Досліджено процеси перетворення в дуговому плазмотроні вхідних потоків енергії в теплову енергію струменя при використанні сумішей повітря з вуглеводневими газами. Встановлений вплив горючої компоненти на частину енергії, яка виділяється у струмені поза межами плазмотрона. Оцінені можливості керування потужністю пристрою та його питомими енергетичними характеристиками зміною режимних параметрів генерації плазми

Ключові слова: плазмотрон, плазмоутворювальна суміш, горючий газ, плазма, запасена енергія, параметри струменя

Исследованы процессы преобразования в дуговом плазмотроне входных потоков энергии в тепловую энергию струи при использовании смесей воздуха с углеводородными газами. Установлено влияние горючей компоненты на долю энергии, которая выделяется вне плазмотрона в плазменной струе. Оценены возможности управления мощностью устройства и его удельными энергетическими характеристиками изменением режимных параметров генерации плазмы

Ключевые слова: плазмотрон, плазмообразующая смесь, горючий газ, плазма, запасенная энергия, параметры струи

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RESEARCH INTO THE ENERGY CONVERSION PROCESSES IN HYBRID PLASMA DEVICES FOR APPLYING THE COATINGS

V. Pashchenko
Doctor of Technical Sciences, Professor
Department of surface engineering
National Technical University of Ukraine
«Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy ave., 37, Kyiv, Ukraine, 03056
E-mail: vn.paschenko@ukr.net

1. Introduction

A promising way to improve the processes of welding and allied technologies and, in particular, applying coatings and the modification of working surfaces is the use of combined and hybrid processes. They increase efficiency of technological processes and functional properties of the created surface layers, make it possible to expand the scope and scale of the implementation of specific technologies.

Traditionally, combined technologies include a set of two or more known technologies that are implemented using existing installations or devices within the same workplace. An advantage of the combined technologies is the combination in space and (if possible) in time of fulfilling various operations of production cycle. Combined plants take up less productive areas, require less service staff, create new opportunities for the automation of technological process. An additional factor in favor of the combined processes for gas-thermal coating application is certain technological advantages that occur as a result of reducing the time between operations of the technological cycle.

In the field of welding and related processes and technologies, an important attribute of combined technologies is considered to be the use of heating sources that are identical in their physical nature and technological properties.

In a case when a combination of known processes leads to the fundamentally new results, the concept of "hybrid process" is applied. The result obtained is not a simple sum of results of employing all components of the combined process and it is unattainable for each individual component of the combined process. Another condition for assigning a process to the category of hybrid ones is the use of two (or more) energy sources different in their physical nature, which leads essentially to the described new technological effect [1].

An attribute of hybrid technology for applying a coating may include:

– a radical change in the physical-chemical conditions and in the mechanism of forming a coating;

– use of equipment for applying a coating, which brings together in one device elements of equipment of different methods;

– control of the composition and structure of coating directly in the process of its formation due to the spatial redistribution of energy that is used to treat the material;

– creation of conditions for the reactions of synthesis with the occurrence of new phases.

The advantages of hybrid technologies are the possibility of improving the operating properties of created coatings compared to the coatings obtained by traditional technologies. There appears a potential possibility to receive coatings, new in their properties, and to significantly increase efficiency of the process of applying a coating.

Hybrid devices for applying coatings are much more complex in their design than similar devices employing the traditional methods. This considerably reduces the reliability of such systems. Given this, the development of hybrid plasma sprays, which use additional sources of energy, without significant complication in design, is an expedient and relevant issue.

2. Literature review and problem statement

There are a large number of variants of the combined and hybrid technologies for the gas-thermal coating application (GTCA), which is a combination of the basic methods of GTCA, or one of the methods of GTCA and a laser energy source.

Combining the plasma and gas-flame methods for applying a coating essentially alters the sequence of stages in the formation of working body. First, a flow of argon plasma is generated. At the next stage, plasma jet mixes with cold auxiliary gas (nitrogen). The formed mixture of hot gases is supplied to the combustion chamber, where the ignition and combustion of oxygen-methane mixture take place, the injection of the powder into a barrel of the burner device and the formation of a supersonic jet. As a result of such combination, gas consumption is reduced. It becomes possible to use combustible gas with a lower heat of combustion. In this case, the stabilization of gas jet improves in the wide range of changes in parameters and the process productivity increases [2]. Using the plasma jet, it is possible to increase temperature of high-speed gas flow by 180 K and its velocity by 250 m/s. This effect is explained by the additional thermal input of plasma (to 6 kW) and by better mixing the combustible gas and oxygen due to the increased level of turbulence in the combustion zone.

