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ON THE EFFICIENCY OF GAS HEATING BY A THREE-PHASE AC SLIDING ARC PLASMA GENERATOR

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The results of an experimental study of the operation of a three-phase single-chamber arc plasma generator with sliding arcs are presented. The efficiency and mass-average temperature values and their dependences on external parameters have been obtained. The structure of the flow in the output cross-section of the plasma generator is considered.

Introduction. To create high-temperature gas flows, arc plasma generators — apparatuses in which energy from the electric arc is transferred to the gas flowing past it — are used. Under real conditions the gas flow in the plasma is, almost without exception, turbulent. This intensifies the heat removal from the arc to the gas, since turbulent pulsations quickly hollow out the arc-heated region of the flow. The increase in the flow turbulence is promoted by the migration of the arc in the plasma generator volume in the absence of forced stabilization when its form depends on the local ratio between the hydraulic and magnetic (external and self-magnetic) fields [1]. Such unstabilized behavior of the arc (arcs) can markedly upgrade the heat-transfer efficiency. Its numerical characteristics are the efficiency of the plasma generator and the value of the mass-average temperature of the outward flow, as well as its structure. It should be noted that the migration of arcs promotes the spread of arc connections over the larger surface of electrodes. This permits decreasing the specific heat flow into the electrodes and increasing their service life.

Below we present the results of the investigation of the thermal characteristics of a single-chamber three-phase ac plasma generator of industrial frequency with arcs sliding along the electrodes.

Object of the Investigation. Figure 1 shows the general view of the three-phase ac plasma generator with sliding arcs. In the plasma generator chamber 1, three electrodes 2 are arranged symmetrically along the axis and are inclined at a certain angle α to the plasma generator axis. In the general case, for nondirect electrodes this angle is not constant and increases toward the output cross-section. The constructional features of these plasma generators are given in [2, 3]. The electric power supply system incorporates a three-phase power transformer and reactors limiting the discharge current.

The conditions for initiating arcs are provided by an injector 3 — a low-power single-phase plasma generator which creates the necessary conductivity in the narrowest part of the interelectrode gap. The injector operates continuously, thus removing the problem of initiating arcs each time the current value goes above zero. According to the data of spectroscopic investigations, the concentration of electrons in the interelectrode gap is 10^{12}–10^{14} cm^{-3}. This suffices to ignite an arc. However, the final formation of a self-sustained arc discharge is determined by the appearance of a cathode spot on the electrode surface. The thus obtained arcs move sequentially over the electrodes to the output cross-section of the plasma generator under the action of the gas flow and the magnetic selffield. The arcing region is bounded by the chamber walls. The plasma-forming gas, air, is fed into the chamber with a tangential swirl to prevent the possible closure (shunting) of arcs on the walls. As the experiments performed with the use of rapid filming show, in the volume no more than two arcs glow simultaneously, and each electrode thereby has time to change polarity twice in a period, acting alternately as a cathode and an anode.

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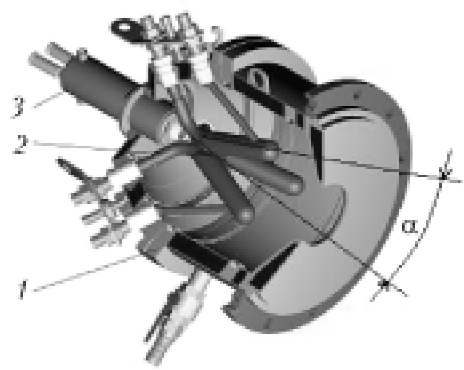


Fig. 1. General view of the three-phase plasma generator.

The glow and motion of arcs over the electrodes is accompanied by shunting. As a rule, on new copper electrodes with a smooth surface a small-scale shunting is observed when an arc slides along the electrode surface leaving on it a characteristic "herringbone" pattern [4]. After 6–8 h of operation the surface of the electrodes becomes rough and covered with cracks. This leads to a stepwise motion of the arc connection, which remains until the electrode collapses. According to the rapid filming data, the arc spot covers the distance along the electrode in 4–6 jumps.

The sliding-arc plasma generator is able to operate under certain conditions in the chamber. The quantity $\rho V/G\tau$ characterizing the ratio between the residence time of the arc plasma in the plasma generator volume and the discharge time can serve as a criterion determining these conditions. If the plasma stays in the plasma generator chamber for a long time and has a sufficient conductivity, then, when the current reaches a value above zero, an arc discharge will be formed not near the injector, but on the conducting plasma. The arc stops moving, since the arc connections are localized in a certain place, as a rule, on the electrode ends. The working surface of the electrodes decreases. Under such conditions there is no need for a continuously operating injector. As a result of this, erosion of the electrodes increases and their service life decreases. Under other conditions, at a short residence time in the volume, e.g., because of the high consumption of the plasma-forming gas, the arc channel may break and the arc may go out and decrease in length, leading to a decrease in the plasma generator power. In the experiments performed with sliding arcs, the value of the criterion was in the range from 4 to 13.

