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Study of the Gas-Dynamic Features of the Design of the Gas-Air Path of the Plasmatron

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Abstract. *The aim of the study is to consider a method for improving the energy efficiency of the technological process of plasma recovering of turbine blades of CHP through the development and implementation of a three-way vortex mixer into the design of the plasma torch. By changing the operating parameters of the mixer, it is possible to adaptively control not only the recovery modes, but also the physical and mechanical properties of the coating. It has been established that structural changes in the technological elements of the plasmatron significantly change its structural characteristics, which leads to a change in the gas-dynamic processes occurring in it. The changes consist in the appearance of additional hydraulic and gas resistance to the flow of the carrier gas with the powder composition. Modernization of the plasmatron and optimization of technological regimes require a gas-dynamic calculation of each element of the gas-air path at the design stage. Studies of the principles of pressure distribution, flow rate, changes in the flow rate of the transporting gas and powder composition made it possible to design the optimal design of the plasmatron while retaining its technical characteristics, regulated by the GOST 4.140-85 standard «System of product quality indicators. Electric welding equipment. Nomenclature of indicators».*

Keywords: *plasmatron, turbine blade recovering, gas-air path, carrier gas, gas dynamic processes, plasma-forming gas, modernization of the plasmatron, phase structure of the part, substandard turbine blades, powder composition, turbine blades, operational characteristics of the plasmatron, three-way vortex mixer, spraying, optimal technological modes.*

Introduction

The main problem in the technological process of recovering turbine blades of CHP is the process of forming the optimal structural-phase state of the metal, which excludes the appearance of cold-drawn cracks and provides vibration resistance to dynamic loads. [1 p. 2, 2 p. 80].

According to [3 p. 21] turbine blades are subjected to technical inspection during operation, according to the results of which they are sent for repair and restoration work or are rejected.

A well-known method of recovering Godovskaya G.V., Khafizova R.Kh. [1 p. 3] has problems in the use of dissimilar materials for surfacing (nickel-iron and cobalt-iron alloys, as well as nickel, cobalt and iron alloys), on the one hand, this technique provides a combination of ductility of the deposited ($\delta_5 = 15\%$) material and high hardness its surface (229-269 HRC), but at the same time leads to the formation of a heterophase layered structure, which reduces corrosion resistance [6 p. 120].

The previously described method for restoring the working blades of steam turbines, proposed by Lappa V.A., Fedin I.V., Khromchenko F.A. [4 p. 15, 5 c. 25], is the need to remove the blades from the rotor, which complicates and increases the cost of work. This method does not provide for post-surfacing heat treatment. Also, a significant disadvantage of this method is the high heterogeneity of the structural-phase composition and the high level of tensile residual stresses.

Consequently, the task of developing an innovative technology and design that allows not only to restore the geometric parameters, but also to improve the quality of the structural and physical-mechanical properties of CHP turbine blades remains relevant and unresolved.

Based on an improved mathematical model of dynamic processes, the main indicators that affect the quality of turbine blade recovery were substantiated. Based on the results of metallographic studies, the optimal phase structure of the base of the repaired part was determined, which ensures a high level of reliability under the action of cyclically changing dynamic loads [6]. To achieve high physical and mechanical properties of the restored blade structure as close as possible to the original ones, a technology has been developed for restoring substandard CHP turbine blades, which involves the introduction of an implant followed by thermal cycling.

In the course of the research, dependences of the influence of technological regimes on the quality of recovery were established, which make it possible to reliably determine the optimal values of recovery modes. Also, in the course of experiments on the restoration of substandard turbine blades, it was decided to modernize the basic model of the plasmatron by introducing a three-way vortex mixer into the gas-air system, which makes it possible to control the modes of the technological process of restoration.