Another variant of the hybrid process is to combine the ultrafast gas-flame and electroarc methods for applying a coating. Spraying a melt of wires in the interval between the arcs is carried out by a jet of hot combustion products [3]. Using a flow of combustion products as a spray gas makes it possible to significantly reduce the overall gas consumption, to extend active zone of the jet where the material is treated, and to organize a partial protection of drops of molten material.

Rather effective is the combination of plasma and detonating methods for applying coatings. Combustion products from the detonation gun trigger the passage of electric current in pulse plasmatron and the generation of plasma flow with high-energy parameters. The use of such plasma for the surface modification and applying a coating makes it possible to significantly change physical-chemical properties of the surface layers of products [4].

Combining in one process for applying a coating the plasma jet and laser beam aimed at using thermal effect of laser radiation energy directly on the surface of the part in the zone of coating formation. In its essence, this process refers to the category of combined laser-plasma coating application processes. The process employs usual plasmatrons and laser installations. Lasers perform the function of cleaning the surface and its heating [5, 6]. A variant of this technology is the PROTAL process as a combination of laser preparation of the base surface with the gas-thermal methods for applying coatings (cold gas-dynamic spraying, plasma spraying, high-speed gas-flame spraying, electroarc spraying, etc.) [7]. The PROTAL process makes it possible to form a coating with a thick interphase boundary "coating – base" due to preheating and preparing the surface for spraying.

Studies on the creation of hybrid laser-plasma systems are based on using the phenomenon of absorption by the plasma jet of the laser radiation energy with the occurrence of zone of laser-arc discharge [8]. The advantage of the combined discharge compared to the optical is a reduction in the required power of laser beam for maintaining the discharge due to the high degree of its absorption in the plasma.

Integrated devices that implement the mentioned hybrid and combined technologies are considerably more complicated in their design and are less reliable than the components of which they are composed.

Application of the mixtures of combustible gases and oxidizers as the plasma-forming ones provides for the possibility to create plasma energy sources, simple in design, in the form of a hybrid of plasma generator and gas-flame burner.

Sufficiently cheap and affordable are the plasma-forming media of the system N–O–C–H and, above all, those that are formed from the mixtures of compressed air with the boundary hydrocarbons of the C_nH_{2n+2} formula. In the homologous series of boundary hydrocarbons, only methane, ethane, propane and butane are in the gaseous state under normal conditions [9].

The occurrence in the composition of plasma-forming mixture of combustible component hypothetically enables to organize combustion of the mixture directly in an arc channel. In this case, a plasmatron can be conditionally represented as a gas burner with extended temperature range of the working body.

Another interesting variant is when limited dimensions of the arc chamber, high velocities of gas passage and the existence of electric arc significantly reduce the probability of gas mixture burning inside the design of plasmatron. When the starting mixture of gases enters the region of high temperatures of electrical arc, it leads to the dissociation of molecular components of the original mixture. Specific composition of the obtained products will be determined by thermodynamic parameters of the medium and by the completeness of the dissociation processes. Creating such plasmatrons is impossible without exploring the processes of transformation of the input energy flows into the thermal energy of the jet and the regularities of formation of the working body in the created hybrid device.

3. The aim and tasks of the study

The purpose of present study is to establish the peculiarities of plasma generation of the system N–O–C–H out of the mixture of air with hydrocarbons and the impact of process parameters on the energy parameters of the obtained jets and characteristics of the plasma generators.

To achieve the set aim, the following tasks are to be solved:

– to define the mechanism for converting the input energy flows into the plasma thermal energy and the character of distribution of energy flows within a plasma generator;

– to establish effect of the hydrocarbon component content on the energy characteristics of plasma jets.

4. Research methods for plasma generators of the system N–O–C–H

Studies were conducted on the basis of laboratory of plasma spraying at the Welding Faculty of NTUU "KPI named after Igor Sikorsky" (Kyiv, Ukraine). Experimental setup consists of current source, the APR-402 type, plasmatron, systems for gas preparation and control over mode parameters of plasma generation. The plasma generator (plasmatron) operates on the mixtures of air with network natural gas, bottled methane or propane-butane (Fig. 1).

4. 1. Determining the local parameters of plasma jets

The studies were conducted using a probe technique. We determined local values of enthalpy, composition and velocity of high-temperature gas medium. The Grey probe was used with a transverse blow over the probe's working edge [10].

Chemical composition of gas systems was determined using the methods of chromatography (chromatographs of the HL-3 and LHM-8-MD type).

4. 2. Determining the integral energy characteristics of plasma generators and plasma jets

Energy characteristics of plasma generators and plasma jets were investigated using the methods for direct measurement of parameters and calorimetry. A calorimeter is a thermally insulated cylinder of length 1200 mm with two contours of water-cooling. Plasma generator is stationary and air tightly connected to the calorimeter. The flow of high-temperature gas passes through the annular gap between the contours for cooling the calorimeter and releases its energy to the setup. The amount of heat is calculated by the known values of cooling substance consumption and its temperature. The temperature was measured by the differential thermocouples "Chromel Copel". The fluid consumption – by rotameters of the PIV type. Mode parameters for the generation of plasma were the variable values of arc current, flow rate and composition of the plasma-forming medium.

