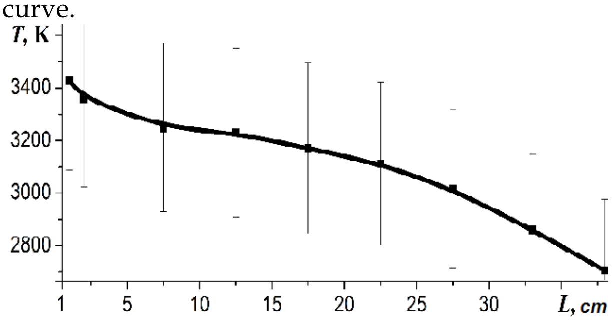

Fig. 1 The distributions of the dispersed phase of the temperature along the axis of the plasma channel.

THE COMPUTATIONAL MODEL

Basic calculations were performed using COMSOL package for physical modelling. Typically, the simulation of low-temperature plasma is possible only in conditions of thermodynamic equilibrium. It is known that low-temperature plasma of RF discharge is the non-equilibrium. Therefore, calculations were performed no for laboratory RF torch discharge, but for the equilibrium low-temperature plasma in a reactor with dimensions taken from the experimental installation. The inner diameter of the plasma reactor was 5 cm, and the length was 45 cm.

Heterogeneity of plasma along the radius of the gas discharge channel with a diameter of 0.3 cm was neglected. As the plasma-forming gas used was argon, supplied to the lower part of the cylindrical shape of the plasma reactor at atmospheric pressure. Flow mode of plasma-forming gas in the plasma reactor shown in work of Myshkin (Myshkin, 2015).

In modeling of plasma phenomena it is also assumed that the coulomb energy of electrons and ions is small compared to their thermal energy, and the ionization and recombination occur on the same path. For the mathematical simulation of the plasma discharge channel was used the drift-diffusion approximation at a pressure close to atmospheric (Wong and Mongkolnavin, 2016). This approach includes the Poisson equation for the electrostatic potential and continuity equations for electrons and ions, which describe the birth and death of the charged particles. On this basis, the drift-diffusion fluxes Γ_e and Γ_i for the one-dimensional case can be written as (Xu, *et al.*, 2013):

$$\begin{cases} \Gamma_e = \mu_e E n_e - D_e \dfrac{\partial n_e}{\partial x} \\ \Gamma_i = \mu_i E n_i - D_i \dfrac{\partial n_i}{\partial x} \end{cases}, \qquad (1)$$

Where μ_e and μ_i-the mobility of electrons and ions, respectively, D_e and D_i-diffusion coefficient of electrons and ions, respectively, n_e and n_i-electrons and ions concentration, *E*-electric field intensity.

For a description of charged particle flows continuity equation will be as follows:

$$\begin{cases} \dfrac{\partial n_e}{\partial x} + \dfrac{\partial \Gamma_e}{\partial x} = \alpha \mu_e |E| n_e - \beta n_i n_e \\ \dfrac{\partial n_i}{\partial x} + \dfrac{\partial \Gamma_i}{\partial x} = \alpha \mu_i |E| n_i - \beta n_i n_e \end{cases}, \qquad (2)$$

Where β–recombination rate, α–ionization ratio that can be calculated from the formula:

$$\frac{\alpha}{P} = A \exp(-\frac{Bp}{E}), \qquad (3)$$

Where *p*–pressure of the plasma-forming gas, A, B-coefficient depending on the ratio *E/P*.

To calculate the electric field inside the plasma chemical reactor plasma torch can be used Poisson equation:

$$\begin{cases} \dfrac{\partial^2 \varphi}{\partial x^2} = \dfrac{q}{\varepsilon_0}(n_e - n_i) \\ E = -\dfrac{\partial \varphi}{\partial x} \end{cases}, \quad (4)$$

Where φ-potential supply electrode, *q*-volume charge density, ε_0-the permittivity of vacuum.

Between the high-voltage high-frequency RF generator electrode and the ground there is capacitive coupling, which provides a self-sustaining electrical discharge in the absence of the second electrode. This inductive conductivity component is much smaller capacitance. The mathematical model of discharge assumed that the plasma formed by the cord is grounded at the output of the plasma chemical reactor, and the voltage applied to the high voltage electrode, varies according to the law:

$$\begin{cases} \varphi\big|_{x=0} = u_0 \sin(2\pi\nu t) \\ \varphi\big|_{x=L} = 0 \end{cases}, \quad (5)$$

where ν–frequency of the supply voltage, *t*-time, u_0-amplitude of the voltage on the electrode.

The temperature and therefore the electron density change along the axis of the plasma channel, which in the simulation can be taken into account by setting the parameters varying along the length. Since the discharge is a plasma column of cylindrical shape, in order to calculate the gas temperature of the plasma used equation Elenbaas-Heller (Benilov and Naidis, 2003).

It is assumed that the heat loss is mainly due to conductive flows:

$$\frac{1}{r}\frac{d}{dr}(\lambda r \frac{dT}{dr}) + \sigma E^2 = 0, \quad (6)$$

Where radius of the plasma channel, λ-coefficient of thermal conductivity, *T*-gas temperature of the plasma, σ-conductivity coefficient.

To determine the ratio of electrical conductivity σ used data (Zaika, *et al.*, 2003).

In this case the heat flux at the plasma axis is absent, and the discharge temperature at the periphery is the temperature of the walls of the plasma chemical reactor T_w:

$$\left.\frac{dT}{dr}\right|_{r=0} = 0, \quad T\big|_{r=R} = T_w. \quad (7)$$

When calculated believed that the electron density at atmospheric pressure of less than 10^{12} cm^{-3}. Transport parameters of charged particles in an argon plasma taken from Hagelaar paper (Hagelaar and Pitchford , 2005). Townsend coefficients in equation (3) for a wide range of pressures are given in paper of Kruithof (Kruithof and Druyvesteyn, 1937). Wall temperature was determined by means of a pyrometer and was 700°C.

Numerical modeling in COMSOL environment (Brezmes and Breitkopf, 2015) calculated the temperature of the plasma channel, depending on the magnitude and frequency of the supply voltage at a distance 1 cm to 2 cm, 2 cm to 9 cm, 3 cm to 17 cm and 4 cm to 25 cm from high voltage graphite electrode (Fig. 2). From Fig. 2 shows that with an increase in the voltage across the high-voltage electrode increases the gas discharge channel temperature. This is due to the fact that increasing the potential for increased graphite electrode power deposited in the discharge. Since the degree of ionization of the plasma in the discharge capacitance type greatly depends on the input power, the amount of carriers increases. Therefore, the total energy of the plasma system transmitted charged particles from the power supply increases.

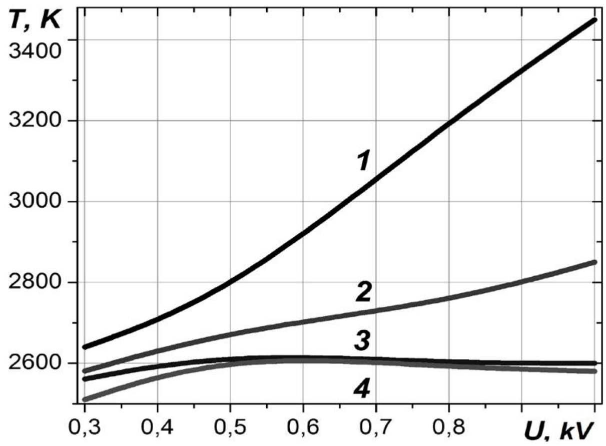

Fig. 2 Dependence of temperature of plasma channel from magnitude of the supply voltage at different distances from the electrode: 1 cm to 2 cm, 2 cm to 9 cm, 3 cm to 17 cm and 4 cm to 25 cm.

Supply voltage frequency significantly affects the temperature of the plasma of electric discharge. Fig. 3 shows that with increasing frequency there is a growth of the gas temperature in the discharge channel. When using a chain of Neumann as a computational model does not take into account the inductive component of the plasma channel.

It is known that the frequency of collisions of particles in the gas phase depends on temperature and pressure. Therefore, we carried out the calculation of the gas temperature of the plasma channel, depending on the initial pressure in the plasma reactor (Fig. 4). Fig. 4 suggests that with increasing pressure the gas temperature in the discharge channel decreases. This is due to the fact that the degree of ionization of the plasma decreases with increasing pressure (O'Connell, *et al.*, 2008). At the same time, the cooling of the plasma leads to a decrease in the concentration of charged particles that carry energy from the electromagnetic field to the plasma particles.

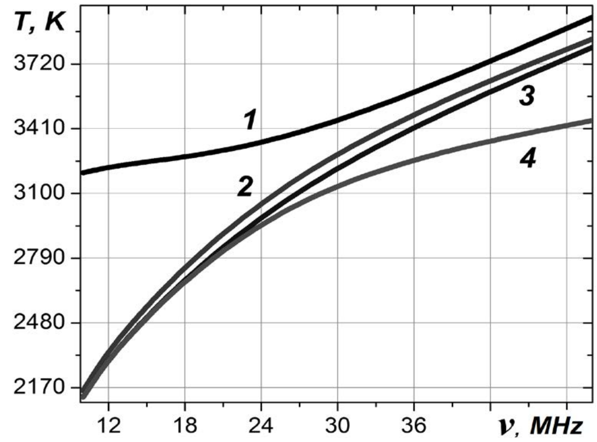

Fig. 3 Dependence of temperature of plasma channel from frequency of the supply voltage at different distances from the electrode: 1 cm to 2 cm, 2 cm to 9 cm, 3 cm to 17 cm and 4 cm to 25 cm.

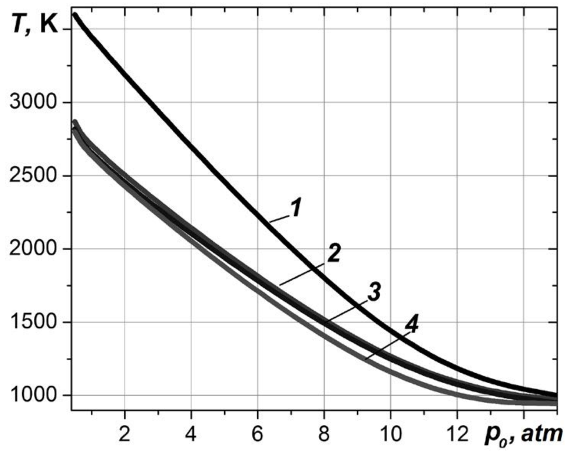

Fig. 4 Dependence of temperature of plasma channel from the pressure inside the plasma chemical reactor at different distances from the electrode: 1 cm to 2 cm, 2 cm to 9 cm, 3 cm to 17 cm and 4 cm to 25 cm.

The contribution of carbon atoms and oxygen molecules in a plasma heating process is neglected due to their small content. Influence of the dispersed phase for various processes in the simulation is also neglected due to the fact that the maximum concentration of atomic carbon and oxygen in the plasma channel does not exceed 0.001 mole fraction.

DISCUSSION

In the photographs of the plasma discharge channel of RF torch discharge recorded a small number of bright tracks along the entire length. On the walls of the reactor, in the area of about 10 cm above the electrode, soot is formed. Therefore we suggest that the dispersed phase comprises two components: the nanoparticles are formed in the electrode region by vapor condensation of carbon and graphite electrodes fragments. In RF torch discharge occurs oxidation of carbon by oxygen impurities in the plasma-forming gas, which penetrates into the reactor due to leaky joints. The decrease in the intensity of the maximum of the Planck curve is due to the oxidation of ultra-dispersed particles. Large fragments do not have time to oxidize and reaches the end of the reactor.

A decrease in temperature of the plasma along the axis of the channel does not contradict the data presented earlier in Manual of Tartu University. At the end of the channel of RF torch discharge is lowering particulate matter temperature to 2700 K. Sufficiently high temperature of the dispersed phase due to the following processes. In the area of electrode pair of carbon have a temperature of the gas phase. Condensation of carbon is accompanied by release of vaporization energy, which heats the soot particles formed above the gas-phase temperature. In what follows the high temperature is maintained by the energy released by the oxidation of the dispersed phase. Therefore, an ultra-dispersed soot temperature slightly above the temperature of the gas phase and has a maximum, in contrast to the gas phase (Kee, *et al.*, 2003).

The ratio of energy emitted by the dispersed particles and atoms was evaluated as the area ratio in the spectrum. Therefore, in the electrode region energy loss of the plasma channel is much higher due to Planck's radiation. The heat capacity change due to changes in the composition of components and temperature change due to energy release of oxidation of carbon plasma system, under these conditions, due to a slight change in the gas mixture in the plasma flow is neglected. However it is possible to analyze the processes leading to heat losses.

The temperature distribution in each cross section along a flow axis defined by a balance between the energy supplied by RF field and losses. In energy balance in the plasma channel of RF torch discharge in different sections of the axis along the plasma channel, the following physical and chemical processes must take into account the relative contribution of that change:

• heating of the plasma by RF field associated with the heating of electronic components and power transmission heavy particles–equation (1), (2), (4);

• heat release during the formation of the dispersed phase and the preferential heating of the soot by that heat (717.7 kJ/mol at 208.16 K);

• The release of energy by the oxidation of particulate carbon (110 kJ/mol).

Processes leading to cooling the plasma flow:

• Heat loss due to heat transfer from the discharge channel to diffuse shell;

• Radiation losses due to soot and gas phase:

$$E = \delta\sigma T^4, \quad (8)$$

$$E = \sum_i \lambda_i A_i g_i \, e^{-\frac{E_i}{kT}}. \quad (9)$$

Other types of energy losses, the value of which cannot be an accurate assessment, make a minor contribution.

An analysis of the processes occurring in the plasma flow of RF to rechdischarge evaporating carbon electrode shows that the temperature of the ultra-dispersed particles is the upper bound of the gas temperature. These particles are formed by vapor having a temperature of the plasma gas. As a result, the carbon condensation releases heat, which is consumed, including for heating of ultrafine particles. Indeed, the dispersed phase temperature determined from the experimental data, the higher the gas temperature calculated for the equilibrium of the plasma of electric discharge.

CONCLUSION

The condensed phase, if present, to a large extent determines the loss of plasma channel energy by Planck radiation. Proposed in the calculation model is suitable for the determination of the electrical parameters of the equilibrium plasma.

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REFERENCES

Benilov, M. and Naidis, G. 2003. Simulation of discharges in atmospheric-pressure air sustained by traveling electromagnetic waves. *IEEE Trans. Plasma. Sci. 31 : 488-494.*

Brezmes, A. and Breitkopf, C. 2015. Fast and reliable simulations of argon inductively coupled plasma using COMSOL. *Vacuum*. 116 : 65-72.

Hagelaar, G. and Pitchford, L. 2005. Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models. *Plasma Sources Sci. Technol.* 14 : 722-733.

Kee, R., Coltrin, M. and Glarborg, P. 2003. Chemically Reacting Flow. Theory and Practice. John Wiley and Sons Inc. Hoboken. New Jersey.

Kruithof, A. and Druyvesteyn, M. 1937. The town send ionization coefficient α and some elementary processes in neon with small admixtures of argon. *Physica*. 4 : 450-463.

Myshkin, V., Izhoykin, A. and Bespala, E. 2015. Carbon and Oxygen Atoms Distribution along Low-Temperature Plasma Torch in the Magnetic Field. *Adv. Mater. Res*. 1084 : 193-96.

Myshkin F, Khan A, Plekhanov V. 2015. Spin Isotope Separation Under Incomplete Carbon Oxidation in a Low-Temperature Plasma in an External Magnetic Field. *Russ. Phys J.* 57 : 1442-1448.

Neyman, M. 1965. The course of radio transmitting devices. Soviet Radio. Moscow.

O'Connell, D., Gans, T. and Crintea, D. 2008. Neutral gas depletion mechanisms in dense low-temperature argon plasmas. *J. Phys : Appl. Physics.* 41 : 1-8.

Wong, C. and Mongkolnavin, R. 2016. Elements of Plasma Technology. *SpringerBriefs. Appl. Sci. Technol.*

Xu, X., Feng, J. and Liu, X.M. 2013. Study of the neutral gas flow on discharges of capacitively coupled plasma in a PECVD reactor. *Vacuum*. 92 : 1-6.

Zaika, E., Mulenko, I. and Khomkin. 2000. Electrical conductivity of fully ionized non-ideal plasma with screened interaction between charges. *High Temp.* 38 : 1-7.