To find the heat flows and determine the plasma generator efficiency, we performed calorimetric measurements. They consisted of determining the water temperature at the input and output of the cooling system of the plasma generator. We used these data to calculate the total heat flow and the flow into the chamber walls. The flow into the electrodes was calculated by the difference between them. Preliminary experiments have shown that the heat flows into the plasma generator casing and into the electrodes are approximately equal, whereas the surface areas having approximately equal emissivities differ by an order of magnitude. This points to the fact that the radiation loss, while it can account for a considerable portion of the total loss, is not determining. The main energy loss in a plasma generator of this type is the loss though the arc connections and convective flows into the electrodes and the casing. The other types of loss due to the ohmic heating of the electrodes and their erosion are insignificant and do not exceed, by estimates, one percent of the total loss.

In our experiments, we used the methods of planning with construction of a two-level symmetrically homogeneous plan [5]. We looked for the dependence of heat flows on such factors as the gas consumption, the output diameter of the plasma generator, and the effective value of the short-circuit (SC) current of the power source. The last factor is convenient because it can be fixed before experiments by varying the value of the circuit inductance. The variation range of parameters (min–max) is as follows: the flow rate of air is 0.02–0.04 kg/sec, the current is varied between 500 and 1000 A (effective value), and the diameter of the output cross-section is 0.03–0.07 m.

It has been established by preliminary experiments that the total loss is independent of the angle of inclination of the electrodes to the axis. In any case, in the range of measurements made α = 5–15^{o}. In all experiments performed, the flow rate of air through the injector was 10^{-3} kg/sec, and the free running voltage of the power source was 480 V (effective value).

To determine the plasma generator efficiency, we used the formula

$$\eta = 1 - \frac{Q_t}{W_{pl} + W_{in}} .$$

The power value and the effective value of the current in the arcs were determined by the method of [6]. Since direct measurement of the current in the arcs in a three-phase single-chamber plasma generator is impossible, the current value and form were found by calculations. The form of the volt-ampere characteristic (VAC) of the arc was given proceeding from the general laws connected with the gas flowing around the arc, and the numerical value of the coefficients entering into the VAC was determined from the condition of the minimal deviation of the calculated voltage drop on the arc from its experimental value.

The mass-average temperature of the output flow was calculated from the mass-average value of enthalpy

$$H = \frac{(W_{pl} + W_{in})\,\eta}{G}$$

by means of the function $T = f^{-1}(H)$ [7]. The error in the temperature estimation determined by the error in determining the efficiency is small due to the weak enthalpy dependence of the temperature in the temperature range under consideration.

The real temperature of the plasma at each point of the output cross-section differs widely from its mass-average value. It is a function of coordinates and time. The value of the plasma temperature on the plasma generator output cross-section was determined experimentally by the relative intensity of the spectral lines of copper atoms λ = 510.6, 515.3, 521.8, 570.0 and (or) calcium atoms λ = 445.6, 457.9 nm [8]. We measured the radiation intensity from the upper to the lower edge of the section, noting its change with time along the line of sight. The image of the considered part of the section was projected by means of an optical system on the entrance slit of two monochromators with FEU-79 photomultipliers. The signal from a photomultiplier after broadband amplifiers was recorded by a C9-8 oscilloscope and then by a computer. We took into account the difference in the sensitivity of the radiation recording channels, comparing signals at the same wavelengths, by sequential tuning of the monochromators.

For numerical estimation of the plasma temperature inhomogeneity in the output cross-section, we introduced the coefficient N equal to the value of the fraction of the time of temperature excess over its mass-average value.