Results

Structural changes in the technological elements of the plasmatron significantly change its operational characteristics, which leads to a change in the gas-dynamic processes occurring in it. This is due to the appearance of additional hydraulic and gas resistance to the flow of the carrier gas with the powder composition. In order to ensure optimal technological regimes, one of the primary tasks in the modernization of the plasmatron is to carry out a gas-dynamic calculation of each element of the gas-air path. The results of the study of the principles of pressure distribution, flow rate and change in the flow rate of the carrier gas (CG) and powder composition made it possible to design the optimal design of the plasma torch without compromising standard technical characteristics.

The formation of a CG flow with powder material is influenced by the processes associated with the gas flow rate in various parts of the gas-air path (GAP) of the device. These features include the expansion and contraction of the CG flow in different areas, changes in the turbulence of the flow and the direction of its flow. Thus, the patterns of change in the process of formation of the CG flow depend on the geometric dimensions of the sections of the gas-air path of the plasmatron, the properties of the gas used, the powder material, and their parameters [6].

Gas-air paths of plasmatrons, which have received the widest distribution, as indicated in [8 p. 160] consist of sections of variable cross section, which leads to the formation of turbulent flows, pressure drops in sections with different cross sections, as well as a stepwise change in the velocity of the transport gas and, as a result, plasma microexplosions and acoustic emission ejection of the transport gas from the nozzle.

Changes in the design of the GAP due to the modernization of the plasmatron should not lead to cardinal changes in the flow and loss of pressure at the outlet of the plasmatron, which in turn can reduce it's efficiency. Thus, it is necessary to analyze the gas flow in the modernized design of the plasmatron. In the course of the analysis, a number of parameters were studied, the main of which are the speed and pressure of the transport gas flow, the uniformity of the distribution of the air-powder mixture over the cross section of the plasmatron channels, and the smoothness of the jet. The listed parameters strongly depend on the design features of the plasmatron.

The GAT design diagram of the plasmatron is a complex system of channels that provide the supply of powder material for plasma spraying. In which six sections can be conditionally distinguished: 1 – inlet (transporting line), 2 – three-way vortex mixer, 3 – transportation channel, 4 – swirler, 5 – nozzle, 6 – outlet (Figure).

Each section of the GAT plasmatron has individual geometric parameters that characterize its shape and dimensions, on which the cross-sectional area of each channel depends. Figure shows the dependence of the change in gas velocity and pressure on the cross-sectional areas of each section in the direction from inlet to outlet (from left to right).

The considered sections of the gas-air path of the plasmatron are characterized by an original design, which, in turn, regulates the parameters of the gas flow in this section.

The first section of the GAT of the plasmatron, in the presented system, is characterized by a constant cross-sectional area, through which the CG and powder are fed.

The main purpose of the second section, where the proposed mixer is located, is to ensure flow turbulence, uniform mixing of powder materials and its direction into the transportation channel.

The third section is an element of the gas-vortex system – a transportation channel designed to equalize the flow of the gas-powder mixture.

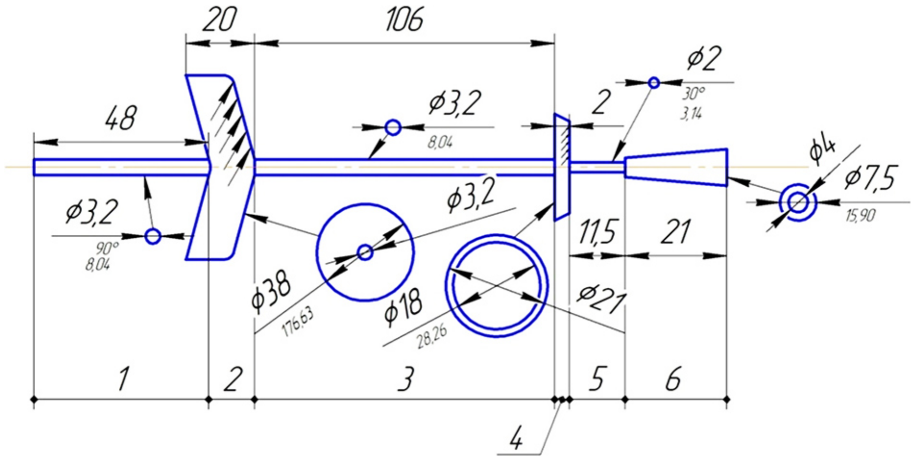
The fourth section is designed to form a swirling flow of the gas-powder mixture and feed it into the nozzle. In this section, the flow velocity increases sharply and a pressure drop occurs due to changes in the cross-sectional area.