The systematization of results, data analysis and processing, construction of graphic dependences were performed by using the data statistical analysis system STATISTICA 7.

5. Results of exploring the processes of transformation of the input energy flows into thermal energy of the plasma jet

Energy to plasma generators on the mixtures of air with hydrocarbon gases is delivered from the electric arc and combustion products of the components of plasma-forming mixture. Under certain conditions, a larger part of the second component of the input energy flow can be implemented beyond the limits of plasma generator.

In order to confirm a practical possibility to displace the region of combustion of gas mixture beyond the limits of plasma generator, we experimentally determined the content of components along the arc channel of plasmatron.

Design of the anode node and output electrode of the plasmatron makes it possible to change the place where the samples are taken, starting from the cathode towards the side of the output opening (Fig. 1).

The samples were brought to measuring vessels with a capacity of 250 ml by pushing the fluid out at the rate not exceeding 0.5 ml/s.

Fig. 2 shows dependences of the content of basic components on the place of taking the samples in the channel of arc plasmatron (starting plasma-forming mixture of methane and air).

When displacing the point of taking the sample towards the nozzle opening of arc channel (an increase in relative distance), there is a substantial increase in the content of hydrogen and carbon oxide (s, % by volume):

$$\overline{l}=l_s/l_{cl}, \quad (1)$$

where l_s is the distance from the end of the cathode to the point of taking the sample, l_{cl} is the distance between the end of the cathode and the nozzle cross-section (length of the arc channel)).

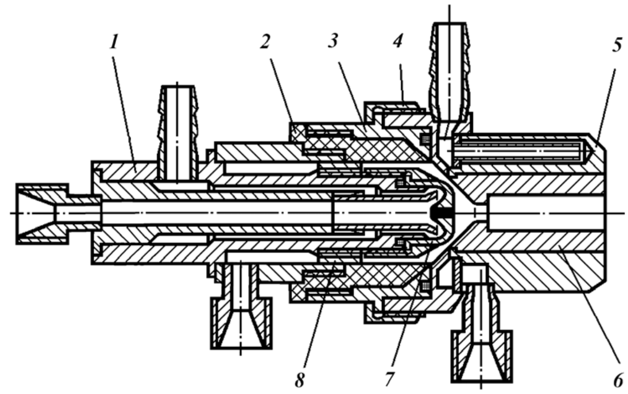

Fig. 1. Experimental plasma spray with a combined energy supply: 1 — cathode node; 2 — insulator; 3 — cup; 4 — union nut; 5 — anode node of middling cooling; 6 — output electrode-nozzle; 7 — thermal-chemical electrode (cathode); 8 — swirler

The relative content of oxygen and methane decreases in parallel:

$$\Delta k=c_{sp}/c_p, \%, \quad (2)$$

where c_{sp} is the content of component in the point of taking the sample, c_p is the content of corresponding component in the starting mixture.

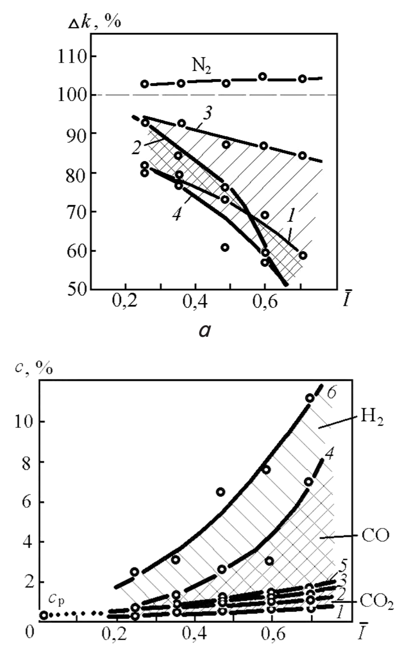

Fig. 2. Change in the content of components of the plasma-forming mixture along the arc channel of sprayer: *a* — starting methane content (CH_4) 12 % (by volume): 1 — methane (arc current I=170 A); 2 — CH_4 (I=250 A); 3 — content of oxygen O_2 (I=170 A); 4 — O_2 (I=250 A); *b* — starting content of methane (CH_4) 12 %: 1, 3, 5 — I=170 A; 2, 4, 6 — I=250 A

Plasma-forming mixtures containing combustible component in a general case change the balance of energy of plasma generators. In this case, we can talk about plasmatrons with a combined energy supply. Energy is delivered to the plasma generator by two channels: main (electrical energy) and additional (energy that is fed with a combustible gas).