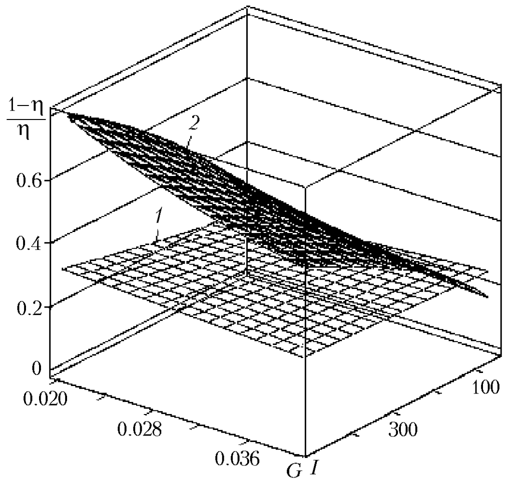
Results and Discussion. The data of calorimetric measurements have made it possible to obtain the dependence of heat losses on the flow rate of the plasma-forming gas, the effective value of the CS current of the power source, and the output diameter. The total energy loss is described by the following regression equation:

$$Q_t = 68.15 + 30.18\overline{I} - 6.4\overline{G} - 4.91\overline{G}\,\overline{I} .$$

In the expression, we used the normalized values of the current and the air flow rate with respect to the central point of the plan with the coordinates: I_{av} = 750 A, $G = 30{\cdot}10^3$ kg/sec, D = 0.05 m. From the relation it is seen that in the chosen range of change in the output cross-section diameter of the plasma generator, it does not influence the loss value. The functional relationship between the heat loss and the output diameter of the plasma generator shows up as a change in the hydrodynamic parameters — the pressure and the flow rate in the chamber. Under the conditions of the experiments performed these changes turned out to be not higher than the heat loss measurement error. The strongest influence is produced by the current. Its influence is almost three times stronger than that of the gas flow rate. An increase in the current leads to an increase in the heat flow, whereas an increase in the flow rate decreases it. The presence of a significant coefficient with the factor of simultaneous influence points to a different degree of influence of one factor at different values of the other. In particular, the heat loss increases with increasing current faster at lower flow rates of the gas. The simultaneous influence of both factors is comparable to the influence of the change in the flow rate of the plasma-forming gas.

With the use of the expression for the total loss the dependences of the efficiency and the mass-average temperature on the given factors have been obtained: for the efficiency

$$\eta = 0.76 - 2.1{\cdot}10^{-2}\,\overline{I} + 1.9{\cdot}10^{-2}\,\overline{G} + 1.1{\cdot}10^{-2}\,\overline{I}\,\overline{G} ,$$



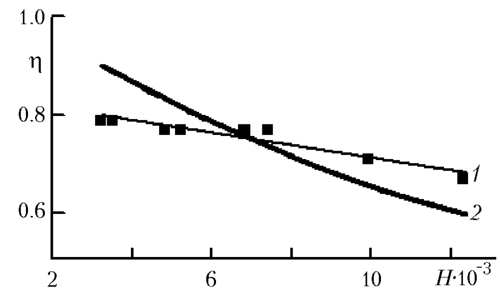


Fig. 2. Relative heat loss versus the current and the gas flow rate: 1) three-phase plasma generator; 2) linear plasma generator. I, A; G, kg/sec.

Fig. 3. Efficiency versus the specific enthalpy: 1) three-phase plasma generator; 2) two-chamber plasma generator. H, kJ/kg.

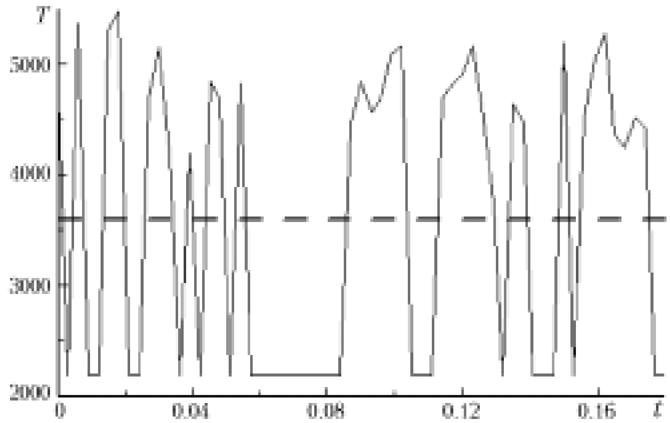
and for the temperature

$$T_{\text{mav}} = 3600 + 670\overline{I} - 360\overline{G} - 130\overline{I}\,\overline{G}\,.$$

In the expression for the efficiency, the effect of the factors considered is approximately equal. The weak influence on the efficiency, compared to the influence on the total loss, is due to the fact that with increasing current the heat loss increases with a simultaneous increase in the power. The relation for the efficiency holds when the SC current of the source is replaced by the arc current (effective value). But since the current value was determined with an error, a check was made to see how significant the influence of this error on the estimates of the regression coefficients is [9]. In this case, the coordinates of the central point of the plan were as follows: I_{av} = 315 A, G = $30 \cdot 10^{-3}$ kg/sec, D = 0.05 m, and the arc current was varied from 100 to 530 A. Passing to the arc current permits comparing the gas heating efficiency in different plasma generators. The existence of the functional dependence for the heat loss of a linear plasma generator [1] has made it possible to consider the operational efficiency of plasma generators in a wide range of change in parameters. Figure 2 shows the dependences of the relative heat loss for the investigated three-phase plasma generator and a linear generator in which the arc is stabilized by the flow along the channel axis. In the considered range of parameter variation, the relative heat loss for the plasma generator with sliding arcs is lower, and the difference widens with increasing current and decreasing gas flow rate. To this range there corresponds the change in the mass-average temperature of the plasma from 3000 to 5000 K.