In the fifth section, a jet of gas and powder composition under pressure exits the plasmatron nozzle.

In the sixth section, the gas-powder mixture enters the plasma-forming gas flow, which leads to the formation of a plasma jet saturated with the elements of the powder composition.

The regularities of the flow of the CG and the gas-powder mixture and its dynamic model are described by the Navier-Stokes dependences. Equations used to characterize the properties of the gas flow and reference data on thermal conductivity, viscosity and temperature are also applied when modeling a stream jet. To describe the change in the nature of the flow, its transition from a laminar state to a turbulent one, the allowed values of the Reynolds numbers are used.

Defined [8 p. 161] that it is possible to evaluate the efficiency of plasmatron design using theoretical dependencies and ratios of known criteria [8 p. 162]. These dependences make it possible to reliably determine the technological and efficiency parameters of the plasmatron. Due to the design features of the transporting line, it is necessary to carry out a



Structural scheme of the GAT plasmatron

gas-dynamic calculation of the elements of the gas-air path.

Since the carrier gas (CG) practically does not change its temperature when passing through the GAP of the plasmatron, except for the region of interaction with the plasma arc in the nozzle assembly, the calculations were performed on cold gas ($T=300$ K) at a constant value of dynamic viscosity. As a carrier gas, a mixture of air and propane is used, the viscosity of which was averaged over the studied temperature and pressure range (0.3÷0.5 MPa). Since the mean free path of air molecules at the indicated pressures is from 0.01 to 0.1 mm, which is much less than the characteristic hydraulic diameters of the GAT (2÷10 mm), the gas in the plasmatron is not Knudsen and its viscosity strongly depends on pressure (($\nu \sim P^{-1}$) and weaker – on temperature ($\nu \sim T^{1/2}$) [17 p. 327]. Taking into account these dependences, the values of the coefficients of dynamic $\mu = 2 \cdot 0^{-5}$ Pa·s and kinematic viscosity $\nu = 5 \cdot 10^{-6}$ m^2/s, respectively, were chosen in the calculations.

The gas-air path of such a plasmatron is a channel of changing shape with sharp changes in the cross-sectional area (Figure). When calculating the hydrodynamic parameters, the plasmatron path was divided into a number of transitions with constant or smoothly changing characteristics. A preliminary analysis made according to the continuity equation (constant mass flow rate) at the operating value of the plasma gas mass flow rate in the plasmatron $G = 1.2 \cdot 10^{-3}$ kg/s showed that the gas flow is turbulent with Reynolds numbers (Re) from 18000 to 320000, and cross-sectional average velocities from 10 to 300 m/s. The calculation of gas-dynamic parameters in the turbulent flow regime was carried out taking into account gas-dynamic functions, according to.

For each section of the gas turbine, dynamic head losses were calculated, including inertial losses due to local hydraulic resistances and linear pressure losses due to viscosity, the cross-sectional average axial gas velocities and the nature of the flow were determined by the Reynolds number.

