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CONTROL OF ENERGY PARAMETERS OF PLASMA FLOWS OF N–O–C–H SYSTEM

V.M. Pashchenko

National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”
37 Peremohy Prosp., 03056, Kyiv, Ukraine

ABSTRACT

The methods to control the plasma flow parameters by changing the geometrical dimensions of the arc channel and superposition of external magnetic fields are discussed. The possibility of increasing the temperature level in the entire volume of plasma flow of N–O–C–H system in the case of increasing the diameter of nozzle opening of the arc channel and compensating the velocity losses without deterioration of temperature characteristics due to a simultaneous increase of plasma-forming mixture flow rate is shown. The effectiveness of application of external transverse magnetic fields for harmonizing the relative position of separate phases of the heterogeneous flow at thermal deposition of the coating was proved. It is shown that transverse field application shifts the spatial position of the high-temperature zone of the plasma flow by 11–12° relative to the arc channel axis. Under the condition of radial feed of the initial material, when the channels of mass transfer of the gas and condensed phases of the two-phase flow do not coincide, it allows increasing the volume of spray-deposited material by 1.5–1.7 times, due to penetration of the greater part of the initial material into the active zone of the flow. Dependence of energy parameters of plasma generator and dimensions of the high-temperature gas jet on the frequency of rotation of the external rotating magnetic field and current in electromagnet windings was studied. It was established that optimization of the rotating field parameters allows significantly (up to 20 %) raising the arc voltage parameters and increasing the volume of the high-temperature zone by 25–30 % with simultaneous equalizing of the parameters over the plasma flow cross-section.

KEYWORDS: plasma generator, arc channel, plasma-forming mixture of air with hydrocarbon gas, temperature and velocity profiles of the flow, active zone dimensions, external transverse magnetic field, angle of flow deviation, external rotating magnetic field

INTRODUCTION

While developing technologies for plasma treatment of materials and in the process of implementing these technologies, methods of controlling the energy parameters of plasma flows by changing the operational parameters of the process: arc current, flow rate and composition of the plasma-forming gas are widely used. In many cases, adjusting the plasma generation mode is sufficient to achieve the aim of the control [1, 2]. However, in some cases, in order to achieve a more radical effect, it is necessary to use means that require optimization of the geometric dimensions of the arc channel or use of additional equipment to implement external effects.

Nowadays, many methods of controlling the energy and spatial characteristics of plasma jets have been developed and are used. This can be a direct effect on the parameters and spatial position of a high-temperature gas flow, or an indirect one, predetermined by the effect on the electric arc already at the stage of the plasma flow formation. The most promising are magnetic and gas-dynamic methods, as well as control of changes in the configuration and geometric dimensions of the arc channel.

Magnetic control due to the effect on the spatial position of the electric arc is widely used in welding technologies and related processes. The use of magnetic fields improves the efficiency of electrode metal melting, makes it possible to control the geometric dimensions of the cross-section of deposited beads and welds, refines the structure of the deposited metal and welds, increases hardness, strength and ductility of the weld metal, increases resistance of welds to hot crack formation [3–6].

By changing the diameter and linear dimensions of the output electrode, it is possible to influence the efficiency of the plasma generator and change the specific energy of the plasma jet, although the distribution of energy in the jet volume changes uncontrollably. For example, an increase in the length of the narrow part of the arc channel or the length of the interelectrode insert increases the value of the voltage drop on the arc, and the use of arc chambers with a diameter extension in the direction of gas outflow allows reducing the level of heat flows into the wall and achieve high values of local efficiency [7].

The use of plasma-forming mixtures of the N–O–C–H system without changing the general trends of control by the mentioned methods makes certain adjustments to the results of the practical implementation of these methods of influencing the energy parameters of the arc and, accordingly, the generated plasma flows. The aim of the work is to study the peculiarities of using methods of external magnetic effect and changes in the dimensions of the arc channel (in particular, diameter of the nozzle opening of the output electrode) with the aim of correcting geometric dimensions, position in space and parameters of the plasma flow of gas systems N–O and N–O–C–H.