The dependence of the efficiency on the specific enthalpy is given in Fig. 3. The same figure also presents the data for the two-chamber plasma generator from [1, 10]. The dependences are given for the same length of the plasma generators. Comparing the efficiency of the given plasma generator to that of the linear plasma generator, it can be noted that at low values of the specific enthalpy the efficiency of the two-chamber plasma generator exceeds the efficiency of the sliding-arc plasma generator. However, as the specific enthalpy increases to more than 7000 kJ/kg, the gas heating efficiency in the plasma generator with sliding arcs becomes higher and weakly depends on enthalpy.

In performing calculations, it is more convenient to use the relation between the heat flows and the hydrodynamic parameters. Therefore, the possible generalization of the form of the dependence of the heat transfer coefficient for plasma generators of the given type was sought preserving the similarity in the Reynolds number and the temperature head. To calculate the convective heat flows from the chamber wall, we obtained the following relation for the surface-average heat transfer coefficient:



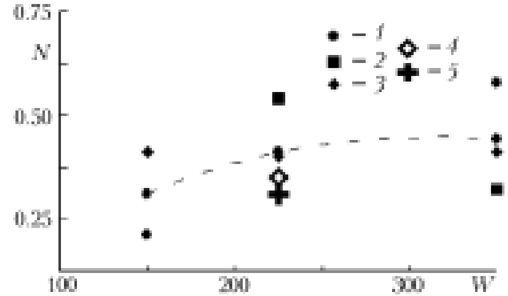


Fig. 4. Plasma temperature in the output cross-section of the plasma generator as a function of time. T, K; t, sec.

Fig. 5. Coefficient of temperature nonuniformity of the flow as a function of power: 1) D = 0.05 m; 2) 0.07; 3) 0.065; 4) 0.04; 5) 0.03. W, kW.

$$\mathrm{Nu}_{\mathrm{av}} = 0.12 \cdot \mathrm{Re}^{0.75} \mathrm{Pr}^{0.6} (\mu/\mu_{\mathrm{w}})^{0.25} (T/T_{\mathrm{w}})^{0.4} .$$

In this relation, the physical parameters of the gas are taken at a temperature equal to the medium temperature between the input and mass-average temperatures. The estimation of the Reynolds number by the diameter of the plasma generator chamber has shown that the heat transfer conditions are close to the laminar-gravitational ones [11]. However, the strong influence of the temperature factor points to a turbulent character, since the temperature density function has a direct effect on the turbulent heat conductivity. The greatest deviation of the value of heat flows calculated with the use of this relation from their experimental values does not exceed 15%.

The given dependence can be used as a basis for checking the values of convective heat flows into the walls of plasma generators of a given type with a wider range of change in parameters.

We failed to select some plausible dependence for the heat flow into the electrodes. It also seems impossible, so far, to solve the heat transfer equation theoretically because of the complicated character of the flow near the electrodes. Therefore, it seems reasonable to use empirical expressions. Thus, the thermal flow into one electrode associated with the plasma generator power can be given as

$$Q_{\mathrm{el}}/W_{\mathrm{pl}} = 0.042 + 3.7 \cdot 10^{-3} \overline{I} - 3.3 \cdot 10^{-3} \overline{G} - 1.9 \cdot 10^{-3} \overline{I}\,\overline{G} .$$

The plasma temperature on the output cross-section differs widely from its mass-average value. The characteristic dependence of the temperature variation with time in the central part of the output section is given in Fig. 4. The dashed line in Fig. 4 shows the value of the mass-average temperature obtained by the calorimetric method. It is seen that temperature fluctuations can exceed its mass-average value by a factor of 1.5. The lower value of the temperature has not been determined because of the limitations connected with the sensitivity of the chosen method. A similar picture of temperature fluctuations is observed at any point of the output cross-section. The existence of such inhomogeneity of the flow points to the fact that the process of temperature equalization between the arcs and the gas has no time to end in the chamber of the plasma generator. Probably, for plasma generators of such a design the existence of such a significant inhomogeneity is fundamental, since, for example, an increase in the residence time of the gas in the volume of the plasma generator may change its operational conditions.

