Radiation energy losses in a single chamber three phase plasma torch with rod electrodes

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Abstract. The paper deals with the results of the study of the plasma energy loss in a chamber of the three phase alternating current arc plasma torch at pressures above atmospheric. It is shown that the loss due to radiation takes the main share. A time-averaged estimation of the radiation power per unit length of the arcs and its dependence on pressure was obtained based on the results of calorimetric measurements of the heat flux into the end part of the plasma torch. The dependence of the fraction of energy loss by radiation versus the total loss in the plasma torch chamber depending on the pressure and gas flow rate are presented. The dependence of the efficiency of the plasma torch versus the gas flow rate and pressure is also given. Studies were conducted on a plasma torch over the power range from 50 to 200 kW. The working gas was nitrogen.

1. Introduction
Low-temperature plasma torches have found a wide usage in various technological applications, in particular, for processing and destruction of hazardous waste, in metal processing, for production of ultrafine particles, cutting metals, etc. A number of three-phase plasma torch designs both of alternating and direct current were created to perform and implement this series of tasks. Three-phase single-chamber plasma torches are, as a rule, short in length, which ensures its high efficiency [1], at normal atmospheric pressure. The energy loss into the plasma torch chamber walls from the plasma radiation under such pressure and not too high currents is 5–10% of the total power and is usually neglected, but the energy loss increases significantly with the pressure increasing in the chamber [2]. The purpose of this work was to determine the radiative loss fraction in the total heat loss into the walls of the plasma torch chamber.

The fraction of the radiative energy loss $\chi$ in the total system of heat losses into the walls of the plasma torch chamber is determined as

$$\chi = \frac{Q_r}{Q_t},$$

where $Q_r$ is the energy loss into the walls of the plasma torch chamber connected with the plasma radiation; $Q_t$ is the total energy loss into the walls of the plasma torch chamber.

The radiation losses into the conical part of the plasma torch chamber entering in $Q_r$ were calculated from the experimentally measured radiating capacity of electric arcs, since the energy losses in this part of the chamber are also associated with convection (complex heat exchange).
The relative radiated power $\varphi$ is determined by the next ratio:

$$\varphi = \frac{Q_r}{W_{pl}},$$

where $W_{pl}$ is the plasma torch power.

2. Experimental installation

The experiments were carried out on a nitrogen single-chamber alternating current plasma torch with rod tungsten electrodes over the pressure range from 0.1 to 5.7 MPa, nitrogen flow rate was of 0.03–0.08 kg/s. Maximum current (short circuit current) was 330 A. The plasma torch is designed to work on inert gases, nitrogen and hydrogen and is calculated for stationary operation over the power range from 50 to 200 kW.

The chamber and body of the plasma torch are made as a single unit of stainless steel. The chamber is equipped with cooling jacket; here is where spiral guides (governing the cooling water flow) are located. The cooling liquid is fed to the most thermally stressed domain of the arc chamber. The thermal stresses occurring due to the electric-arc chamber heating are compensated with silphon type corrugation, located on the cooling shield. The gas is fed via gas nipple, located on the circular chamber used for working gas feeding and swirling. The internal ring of the gas chamber is combined with the arc plasma torch chamber and has a number of holes located tangentially on the arc chamber surface. Three tungsten electrodes with a length and diameter of 0.01 m were located symmetrical with respect to the axis at a distance of $a = 0.02$ m.

Figure 1 shows the structural model of the plasma torch chamber, where, in order not to clutter the figure, position 3 represents only one of all possible positions of the arc column. The following list shows the geometrical dimensions of the plasma torch:

- radius of the electrode unit $R = 0.07$ m;
- length of the electric arc chamber $L = 0.14$ m, including the length of the conical part $l_1 = 0.1$ m;
- radius of the outlet section $r = 0.03$ m.
The electrode is a copper tubular element in which a set of tungsten rods is installed. The electrode holders have channels for supplying cooling water and a pad for mounting the current supply bus. The electrode holders are installed in cooled heat resistant electrically insulated insert. The insert consists of a washer made of extruded aluminum oxide, and, the cooling washer, a hollow metal disk with three bushings and ceramic tubes set into them; these tubes provide electric insulation for the electrode holders from the cooling washer. The ceramic washer, the cooling washer, and the insulating bushings are fastened together by means of high-alumina cement grouting. In the rear plasma torch part, glass fiber laminate washer is installed; it takes up the mechanical load caused by the working gas pressure in the arc chamber. The plasma torch is sealed hermetically by sealing the electrode holder on the textolite washer and the washer on the plasma torch case [3, 4].

The plasma torch was connected to a cylindrical tube by the outlet flange, at the outlet of which interchangeable nozzles were placed, which allowed maintaining a different pressure in the plasma torch chamber at a constant gas flow rate.

The energy losses into the wall of the electrode unit and the conical part of the chamber were determined separately by the calorimetric method using cooling water. The sum of these losses was the total losses by which the plasma torch efficiency was determined.

The following method was used to determine the radiative loss. The surface of the electrode unit from the chamber side, interacting with the cold gas supplied to the plasma torch, receives mainly the radiative energy of the arcs burning in the axial part of the chamber. When the degree of blackness of the wall is close to unity, the falling and absorbed energy fluxes are equal. Therefore, by determining the heat flux into the wall of the electrode unit, under certain conditions, it is possible to find the integral radiative flux from the burning arcs and estimate the total radiative losses.