RESEARCH PROCEDURES

An experimental study of the plasma flows of the N–O–C–H system was carried out using the Gray's enthalpy probe [8]. The distribution of parameters in the volume of the plasma jet was studied by moving the sampling probe in space using a three-coordinate manipulator. To determine the enthalpy, using the Gray's probe, the heat flow was measured perceived by the sampling probe when a gas sample was pumped through it at a specific local point of the flow. The chemical composition of the selected sample was analyzed in chromatographs of type KhL-3 and LKhM-8-MD. According to the known composition of the cold gas sample, the real chemical composition of the medium was calculated at the point of sampling, taking into account the actual temperature. The temperature was determined by the results of measuring the probe of enthalpy values at a particular point of the plasma flow. The dynamic pressure of the flow was determined by the U-shaped water manometer, to which a capillary of the sampling probe was joined. The energy characteristics of the plasmatron were determined by the results of measuring current, voltage and heat losses to the structure elements by the known procedures [8].

RESEARCH RESULTS AND THEIR DISCUSSION

The studies were conducted in a two-electrode plasmatron of up to 50 kW capacity with a thermochemical cathode, eddy stabilization of the arc in the center of the arc channel and auto gas-dynamic stabilization of the arc length. The local values of plasma temperature and flow velocity, as well as chemical composition of the medium at local points of the plasma jet volume were determined.

According to the results of the studies, the distributions of temperature, velocity of the medium by the