Figure 5 presents the coefficient of temperature inhomogeneity of the flow depending on the plasma generator power at different diameters of the output cross-section. It is seen that beginning with about 200 kW the inhomogeneity coefficient remains almost unaltered. This is likely to be due to the fact that with increasing current the magnetic force begins to play an important part in the directional motion of the arc. Under its action the arc experiences a hydrodynamical drag of the flow. As a result, a certain balance between the magnetic and hydrodynamic forces is established. The break of the running-out arc in the output cross-section and its interaction with a cooler flow lead to the formation of a medium with a considerable temperature nonuniformity. In many cases, however, e.g., in heating bodies, cutting, melting, burning, etc., temperature fluctuations of the outward flow play no important part. Undoubtedly, when the requirements for uniformity and homogeneity of the flow are determining, it is necessary to have a stabilizing chamber or a mixing chamber. In designing it, the inflow nonuniformity should be taken into account.

CONCLUSIONS

1. The characteristics of the efficiency of gas heating by a three-phase plasma generator with sliding arcs are the same as the efficiency and the mass-average temperature and are independent of the output diameter of the plasma generator. The efficiency of the plasma generator decreases weakly with increasing specific enthalpy of the heated gas.

2. The temperature field on the output cross-section of the plasma generator is highly nonuniform in space and time. The local value of the plasma temperature can exceed its mass-average value by a factor of 1.5.

3. As the plasma generator power is increased from 100 to 350 kW, the nonuniformity coefficient of the flow in the output cross-section tends to a constant value.

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NOTATION

D, diameter, m; G, gas flow rate, kg/sec; $\overline{G} = 2(G - G_{av})/(G_{max} - G_{min})$, dimensionless value of the flow rate; H, specific enthalpy, kJ/kg; I, current, A; $\overline{I} = 2(I - I_{av})/(I_{max} - I_{min})$, dimensionless value of current; N, coefficient of temperature nonuniformity; Nu, Nusselt number; Pr, Prandtl number; Q, heat loss, kW; Re, Reynolds number; T, temperature, K; t, time, sec; V, volume, m^3; W, power, kW; α, angle, deg; η, efficiency; μ, viscosity, N·sec/m^2; ρ, density, kg/m^3; τ, characteristic time, sec. Subscripts: t, total; pl, plasma generator; in, injector; av, average; mav, mass-average; el, electrode; w, wall; max, maximum; min, minimum; bar, dimensionless value.

REFERENCES

1. M. F. Zhukov, A. S. Koroteev, and B. A. Uryukov, *Applied Dynamics of Thermal Plasma* [in Russian], Nauka, Novosibirsk (1975).
2. Ph. G. Rutberg, A. A. Safronov, S. D. Popov, A. V. Surov, and Gh. V. Nakonechny, Multiphase stationary plasma generators working on oxidizing media, *Plasma Phys. Controlled Fusion*, **47**, 1681–1696 (2005).
3. Ph. G. Rutberg, A. A. Safronov, V. L. Goryachev, and A. Ph. Rutberg, Powerful ac plasma generators, *Izv. Ross. Akad. Nauk, Énergetika*, No. 1, 80–92 (1998).
4. I. G. Kesaev, *Cathodic Processes of an Electric Arc* [in Russian], Nauka, Moscow (1968), p. 123.
5. Yu. P. Adler, E. V. Markova, and Yu. V. Granovskii, *Planning an Experiment in the Search for Optimal Conditions* [in Russian], Nauka, Moscow (1976), p. 69.
6. V. B. Kovshechnikov, Current-voltage characteristic of a three-phase single-chamber ac plasma generator, *Inzh.-Fiz. Zh.*, **72**, No. 4, 741–744 (1999).
7. N. B. Vargaftik, *Handbook on Thermophysical Properties of Gases and Liquids* [in Russian], Nauka, Moscow (1972), p. 603.
8. H. R. Griem, *Plasma Spectroscopy* [Russian translation], Atomizdat, Moscow (1969).
9. V. V. Fedorov, *The Theory of the Optimal Experiment* [in Russian], Nauka, Moscow (1971), p. 45.
10. M. F. Zhukov, A. S. An'shakov, I. M. Zasypkin, et al., *Electric-Arc Generators with Interelectrode Inserts* [in Russian], Nauka, Novosibirsk (1981), p. 136.
11. B. S. Petukhov, *Heat Transfer and Resistance in Laminar Flow of a Liquid in Tubes* [in Russian], Énergiya, Moscow (1967).