The experiments with high-speed filming in a three-phase plasma torch, as well as in a linear scheme plasma torch, in the initial part of the arc column remains straight, since it is not yet affected by the turbulent boundary layer of the incoming gas. The closure of the arcs takes place outside the plasma torch chamber. It can be assumed that three arcs are burning near the axis of the three-phase plasma torch in the time-averaged process. The simplified scheme of processes in the discharge chamber upon the initial section was taken as the basis for further consideration [5].

Inside the discharge chamber, near the axis, there are plasma columns whose temperature varies only in radius. Each point of such column is a volume isotropic radiator. The constancy of the arc voltage drop within a half-period of current oscillation and the absence of any significant interaction of the arc channel with the gas flow at the initial section indicates the constancy of the field strength in the arc channel and, as a result, the radiation capacity is constant per unit of the arc length within the plasma chamber. In this case, the radiation falling on the electrode unit will depend only on the space angle, the magnitude of which is related to the longitudinal coordinate \( z \) (shown in figure 1). Thus, by measuring the heat flux into the wall of the electrode unit, one can estimate the time-averaged radiation flux per length unit of the arc.

The time-averaged integral radiation capacity of the arc in a three-electrode plasma torch can be determined from the relation

\[
\varepsilon_d = \frac{4\pi Q_{el}^l}{3 \int_0^{l_1} f(z, R, a) dz},
\]

where \( Q_{el}^l \) is the averaged power of the heat removal through the electrode unit, taking into account the degree of blackness of the wall (measured experimentally); \( f(z, R, a) \) is the function determining the value of the space angle under which the electrode unit is visible from the arc element \( dz \) located at a distance \( z \) displaced from the symmetry axis of the electrode unit by amount \( a \); \( l_1 \) is the electrode length. Integration is carried out along the length of the arc from
The value of the time-averaged integral radiation capacity of the arc channel versus pressure in the plasma torch chamber.

Figure 2 shows a graph of the time-averaged integral radiation capacity of the arc channel inside the plasma torch chamber versus pressure. This graph covers the power range of the plasma torch from 49.2 to 205.3 kW, where the experiments were conducted. The arc (arcs) length from the electrode surface to the output section of the plasma torch remained approximately constant and independent of the power in the selected power range.

This dependence of radiation capacity versus pressure from figure 2 can be approximated by the function (dashed line)

\[ \varepsilon_d = A_2 (P/P_1)^{0.57}, \]

where \( A_2 = 50.78 \) kW/m, \( P_1 = 1 \) MPa; \( P \) is the pressure in the plasma torch chamber.

This expression allowed us to approximate the obtained experimental values of \( \varepsilon_d \), and to obtain the dependence of \( \varepsilon_d \) versus pressure in the plasma torch chamber. This approximation allowed us to simplify the calculations of \( \varepsilon_d \) with respect to the dependence proposed in [5]. The radiative loss through the output section of the plasma torch and into the inside of the chamber were calculated using this expression. The obtained radiative losses were compared with the total energy losses obtained in the experiment.

3. Results and discussion

Figure 3(a) shows the fraction of radiative loss as a function of pressure. It is seen from the figure that the radiative loss increases rapidly with the increasing of gas pressure in the plasma torch chamber, reaching a maximum value at pressure of 1.0–1.5 MPa and then remains approximately unchanged, amounting to 0.75–0.8. This behavior can be explained by the fact that with the
Figure 3. (a) Fraction of radiative loss versus pressure and (b) change of relative radiated power versus pressure at $G = 0.03$ (triangles) and 0.08 kg/s (circles).

increase in pressure, energy losses due to convection, as well as losses to electrodes and their erosion, also increase. There is a weak dependence of radiative loss on the gas flow rate. So three times increase in flow rate leads to a change of radiative loss by 10–13%.

Figure 3(b) presents the change in relative radiated power versus pressure. The radiation flux increases with the pressure increasing. However, with higher gas flow rate it grows slowly. This is due to the fact that with an increase in gas consumption, the power of the plasma torch increases. Here, one can also note its weak dependence on the gas flow rate. The relative radiated power remains a growing function with the increasing of pressure.

The efficiency of the plasma torch was calculated from the ratio

$$\eta = 1 - \frac{Q_r + Q_{r,\text{out}}}{W_{pl}},$$

where $Q_{r,\text{out}}$ is the power through the outlet section of the plasma torch.
Figure 4 shows a graph of the efficiency versus of pressure. The efficiency of the plasma torch decreases with pressure increasing and is approximately equal to 0.55 at a pressure of 5.7 MPa, since the main energy losses at increased gas pressures are radiative losses, which are weakly depend on the gas flow rate.

4. Conclusions

Studies show that the gas pressure increasing in the chamber of the three-phase plasma torch leads to a sharp increase in radiative energy losses. These losses are the main losses reducing the efficiency of the plasma torch. It is possible to increase the efficiency of this type of plasma torches using the reflective walls of the chamber, allowing reducing the thermal load on them. One of the possible ways to increase the reflectivity of the walls can be the polishing of the internal chamber of the plasma torch in the area of the electrode block and in the area of the conical narrowing of the plasma torch case, as well as the usage of special coatings.

References

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