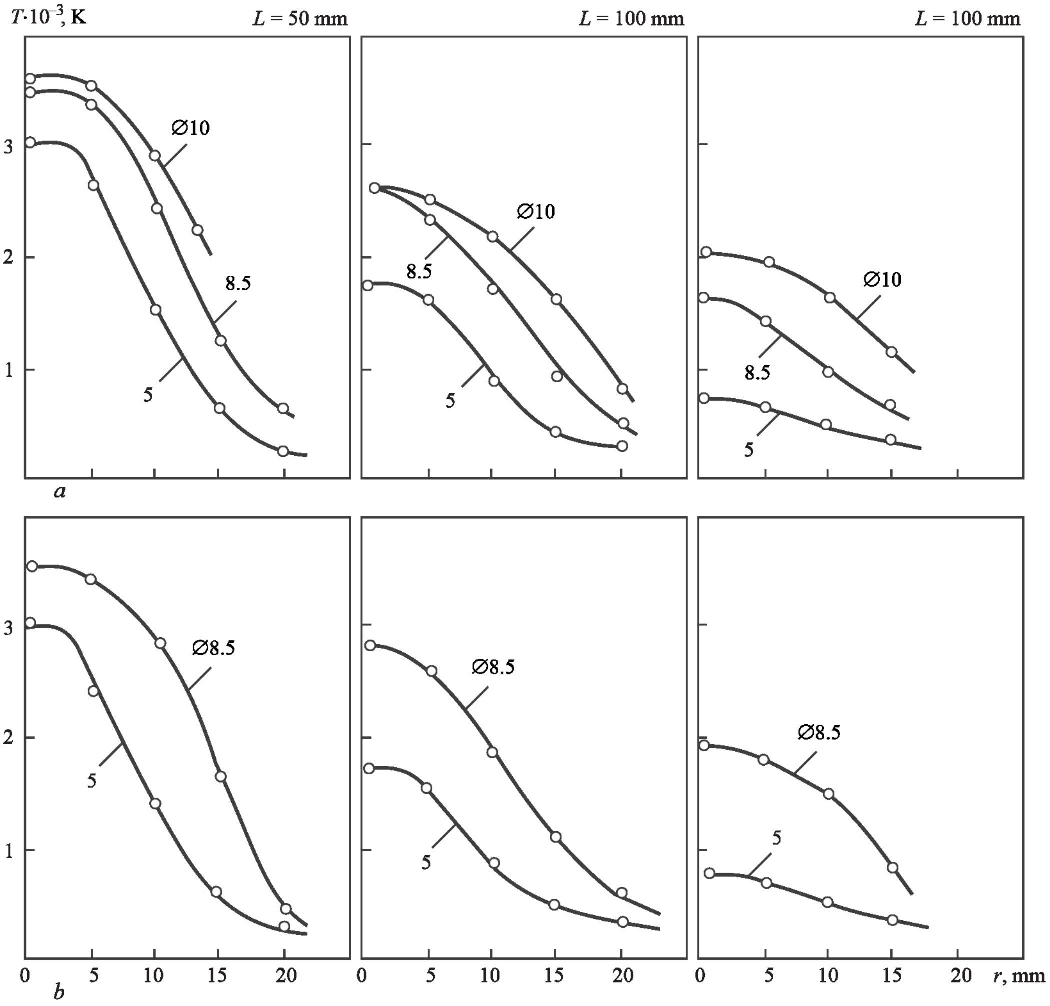

Figure 1. Radial distributions of temperature of plasma gas-air jet under the condition of different diameters of the nozzle opening of the arc channel: *a* — $Q_\Sigma = 3.7$ m³/h, α = 0.65, *I* = 200 A; *b* — $Q_\Sigma = 7.8$ m³/h, α = 0.65, *I* = 200 A (r is the distance from the axis of the arc channel on the cross-section of the plasma flow; α is the oxidant flow rate factor)

length of the jet and in its cross-sections were established.

The simplest method as to its technical implementation of effecting the gas-air plasma jet and its sizes on the structure, may be the change in the geometric characteristics of the regions of the arc channel. In particular, it goes about the diameter.

For the studied plasma generator, which was designed for deposition of coatings, the standard diameter of the nozzle part of the output electrode (anode) is 8.5 mm. This size was optimized in terms of achieving a balanced effect in spraying materials of all the most commonly used groups of materials that can be significantly different in melting point and other physicochemical characteristics.

The universal size of the nozzle opening in the arc channel is not always optimal during deposition of specific material. Heating of refractory substances with low thermal conductivity (e.g., oxides) requires an increase in the time of stay of particles in the active plasma jet zone and the sizes of this zone with the preservation (increase) of energy characteristics of the flow. It is not always possible to achieve the required result by a change in the mode characteristics of the process. In addition, the requirement of providing the maximum possible uniformity of temperature and velocity of jet to create the same heating conditions and accelerate the entire array of source material in the whole volume of the two-phase flow should be taken into account. In this case, one of the ways to solve the problem can be a change in the diameter of the nozzle opening of the arc channel.

Figure 1, *a* shows the distribution of the plasma jet temperature for three different diameters of the nozzle opening in the arc channel (the other mode parameters of the plasma generation process being unchanged).

According to the results of the measurements, with an increase in the diameter of the nozzle opening in the arc channel, the temperature at all distances from the section of the plasmatron nozzle (Figure 1, *a*) raises almost proportionally. The relative temperature growth is higher at larger distances. This is the result of intense mixing of a “thin” plasma jet with surrounding air with a reduction in the high-temperature area of plasma jet.