The calculation of hydraulic losses for each transition was carried out according to the formulas:

$$\Delta P_z = \sum_i \frac{\Delta P_i}{\Delta x_i} \cdot L_i + \sum_j \Delta P_j,$$

где $\Delta P_j = \xi \cdot \dfrac{\rho_i \nu^2}{2}$ – local resistances taking into account inertial losses,

ξ – resistance coefficient depending on the shape of the hydraulic transition;

L_i – characteristic transition length;

$\dfrac{\Delta P_i}{\Delta x_i} = \zeta \cdot \dfrac{\rho_i \nu^2}{2D_r}$ – linear pressure loss due to viscosity,

$\zeta = \dfrac{\Delta}{\mathrm{Re}}$ – with laminar flow,

$\zeta = f\left(\mathrm{Re}, \dfrac{\Delta}{D_r}\right)$ – in turbulent flow,

Δ – ruggedness,

$\mathrm{Re} = \dfrac{vD_r}{\nu} = \dfrac{\rho \nu D_r}{\eta}$ – Reynolds number,

$D_r = \dfrac{4F_s}{P_s}$ – characteristic hydraulic diameter of the transition and the corresponding gas path, introduced to assess the effect of the section shape on the loss of hydraulic head;

F_s – cross-sectional area, P_s – section perimeter;

$\rho_i = \rho_0 \left(\dfrac{P_i}{P_0}\right)^{\frac{1}{\gamma}}$ – density in the i-th section,

P_i and P_0 – pressure at the i-th section and at the entrance to the plasmatron, $\gamma \approx 1{,}4$ – gas adiabatic index.

The gas-dynamic parameters of the gas in separate sections were calculated sequentially, starting from the entrance to the plasmatron, corrected for the pressure loss in the previous sections of the gas turbine. The dependence of viscous losses on the Reynolds number characteristic of the selected profile was taken into account. Since the nature of the CG flow of the developed plasmatron is a turbulent flow, the resistance parameters ξ practically do not depend on the properties of the gas and its velocity. The calculation of the parameters of the change in the nature of the flow of the CG flow depending on the change in the cross-sectional area of each section was carried out according to the average indicators of the change in their sections in places of sharp drops. In areas with smooth drops, the nature of the change in the hydraulic diameter Dg was used to evaluate them [9 p. 211]. The hydraulic parameters of each transition were calculated sequentially, starting from the entrance to the plasmatron, where the pressure P0 was experimentally controlled.

For calculations and comparative analysis, as well as for numerical modeling, the average values of the gas-dynamic parameters of the gas were taken, which are acceptable for most of the investigated plasmatrons $G=0.0005$ kg/s.

The results of the gas-dynamic calculation are obtained based on the design in Figure and are shown in Table.

In order to improve the efficiency of the plasmatron, the need to change some of its structural elements has been proved by calculation. During the modernization of the plasmatron, the principles of the integrity of its structure were observed, which ensures the preservation of the optimal parameters of the technological process. Studies have established that the quality of the technological recovery process is affected by regime parameters, the main of which depend on the design of the plasmatron. For example, high values of adhesion are achieved by high-speed regimes of the plasma jet. The speed of the plasma jet and its thermodynamic characteristics depend on the type and cross-sectional area of technological openings of the gas-air path.

Analyzing the results presented in Table, it was found that the gas-dynamic parameters of the carrier gas and the powder mixture in certain sections of the GWP of the plasma torch change in proportion to the pressure ($P_{in}=0.3\div0.5$ MPa). At $P_{in}=0.3$ MPa, the flow velocity of the CG in the conveying line is 153 m/s with a cross-sectional area $F=8.04$ mm^2 when it enters a three-way vortex mixer, it decreases to 7 m/s, which is associated with the appearance of resistance forces that increase losses speed mode. This design feature is inevitable, since there is a technological need for a uniform distribution of the fractional composition of the powder composition.

To ensure efficient technological conditions, a transportation channel with a cross-sectional area of 8.04 mm^2 is structurally provided, which makes it possible to provide a flow rate of up to 185 m/s in a short period of time. To ensure high values of adhesion, the effect of «implantation of a molten particle» is used, which is created in the swirler (section 4). Vortex mixing of the powder composition inevitably leads to a turbulent flow at $Re=97\cdot10^3$, which creates additional resistance forces and leads to a decrease in pressure and gas flow velocity to 56 m/s. At this stage, one of the priority tasks is not only to improve the physical and mechanical properties of the coating, but also to effectively control the modes of the technological process. After the loss of speed in section 4, it is necessary to compensate for this parameter, for which the design of the working nozzle provides additional inlet sections that increase the speed of the gas mixture to 440 m/s. Next, the gas-powder mixture enters the plasma-forming gas flow, which leads to the formation of a plasma jet saturated with the components of the powder mixture. The shape of the nozzle outlet channel also allows you to adjust the speed of the plasma flow within 350 m/s.

The data obtained from the analysis of the design features of the GAT of the modernized plasmatron prove that the use of a device for mixing powder materials in the plasmatron provides the ability to control the optimal technological modes that affect the efficiency of its operation.

Gas-dynamic parameters of the carrier gas and powder mixture in separate sections of the GAP of the plasma torch

Options		Lot number						Total values of indicators
		inlet (transporting line)	three-way vortex mixer	transportation channel	swirler	nozzle	outlet	
Cross-sectional area, F mm^2	8.04	176.63	8.04	28.26	3.14	15,90	-	
Hole diameter, D mm	3.2	15	3,2	6	2	4.5	-	
Section length, L mm	48	20	106	2	11.5	21	208.5	
Gas flow rate, V m/s	Pin = 0.3	153	7	185	56	440	255	-
	Pin = 0.5	135	6	151	45	120	121	-
$Re\cdot10^3$	Pin = 0.3	85	4	85	97	154	55	
	Pin = 0.5	108	7	108	122	108	67	-
Pressure difference ΔP MPa	Pin = 0.3	31.1	0.3	32.4	17	138.6	21	240.4
	Pin = 0.5	34.6	0.3	36.3	21	145.2	18	255.4

Conclusions

The gas-dynamic calculation of the developed elements of the gas-air path made it possible to design and develop the design of a three-way vortex mixer [10]. An analysis of the efficiency of the GAT system of the upgraded plasmatron showed an improvement in the gas-dynamic parameters of the CG flow in comparison with the basic design of the plasma torch by up to 2.8%. The introduction of this design into a complex system of the recovery complex makes it possible to control the physical and mechanical properties of the resulting surface during the deposition process in real time. The turbulence effect of the gas-powder mixture is based on the application of the well-known Bernoulli's laws. This principle of mixture formation increases the adhesive properties of the sprayed material due to the acquired acceleration during droplet impact of particles on the surface to be restored.

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Плазматронның газ-ауа арнасының құрылысының газ-динамикалық ерекшеліктерін зерттеу

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Аңдатпа. *Зерттеудің мақсаты үш жақты құйынды араластырғышты әзірлеу және плазматронның конструкциясына енгізу арқылы ЖЭС турбина қалақтарының плазмасын рекуперациялаудың технологиялық процесінің энергия тиімділігін арттыру әдісін қарастыру болып табылады. Араластырғыштың жұмыс параметрлерін өзгерту арқылы қалпына келтіру режимдерін ғана емес, сонымен қатар жабынның физикалық және механикалық қасиеттерін де бейімдеуге болады. Плазматронның технологиялық элементтеріндегі құрылымдық өзгерістер оның құрылымдық сипаттамаларын айтарлықтай өзгертетіні анықталды, бұл онда болып жатқан газ-динамикалық процестердің өзгеруіне әкеледі. Өзгерістер ұнтақ қоспасы бар тасымалдайтын газ ағынының қосымша гидравликалық және газ кедергілерінің пайда болуынан тұрады. Плазматронды жаңғырту және технологиялық режимдерді оңтайландыру жобалау кезеңінде газ-ауа құбырының әрбір элементінің газ-динамикалық есебін талап етеді. Тасымалдаушы газдың және ұнтақ құрамының қысымының, шығынының өзгеруінің таралу принциптерін зерттеу оның техникалық сипаттамаларын сақтай отырып, МