Criteria for similarity of the processes taking place in vacuum plasma torches with hollow cathodes

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Abstract. The article demonstrates that using the vacuum because of its properties as a medium of zero conductivity has enabled to create the construction of hollow cathode plasma torch. An analysis of thermophysical processes inside the cathode channel was carried out. Conditions were determined for the generation of high enthalpy plasma in the cathode channel and the gas-dynamic output of the plasma into the discharge column in the axial direction. A model of the development of the processes of energy input into the cathode channel is considered. General patterns of the working modes are demonstrated, and criteria of similarity for hollow cathode discharges are formulated based on the Knudsen number, the Reynolds criterion and the interconnected electromagnetic parameters.

1. Introduction

In order to clarify the nature of the basic electrophysical processes that define the functioning of vacuum plasma torches with hollow cathodes let us consider the initial conditions for the steady burning of gas discharges in such electrotechnical system.

The features of currents in partially or fully ionized gas (plasma), that is in gas discharges, have been studied for a long time [1-5]. In particular, it is known that the conductivity of plasma increases with the growth of temperature in proportion with $T^{4.5}$ up to about $10^{10}$ S/m, thus amounting to the conductivity of metals. Therefore, one of the functional tasks of plasma torches is the heating of the gas.

These general considerations must be applied to the conditions existing in a vacuum plasma torch. The knowledge of physicists about vacuum and the vacuum state is both ample and very scarce. Without going into the established conceptions of vacuum in classical physics and quantum mechanics, let us first consider the main properties of the electromagnetic field in a perfect theoretical vacuum.

In terms of classical aerodynamics, a vacuum is a medium with absolute values of dielectric and magnetic permeability, which equal the electric and magnetic constants:

$$
e_0 = \frac{1}{36\pi} \cdot 10^{-9}, \ F/m; \quad \mu_0 = 4\pi \cdot 10^{-7}, \ H/m.$$

These properties of the vacuum are well known and most often considered, and they allow these quantities being accepted as electrophysical constants in many mediums under atmospheric or any other level of pressure. What is much more rarely paid attention to is that the perfect vacuum is a medium that possesses infinite dielectric strength and zero conductivity. In theory, no electric field of
any strength can produce electric currents in the vacuum. In other words, the strength of the electric and magnetic fields, as well as the density of electromagnetic energy in vacuum defined by the product of their multiplication can be infinitely high.

This theoretical statement, applied to discharges in hollow cathodes, leads to a rather important conclusion: electromagnetic energy can be concentrated in any finite volume (for example, the cathode channel) and it can be introduced into the plasma contained in a theoretical vacuum.

The degree of efficiency of this process, that is, of the transformation of electrical energy into the energy of plasma, is determined by the properties of said plasma and consequently by the properties of plasma gas. Of course, one cannot take the possibility of extra-high energies being introduced into the cathode channel. As will be demonstrated further, the processes of transferring energy to plasma have a wide range of stable parameters, which is limited on the lower end by the development of natural plasma fluctuations, and the higher end – by the processes of interaction with the hard surface of the cathode.

2. Processes in discharges with hollow cathodes

In order to bring this property of a vacuum as a medium to practical use in engineering, the plasma torch was invented. Its characteristic trait is that the cathode tube is positioned on the same axis as the direction of the axial movement of the plasma gas. That ensures the development of processes near the cathode along the radial coordinate, enabling the oscillation of electrons inside the tube and the transformation of electrical energy into the energy of high enthalpy plasma in a vacuum within the active zone of the plasma torch [6]. For normal operating modes of the plasma torch, the working pressure in the furnace chamber must be under 13.3 Pa. Plasma gas pressure within the cathode can vary within the range 100...1500 Pa, which guarantees the gas-dynamic issue of plasma out of the cathode that shapes the discharge column [7]. Continuous output of high enthalpy plasma from the cathode channel in the direction of the anode provides a balance between the input and output of plasma energy.

It should be noted that these theoretical statements were formulated according to the positions of classical electrodynamics and can only be viewed as qualitative, as the conductive medium (plasma) generates its own electric and magnetic fields through organized movement of the charges, which interact with the electric fields of the a vacuum space between the electrodes.

The limits of the density of the energy within the cathode channel filled with axially moving high enthalpy plasma are defined by the interactions of this plasma with the hard surfaces of the cathode. A cylindrical or conic column of current-carrying plasma with clearly defined shape and visible discharge diameter is shaped between the cathode and the anode. Figure 1 shows a typical photograph of a hollow cathode discharge in high-current normal operating mode, which allows devising a scheme of a model (Figure 2) pointing out the areas that must be examined in the course of analyzing the magnetic-gas-dynamic processes within the cathode and the discharge column [8].

The examined model of how the processes of introduction of electromagnetic energy into the cathode develop includes the speed with which the high enthalpy plasma exits the cathode channel. With the growth of this speed, the integral power transferred from the cathode channel towards the anode also rises. The kinetic energy of plasma and the difference in pressure (particle concentrations) within the cathode channel and the discharge column determine the intensity of plasma release. As has been established, with the growth of current and therefore of plasma enthalpy within the channel pressure in the active zone increases and consequently the difference between the pressures in the cathode channel and the discharge column rises as well. The processes of energy input into the plasma and its issue from the cathode channel take place simultaneously, and they determine the working range of the parameters of the plasma torch [7].

The near-cathode layer is, above all, the space where electric energy is transformed into the kinetic energy of the electron stream coming radially into the cathode channel by means of thermoautoelectronic emission from the cathode surface in the active zone area. The electrons gain acceleration along the radial coordinate in the near-cathode area and, moving within the active zone, ensure the ionization of the plasma gas, which has substantial kinetic energy directed along the axis of the discharge. The resulting high enthalpy plasma is ejected from the active zone in the direction of the
anode. Thus, through maintenance of uninterrupted ionization of the gas moving along the discharge axis by oscillating electrons, the energy introduced into the electron stream in the near-cathode area is transferred to the plasma of the discharge column.

![Figure 1. Hollow cathode discharge](image1)

![Figure 2. The scheme of hollow cathode model](image2)

The release of the maximum energy introduced into the discharge within the cathode channel is supported by the experimental dependence of the energy conversion efficiency of the discharge on the distance between the cathode and the anode \( \eta = P_a / P_d \), where \( P_a \) - power released at the anode, \( P_d \) - power of the discharge. With decreasing length of the discharge column, which is restricted by the influence of the wave reflected from the anode on the processes within the cathode channel, this indicator reaches 88...92% without any substantial voltage decline in the discharge [9, 10].

3. The criteria of similarity formulated on the basis of the physical processes taking place in the cathode channel

The facts observed in experiments lead to the conclusion that changes in the diameter of the cathode channel, the discharge current and the consumption of plasma gas lead to a transfer of the working zone where the plasma interacts with the cathode surface along the axial coordinate. Thus, a certain parameter characterizing the state of plasma in the working zone of diameter \( d \) is made constant. The fitting parameter is the Knudsen number, which expresses the ratio between the electrons' mean free path and the definitive geometric parameter - the diameter of the cathode channel \( d \), that is, \( \text{Kn} = \lambda_e / d \sim T / pd \). The value of \( \lambda_e \) depends on the density of the gas in the channel \( \lambda_e = 1 / n \sigma_S \), which is determined by the consumption of plasma gas \( n = G / mvS_{cc} \), where \( m \) is the atom mass of the plasma gas, \( v \) - average speed of the gas flow within the cathode. \( S_{cc} = \pi d^2 / 4 \) is the cross-section of the cathode channel.

Then

\[
\text{Kn} = \lambda_e / d = \pi m v d / 4 \sigma_S .
\]  

(1)

For a certain plasma gas (e.g. argon, helium or nitrogen) the values of \( m \) and \( sS \) in steady-state remain constant and do not depend on the diameter of the cathode channel. The cathode's constructive execution ensures the average speed of the gas flow. It is close to the speed of sound and can be considered independent from \( d \). Therefore, in order to guarantee the stability of the Knudsen number during the functioning of a cathode of any diameter, the ratio between the consumption of plasma gas and the cathode diameter must remain constant, that is

\[
C / \text{Kn} = C_i G / d = \text{const} ,
\]

(2)

where \( C_i \) is a constant coefficient depending on the type of plasma gas.
The obtained expression (2) is the Reynolds number

\[ \text{Re} = \frac{4G}{\pi \eta d} = \frac{C'G}{d}, \]  

(3)

where \( \eta \) is the dynamic viscosity of the gas.

The maximum value of the Reynolds number determined according to the expression (3) for the minimal values of the cathode channel diameter and the working consumption of plasma gas (for instance, argon) in cold mode does not exceed 640, which indicates a laminar flow of the gas within the cathode. Meanwhile, the active zone becomes set at the coordinate on the axis of the cathode where the Knudsen number is also constant. As would be expected, the Reynolds number can be used as a criterion of similarity for discharges in hollow cathodes in a vacuum plasma torches.

In order to analyze the two other defining parameters – the discharge current \( I \) and the pressure in the cathode channel \( p_{\text{cc}} \) – let us consider the flow of plasma gas within the channel. In steady modes, the electrodynamical forces emerging in the discharge column due to the flow of current balance the gas-dynamic pressure of the gas introduced into the cathode channel. For a certain cross-section, size the pressure inside the channel should be

\[ p_{\text{cc}} = p_n + kT_e n_e + kT_i n_i = \text{const}, \]  

(4)

where \( p_n \) – pressure of the neutral gas, \( T_e, T_i, n_e, n_i \) - temperatures and densities of electrons and ions respectively. With \( n_i \approx n_e \) and \( T_i \ll T_e \) we have

\[ p_{\text{cc}} = p_n + kT_e n_e = \text{const}. \]  

(5)

On the other hand, the flow of electric current through plasma along the channel produces a vortex-shaped magnetic field squeezing the discharge column. Since the squeezing force is only passed on to the charged components, the equation of plasma movement in a cylindrical coordinate system brings us to

\[ \frac{\partial p_e}{\partial r} + j_z \times B_0 = 0, \]  

(6)

where \( j_z \) and \( B_0 \) are components of the vectors of current and magnetic field induction. Meanwhile

\[ B_0 = \frac{\mu_0 I}{r} \int_{0}^{r} j_z \, dr. \]

Then from (6) we get

\[ p_e = -\mu_0 I \int_{0}^{r} \left( j_z \int_{0}^{r} j_z \, dr \right) \, dr + \chi(r), \]  

(7)

where \( \chi(r) \) is a certain unknown function.

For the qualitative analysis, we shall assume that the density of current is evenly distributed within the examined section with \( r < R_1 \), where \( R_1 \) is the radius of the cathode channel. Then from (7) we have

\[ p_e = -\left[ \mu_0 I^2 / 4\pi^2 R_1^4 \right] + \chi(r). \]

Assuming that the pressure of electrons with \( r < R_1 \) equals zero, we get

\[ \chi(r) = \mu_0 I^2 / 4 I_z R_1^2 = \mu_0 I^2 / 4\pi^2 R_1^2 \]  

(8)

and

\[ p_e = \frac{\mu_0 I^2}{4} j_z^2 \left( R_1^2 - r^2 \right). \]  

(9)

The pressure of electrons on the axis of the cathode will be

\[ p_{\text{max}} = \left( \mu_0 I^2 / 4\pi^2 R_1^2 \right). \]  

(10)
Analysis of the expressions (8) and (10) leads to the conclusion that for a certain section within the cathode channel, the following relation should be observed:

\[ \frac{p_e(r)}{p_{cc}(r)} = \text{const} , \]

that is, for modelled discharges the relation of electron pressure \( p_e \) in the plasma column to the pressure in the cathode channel \( p_{cc} \) should remain constant if there are any changes to the discharge current and the cathode channel diameter. Then with the cathode diameter, we have

\[ \frac{p_e(r)}{p_{cc}(r)} = \mu_0 \mu_r I^2 / \pi^2 d^2 \text{ const} . \]  

Expression (11) is the criterion of similarity.

Thus, with the Knudsen number and the Reynolds criterion for the modelled arcs kept constant, the relation of the discharge current to the cathode channel diameter is constant, that is, \( I/d = \text{const} \).

4. Conclusion

The developed model of thermophysical processes inside the cathode channel of a vacuum plasma torch enabled us to demonstrate the general patterns of the gas-dynamic and electrotechnical parameters of the discharge. Based on the results of the analysis, criteria of similarity for hollow cathode discharges were created, which should help generalize the results of experimental research.

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