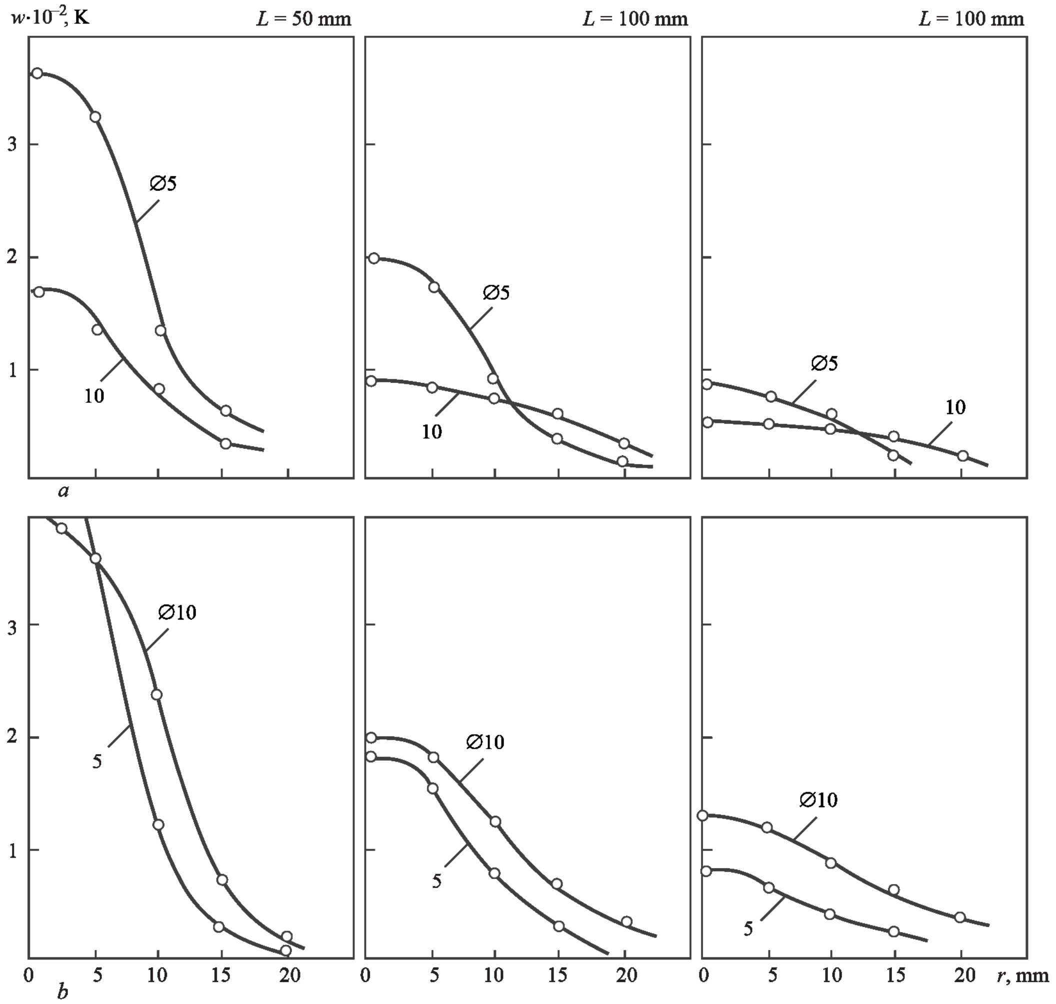

Figure 2. Radial distributions of velocity of gas-air jet under the condition of different diameters of the nozzle opening of the arc channel: *a* — $Q_\Sigma = 3.7$ m^3/h, α = 0.65, $I = 200$ A; *b* — $Q_\Sigma = 7.8$ m^3/h, α = 0.65, $I = 200$ A

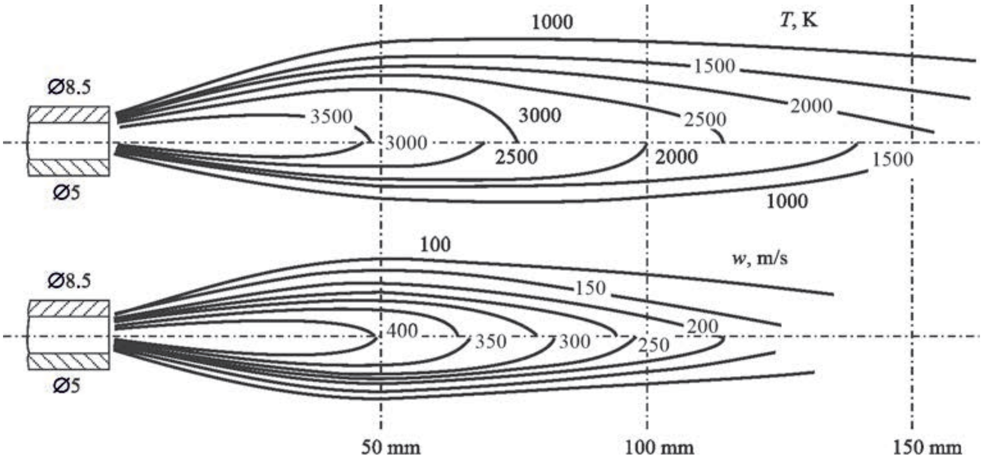

Figure 3. Temperature and velocity profiles for two diameters of the nozzle opening with the compensation for velocity loss by an increase in the flow rate of a plasma-forming mixture