The impact of relation between energy flows at the input to plasmatron by the types and the relation of energy flows at the output of plasma generator were investigated experimentally at a specialized device. The device includes a plasmatron with the auto-gas-dynamic stabilization of arc and a calorimeter rigidly connected to it. Such a design makes it possible to take and measure the energy of plasma jet without the suction of air from the atmosphere and substantial heat exchange with the environment.

The power that is supplied to the spray consists of electrical power:

$$P_{el}=U\,I \tag{3}$$

and thermal capacity, which can be implemented in the event of full combustion of hydrocarbon gas:

$$P_{hg}=a\,Q_{hg}, \tag{4}$$

where a is the lower working caloricity of hydrocarbon gas, kW·h/m^3; Q_{hg} is the consumption of hydrocarbon component m^3/h.

Specific energy that is equal to the mean mass enthalpy of products at the output of plasmatron is calculated using expression:

$$\varepsilon = P_{us}/Q_{\Sigma} = (UI + P_{ng} - P_l)/Q_{\Sigma},\ \text{kW·h/m}^3, \tag{5}$$

where $Q_{\Sigma}=Q_{ng}+Q_{air}$ is the total volumetric consumption of starting mixture; P_{us} is the useful capacity of plasmatron (total capacity except for the losses in the elements of setup); Q_{ng}, Q_{air} m^3/h are the consumption of gas and air, respectively (reduced to normal conditions); P_l are the losses of energy into the plasma generator design elements.

Thermal capacity of plasma jet P_h of the gas system N–O–C–H was determined as the power released by a flow of high-temperature gas to the calorimeter's walls with regard to residual heat of partially cooled gas components of the jet. But a part of the energy in this case (in case there is a lack of oxidizing components in the starting plasma-forming mixture) was considered as stored P_{st}. Stored energy will be released beyond the limits of calorimeter during its interaction with oxygen in the environment.

The accuracy of determining the indicated magnitudes was tested by compiling an equation for energy balance of the system "plasmatron – calorimeter" considering heat losses in the elements of plasmatron design:

$$P_{el}+P_{hg}=P_h+P_{st}+P_l. \tag{6}$$

The balance converged with accuracy not worse than 0.5 %.

In turn, thermal capacity of plasma jet of the plasmatrons that run on the mixtures of air with hydrocarbon gases in a general case consists of two components:

– a part of electric energy converted into heat within the design of plasma generator;

– a part of the energy that was released as a result of the passage of exothermic chemical reactions of interaction between the components of the original plasma-forming mixture.

Fig. 3 shows the experimentally determined dependence of the components of capacity of plasma jet on the content of hydrocarbon component (natural gas) in the plasma-forming mixture.

In order to characterize the relationship between the combusting component and oxidizer, we use a characteristic parameter that is employed in the theory of combustion – oxidizer consumption coefficient α. Coefficient α is the ratio of actual air consumption Q_{air} to the amount of air $Q^{\hat{\imath}}_{air}$, which is theoretically required for the complete combustion of combustible gas of the given composition. In the case of complete combustion:

$$\alpha = Q_{air}/Q^{\hat{\imath}}_{air} = 1. \tag{7}$$

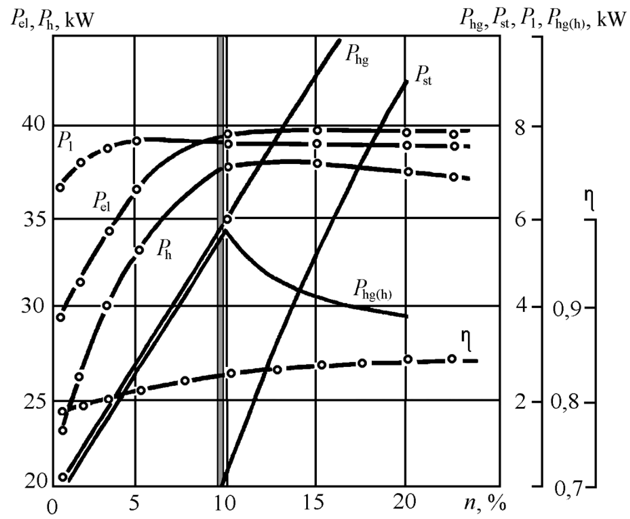

Fig. 3. Dependence of the components of capacity of plasma jet on the content of hydrocarbon component (methane) in the original plasma-forming mixture

In accordance with the results obtained by applying calorimetry to plasma jet, under condition of using "poor" and stoichiometric mixtures of air with methane, all the energy of hydrocarbon gas transfers into the thermal capacity of plasma jet. But starting at α=1 and lower, the growth in the level of "stored" energy begins. In this case, the share of thermal energy of plasma jet does not grow, and even slightly decreases, due to the removal of part of the energy for chemical conversions.