The radial profile of velocities of a "thin" plasma jet is narrower and "sharper" (the absolute value of velocity in the central part of the flow is significantly higher than in the channel velocity profile with a larger diameter). The rate of velocity drop is approximately the same for both diameters, but starting at a distance of 7–8 calibers of the outlet diameter of the arc channel, the generator plasma flow with a larger diameter of the nozzle opening of the arc channel in the peripheral part of the cross-section has already higher velocities than in the plasmatron with a smaller channel diameter (Figure 2, *a*).

Given the abovementioned case, in the general case, an increase in the outlet diameter of the nozzle opening of the arc channel improves the thermal characteristics of the plasma flow of the N–O–C–H system, but, at the same time, its velocity parameters are deteriorated.

A possible compromise may be an attempt to compensate for the velocity drop while increasing the nozzle opening of the arc channel with an increase in the flow rate of the plasma-forming mixture (combination of methods of control of plasma flow energy parameters by changing the plasma generation mode and changing the geometrical sizes of the arc channel). In Figure 1, *b* and Figure 2, *b* present the results of such a control.

A 2.9 times drop in the flow rate due to an increase in the passing opening of the arc channel (from a diameter of 5 mm to a diameter of 8.5 mm) was compensated by a 2.16 times increase in the flow rate of a plasma-forming mixture. Under these clearly worse conditions (compensation for flow rate reduction is inadequate to increase the passing opening), the plasma jet of the generator with a larger diameter of the nozzle opening of the arc channel has higher temperatures at all distances over the whole cross-section of the jet. In this case, the rate of the flow rate drop along the jet axis is lower and the velocity rate on the periphery is higher. While transferring to traditional plasma-forming mixtures, such as air (N–O system) or nitrogen, such effect is not observed.

Given the abovementioned, in the general case, an increase in the outlet diameter of the nozzle opening of the arc channel improves the thermal characteristics of the plasma jet of the N–O–C–H system, but its velocity parameters are deteriorated.

Figure 3 shows profiles of temperature and velocity of plasma jet for the case considered above. The use of plasma generators with an increased diameter of the nozzle opening of the arc channel and a simultaneous compensation of the velocity drop by an increase in the flow rate of a plasma-forming mixture allows increasing the volume of the active plasma flow zone by more than 3 times, and its length — by 1.6 times (without deterioration of the plasma flow).

The use of external effects (in particular, magnetic) to control the plasma flow parameters is somewhat more complex in practical implementation. The effect on the plasma flow is carried out indirectly due to the action on the electric arc. To organize such a control, the use of special magnetic systems is required. Unlike the magnetic effect used in welding and surfacing technologies, the methods of surface engineering, in particular, coating technology, magnetic system is usually located on the plasma generator body, and electromagnetic field acts on the arc, burning in the arc channel within the plasmatron design [8].

External transverse magnetic fields (ETMF) of a permanent and alternating direction and a rotational magnetic field (ERMF) have found practical application in surface engineering technologies.

The aim of the magnetic control of ETMF of the permanent direction during deposition of coating is spatial coordination of channels of mass transfer of the solid and gas phase of the heterogeneous flow. In

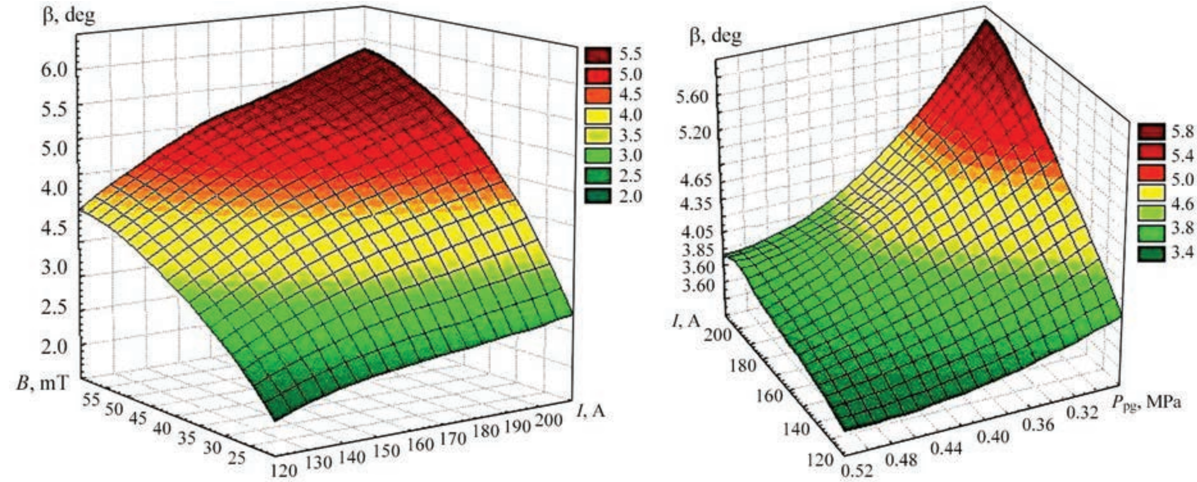

Figure 4. Dependence of the deviation angle of the flow on the mode parameters of plasma generation and magnetic field characteristics

case of using ETMF, the direction of induction of the magnetic field is perpendicular to the current direction in the arc column. By changing the electric arc position within the arc channel and the place of the arc binding by the magnetic field, it is possible to rebuild the energy characteristics of the arc in space (both integral, as well as local values of enthalpy, velocity, chemical composition of the working medium). Practically, the result of ETMF effect is a deviation of the plasma outflow direction from the longitudinal axis of the arc channel. It is known that the direction of transfer of the solid phase in a two-phase flow in the case of using radial supply of the source material in the gas flow, which is the most common in practice deposition of thermal coatings, does not coincide (by a few degrees) with the direction of the plasma outflow from the axisymmetric channel. Thus, using ETMF, it becomes possible to coordinate the directions of transferring the solid phase of the heterogeneous flow and the spatial profiles of temperature and velocity of a high-temperature gas flow. The result of such coordination will be improving the conditions of heating and accelerating of a larger fraction of particles of the source material and, accordingly, the quality of the produced coating and the efficiency of the spraying process.

The direction and deviation angle depend on the direction of the magnetic field induction.

The dependence of the deviation angle of the plasma flow β on the induction of the external magnetic field B and the pressure of the plasma-forming gas P_{pg} at different values of the arc current I_a is presented in Figure 4.

The induction of the magnetic field varied in the range of $18–55\cdot10^{-3}$ Tl, and the arc current of the plasmatron I_a varied within 130–200 A. As is seen from Figure 4, an increase in the arc current and the value of the magnetic field induction lead in general case to an increase in the deviation angle of the plasma flow due to a proportional increase in the Ampere force. In the studied range of variation in the mode parameters, the total possible deviation angle reaches 11–12°.

In the case of using ETMF in the course of coating deposition, the effect of the magnetic field can be most clearly observed on the example of the "spraying spot" formation on the surface of the base (Figure 5). The shape of the spraying spot becomes more symmetrical and noticeably increases by area.

Under the condition of using the field of permanent direction, the volume of sprayed material significantly increases (for example, by 1.5–1.7 times for PG-19M-01 powder) and the thickness of the coating layer considerably grows, especially in the central part of the spraying spot.

The aim of the magnetic control of ERMF during deposition of coating is to equalize the parameters of the plasma jet in the cross-sections at the active region of the flow and intensify heat exchange between the phases of a heterogeneous flow. A multipolar magnetic system is used, in which a pair of mutually perpendicular poles of electromagnet is switched on in a certain sequence [8]. As a result, a rotational magnetic field is generated, that changes by the program the direction and speed of rotation, as well as the value of magnetic induction in the gap between the poles.

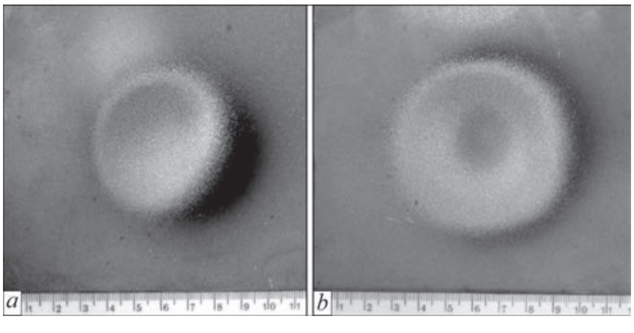

Figure 5. Spot of spraying ferromagnetic material PG-10N-04: *a* — without field; *b* — ETMF of permanent direction

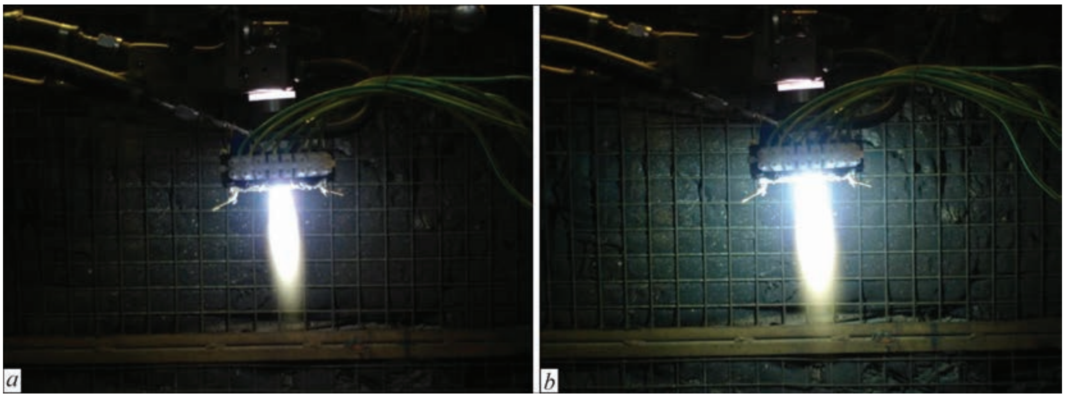

Figure 6. Plasma jet under the condition of action of rotational magnetic field: *a* — at the absence of field; *b* — at the presence of magnetic field

The studies prove that during superposition of the rotational magnetic field, the visible volume of a high-temperature zone of the plasma flow is changed (Figure 6).

The change in volume can be recorded by videos digital camera with the subsequent processing of the obtained by means of the scanning image processing program.

It was established that in the case of coincidence of the rotation directions of the magnetic field and the initial twist of the gas, a significant visible change in the volume of a high-temperature flow area is not observed in the whole studied range of changes in the field rotation frequency. The value of voltage on the arc is also almost does not change.

In the case of opposite directions of the field rotation and the initial twist of a plasma-forming gas due to a significant change in the conditions of heat exchange of arc with gas, the integral value of the arc voltage increases by 15–20 % (obviously, due to a local increase in the field intensity on the part of the arc column and the near-electrode area of the arc on the output electrode) (Figure 7).

The dependencies bear an extreme character. The maximum voltage value is achieved at a certain frequency of field rotation (moreover, the position of the extremum changes depending on the current in electromagnet windings).

Increasing the voltage at a constant current leads to an increase in the power of the device, which, in turn, leads to an increase in the volume of a high-temperature region of the plasma flow (Figure 8). Simultaneously, equalization of temperature and velocity profiles in the plasma jet occurs.

The dependence of the volume of a high-temperature part of the jet on the frequency bears an extreme nature. The position of the extremum to some extent depends also on the current in electromagnet windings: it shifts into the area of lower frequencies with a decrease in current.

The emergence of extremum can be explained by the arc getting in its “hot” trace in the arc channel of

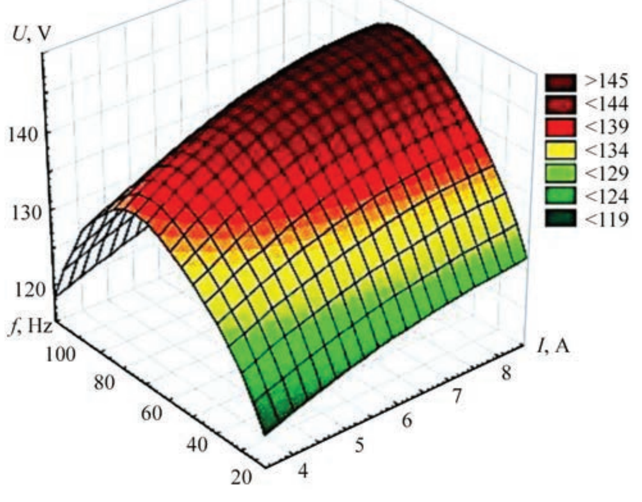

Figure 7. Effect of field rotation frequency and current in electromagnet windings on the integral value of arc voltage

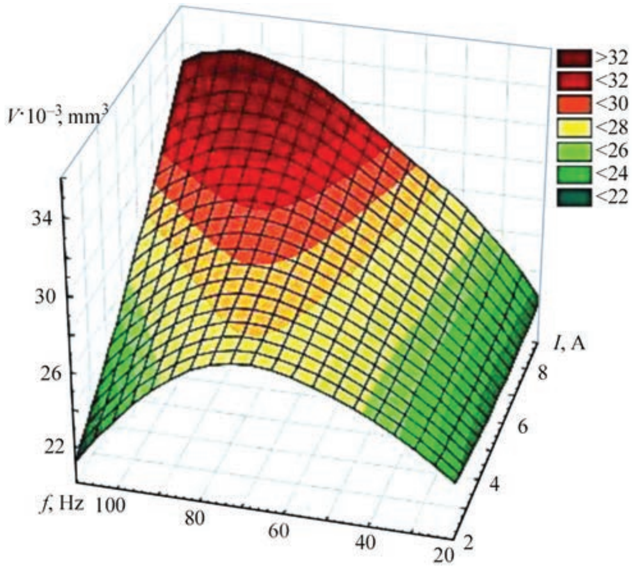

Figure 8. Dependence of plasma jet volume on frequency of external magnetic field and current in electromagnet windings

the plasma generator at an increased frequency of field rotation.

Moreover, the nature of the heat exchange of the arc with gas is noticeably changed by additional factors that affect the appearance of extreme dependence of volume on frequency, is to reduce the radius of the arc precession in case of lagging of its velocity from that of the field, as well as reducing of the effective value of current in electromagnet windings due to an increase in their inductive resistance and reducing the time of current passing in each winding.

CONCLUSIONS

The use of air mixtures with hydrocarbon gases makes the method of controlling the sizes of the active temperature zone of the plasma jet by changing the diameter of the nozzle opening of the arc channel with simultaneous compensation for the loss of velocity by increasing the flow rate of a plasma-forming mixture promising. The use of this method allows increasing the volume of the active plasma flow zone by more than 3 times, and its length — by 1.6 times (without deterioration of the plasma flow velocity characteristics).

The external transverse magnetic field due to the effect on the position of the electric arc in the arc channel of the plasma generator harmonizes the mutual position of the channels of mass transfer of gas and condensed phase of a two-phase flow during radial supply of the source material that allows 1.5–1.7 times increase in the volume of sprayed material and an increase in the thickness of the coating layer, especially in the central part of a spraying spot.

In the case of using a rotational external magnetic field due to a significant change in the conditions of heat exchange of the arc with gas and a change in intensity in individual regions of the arc column and its near-electrode area, the voltage on the arc increases significantly by 15–20 % and the volume of a high-temperature zone increases by 25–30 % with a simultaneous equalizing of the parameters on the cross-section of the plasma flow.

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ORCID

V.M. Pashchenko: 0000-0003-3742-6913

CORRESPONDING AUTHOR

V.M. Pashchenko
National Technical University of Ukraine
“Igor Sikorsky Kyiv Polytechnic Institute”
37 Peremohy Prosp., 03056, Kyiv, Ukraine.
E-mail: vn.paschenko@ukr.net

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