Losses into the elements of plasmatron design remain constant over the entire examined range of change n, that is, the energy of combustible gas is passed through plasma generator with virtually no additional losses.

Adding a hydrocarbon component to the original plasma-forming mixture significantly improves the component of electrical energy, which is introduced to the plasma-forming gas. This is the result of increasing voltage on the arc that passes from burning in the medium of gas system N–O to the combustion in the gas system N–O–C–H.

Starting at n=12.7 % by volume and higher (α≤0.7), the growth in electric capacity of plasmatron is not observed due to almost unchangeable value of voltage on the arc. At the same time, losses into the elements of the spray design, in the case of n=12.7 % by volume, are approximately equal to the energy introduced with combustible gas. Under such conditions, further increase in the amount of hydrocarbon gas in the original plasma-forming mixture results in the proportional increase in the total useful capacity of plasma jet:

$$P_j = P_h + P_{st}. \quad (8)$$

Accordingly, the efficiency of plasmatron with the combined supply of energy improves. The growth in efficiency can only be limited by possible formation of condensed carbon on rich mixtures and the technological requirements for obtaining a particular working medium.

Thus, the total useful capacity of plasma jet in a hybrid device is considerably larger than a simple arithmetic sum of capacities of air plasmatron and the energy introduced with a hydrocarbon gas.

Additional possibilities to control energy state of plasma jet are provided by changing the operational parameters of plasma generation. Fig. 4 and Fig. 5 show dependences of specific energy and total energy of plasma jet on the consumption of plasma-forming gas and the current of arc (attached electrical power).

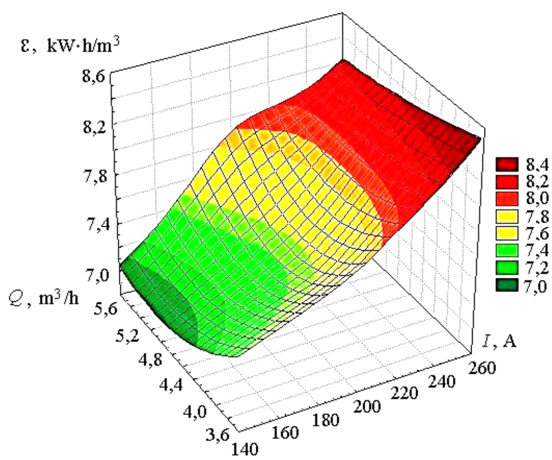

Fig. 4. Dependence of specific energy of plasma jet on the operational parameters of the gas-air plasma generation process (α=0.4)

Specific energy of the gas-air stream, under condition of significant content of a hydrocarbon component, depends largely on the arc current than the consumption of plasma-forming mixture (Fig. 4). Total capacity of the plasma jet, which generally defines performance efficiency in the processes of materials treatment in the processes of surface engineering, depends to a larger degree on the consumption of plasma-forming gas than on the arc current. It is associated with the increasing voltage when the consumption of gas rises and reducing losses into the elements of plasma generator design with the improvement in the conditions for arc stabilization in the arc channel. With an increase in the arc current (subject to falling volt-ampere characteristic), the value of voltage on arc is reduced and, in addition, the losses into plasmatron's electrodes somewhat increase, which are proportional to the current.

Multichannel phased introduction of energy to a plasma-forming gas slightly alters the essence of generally accepted concept "specific energy of the plasma jet". At a single-channel introduction of energy, this characteristic describes a capability of the medium to effectively heat a source material in the processes of surface engineering.

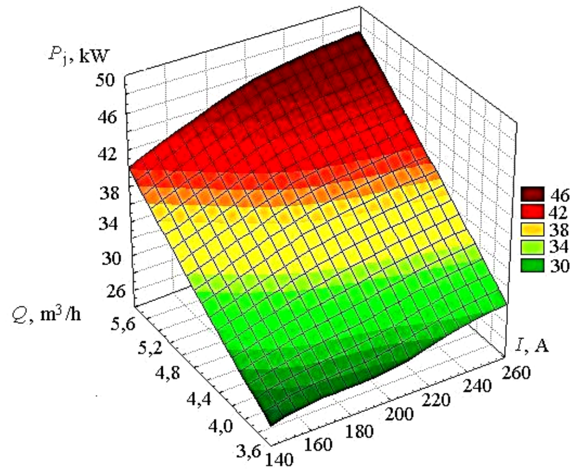

Fig. 5. Dependence of plasma jet capacity on the operational parameters of the gas-air plasma generation process (α=0.4)

Creating a high-energy medium without providing for the necessary spatial distribution of its parameters does not warrant efficient use of energy for heating and accelerating the particles of original material. This is particularly true for materials with high melting temperature and low thermal conductivity. Simultaneous introduction of energy to plasma-forming gas without targeted maintaining the parameters of jet over the entire active area of material treatment leads to substantial non-uniformity in the conditions of interaction between a high-temperature gas and the spraying material. Due to the ambient air suction and removal of energy for heating and accelerating the material, initial value of the mean-mass specific energy of the plasma jet begins to decline sharply in all directions. Therefore, in order to guarantee the required values of this parameter in the region of active influence on the treatrd material, there is a need to increase the initial values ε to compensate for the natural decrease in its magnitude. In addition to the unproductive losses of energy, this leads to the uncontrolled evaporation of the starting material at the initial stage of its treatment.

A much more rational approach may prove to be a provision at the output of plasma heater of minimum required value ε. Consequently, the assigned level ε is supported by the consistent introduction of additional portions of energy (including non-electrical in origin).

The use of gas-air plasma-forming mixtures provides for such possibility. In the volume of plasma jet at adding a hydrocarbon gas to the original air, there appears a significant number of components (Fig. 6, *b, c*), which have the ability to oxidize additionally in case there is a suction of oxygen from the environment with the release of considerable amount of thermal energy.

This energy in balance equation (6) is denoted as P_{st}. The amount of "stored" energy P_{st} in the first approximation is almost proportional to the amount of hydrocarbon gas in the mixture, or consumption of plasma-forming mixture (in the case of a constant ratio between components of the mixture). Enriching the original mixture and increasing its consumption may enable changing in a wide range the content of combustible components in the volume of plasma jet. By so doing, control is carried out over the intensity of volumetric release of energy when treating the materials under conditions of open environment.

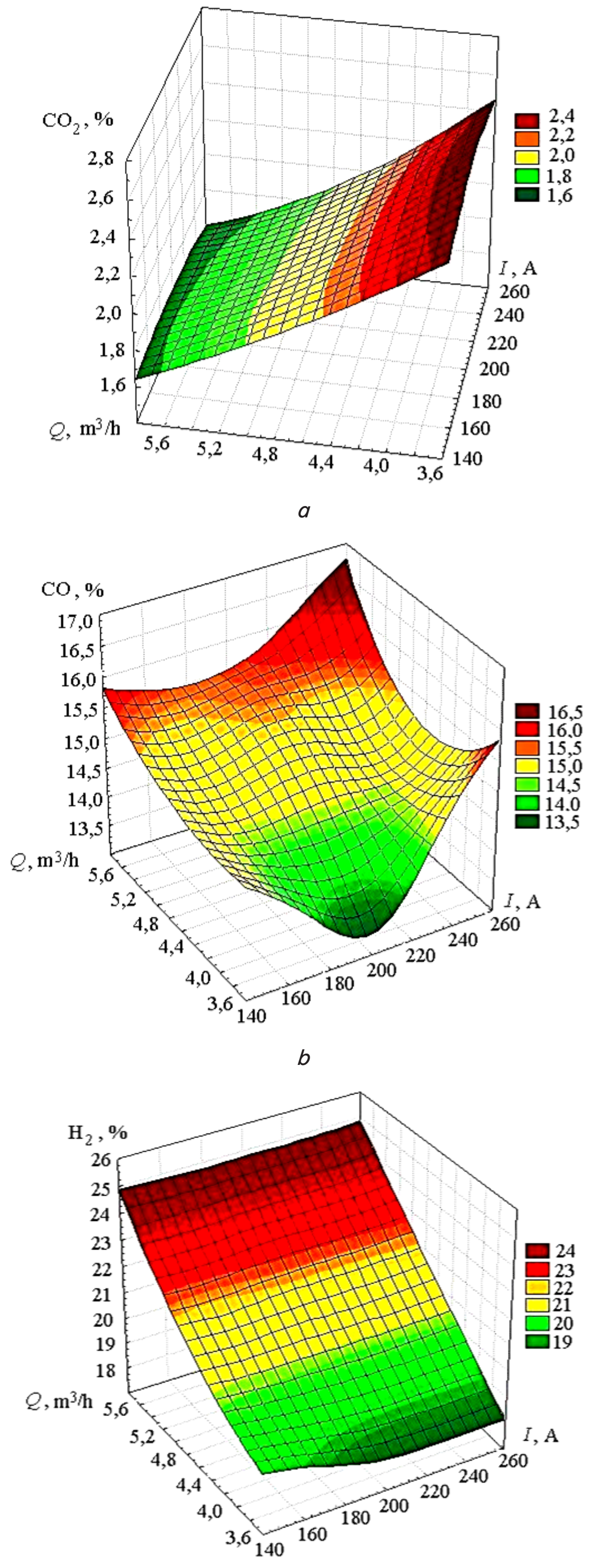

Fig. 6. Dependences of the content of basic components of gas jet on the operational parameters of plasma generation (α=0.4): *a* — carbon dioxide; *b* — carbon oxide; *c* — hydrogen

Interesting is the dependence of the content of carbon dioxide on the operational parameters of plasma generation. The CO_2 content is almost not affected by the amount of the introduced electric power while is substantially affected by the consumption of plasma-forming mixture – reducing its consumption will increase the content of CO_2 (Fig. 6, *a*). The independence of the CO_2 amount on the arc current indirectly confirms the absence of preliminary combustion of methane in the arc channel of plasmatron. Inverse dependence of the content of carbon dioxide on the consumption of plasma-forming mixtures indicates the course of processes of additional oxidizing within the limits of calorimeter. These processes are slowing down with increasing speed in the passage of products through the cooling system at the increase in consumption of the original mixture.

Probe studies of energy parameters of plasma jet register a significant reorganization of its structure after the transition from the plasma-forming air to the air mixture with hydrocarbons.

An increase in power of electric arc and additional heat release during combustion of components of the mixture with the participation of oxygen from the environment increases the level of temperature (up to 40 %) in the jet at all distances of measurements. In addition, the temperature profile becomes more fulfilled (Fig. 7).

A similar effect is observed in the velocity profiles of the gas-air plasma jet.

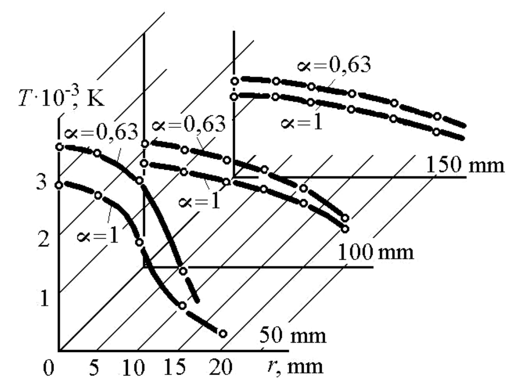

Fig. 7. Radial temperature distributions of plasma gas-air jet under condition of change in the composition of plasma-forming mixture (Q_Σ=3.5 m³/h)

A change in the coefficient of oxidizer consumption from α=∞ (air) to α=1 leads to the increase in enthalpy along the jet's axis at distance from 50 to 200 mm by 3–8 %; and at a distance less than 40 mm, even more significantly – by 20–25 % (Fig. 8). At the same time, there is an increase in the temperature of plasma jet: at a distance of 50–130 mm, this increase amounts to 8–10 % of the original level (in the air).

Transfer from the coefficient of oxidizer consumption α=1 to α=0.63 leads to the increased enthalpy at a distance of 50 to 200 mm by 8–10 %, and at a distance less than 40 mm – by 30–40 %. The temperature of plasma jet substantially increases: at a distance of 50–130 mm, the rise in temperature is 30–40 % of the original level. This fact can be explained by the additional heat release during combustion of components of the mixture at suction of oxygen from the atmosphere.

In a general case, despite the lower estimated mean-mass plasma temperature at the output of plasmatron, the mixtures with a higher content of hydrocarbons are characterized by the increase in temperature and enthalpy. It occurs in the cross section of the jet at distances of 3–5 calibers of the original diameter of the nozzle to the distance of spraying (20–25 calibers). Velocity of the plasma jet also increases due to the increase in the volume of products of dissociation of the original mixture. This speed increase is maintained at all distances of the jet's active zone (the region of plasma jet in which it is possible to heat and accelerate the dispersed material when applying coatings).

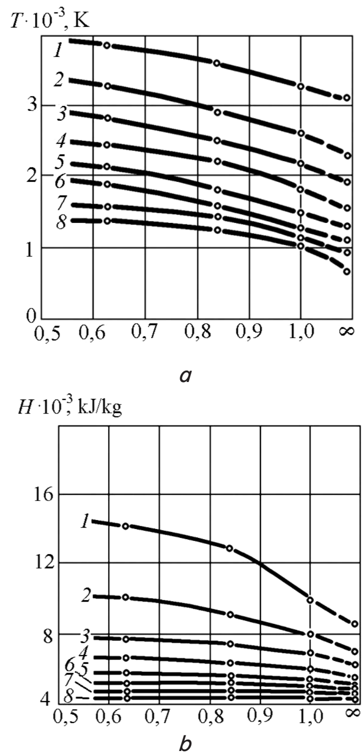

Fig. 8. Dependence of temperature and enthalpy on the coefficient of oxidizer consumption of plasma-forming mixture (along the longitudinal axis of plasma jet): *a* – dependence of temperature; *b* – dependence of enthalpy; 1 – distance of 40 mm; 2 – 60 mm; 3 – 80 mm; 4 – 100 mm; 5 – 120 mm; 6 – 140 mm; 7 – 160 mm; 8 – 180 mm (I=200 A; Q=6.3 m^3/h; P=24 kW)

Thus, the transition from a complex mixture of non-combustible molecular gases (air plasma jet) to the mixture with a combustible component increases the longitudinal dimension of active zone by 1.5–2 times, and its volume by 4–5 times.

6. Discussion of results of exploring the processes of energy conversion in the plasma generators with a dual-channel introduction of energy

The occurrence of a hydrocarbon component in the plasma-forming mixture radically affects the distribution of energy parameters in the volume of the jet.

Adding hydrocarbon (natural) gas to the plasma-forming air makes it possible to expand by 1.5–1.7 times the range of attainable values without increasing the current load on the electrodes of plasmatron. The overall capacity of plasma jet can be increased by almost 2 times (Fig. 9).

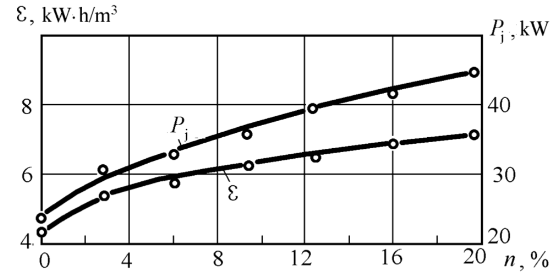

Fig. 9. Dependences of the total useful capacity and specific power of plasma jet on the content of hydrocarbon component in the original plasma-forming mixture (I=200 A, Q_Σ=5.3 m^3/h)

The presence of hydrocarbon component in the original plasma-forming mixture changes conditions for the existence of electric arc. The arc passes from combustion in medium of the gas system N–O to the combustion in the gas system N–O–C–H. This significantly improves the component of electrical energy, which is introduced to the plasma-forming gas by increasing voltage on the arc. Accordingly, thermal energy of the plasma jet, which is formed, grows.

Study of the structure of near-wall gas proves that due to the limited volume of the arc chamber and limited time when a plasma-forming mixture is in it under condition of high temperature, a part of the gas dissociates into the corresponding components. Main volume of the gas mixture that moves along the arc channel in the colder peripheral areas gradually changes its chemical composition. This is due to the parallel passage in time of the processes of gas-air mixture combustion and its mixing with the products of dissociation in the electrical arc. According to the results of chemical analysis of near-wall layer of gas mixture, a volumetric part of oxygen, methane gradually decreases as the gas moves towards the exit of arc channel while the volumetric part of CO, H_2, CO_2 increases. The intensity of dissociation of the original components and the formation of new ones increases with increasing arc's current.

Enrichment of the mixture (under conditions of other constant plasma generation parameters) does not affect the nature of the processes that proceed, although the volumetric fraction of CO, H_2, CO_2 in the same points of taking the samples increases with an increase in the volumetric part of hydrocarbon component in the original plasma-forming mixture.

The nature of growth in the carbon dioxide content as it approaches the exit of the arc channel proves the possibility of practical exclusion of hydrocarbon component combustion within the limits of the plasma generator design.

Results of applying calorimetry to the plasma jet allow us to argue that the energy, which reaches plasmatron with hydrocarbon gas (methane), insignificantly increases the level of thermal energy of the plasma jet. Combustible components pass the arc channel practically without interacting with the oxidizer. Moreover, a part of thermal energy of the jet is spent on the dissociation of original compounds of gas mixture and the level of thermal energy slightly decreases with the "enrichment" of the plasma-forming substance.

At the same time, with the addition of hydrocarbon, the "stored" energy of plasma jet grows. It is realized outside the limits of plasma generator design, in the active zone of plasma jet, as a result of chemical interaction with the oxygen contained in the original mixture and sucked from the environment.

7. Conclusions

1. Thermal power of plasma jet in the system N–O–C–H is formed of two components. The first component is a part of electrical energy, which is converted into the thermal within the design of plasma generator. It is the result of interaction between electric arc and a flow of plasma-forming gas. The second component is a part of the energy that is released during the combustion of components of the plasma-forming mixture. A larger part of this component is released beyond the limits of plasmatron design in the plasma jet.

2. A change in the content of hydrocarbon component in the original plasma-forming mixture leads to changing the burning conditions of electric arc and, as a result, significantly increasing its energy parameters. In this case, release of thermal energy in the arc channel as a result of combustion of the components of plasma-forming mixture is slowed down and is almost missing. This energy is released outside the plasma generator design in the volume of plasma jet, causing a significant reorganization in the structure of the jet. Total power of electric arc increases due to growing voltage on it. This factor, as well as additional heat release during combustion of the components of original mixture, contributes to the increase in overall temperature level and velocity in the entire volume of plasma jet. At the same time, the profiles of jet's parameters become more filled.

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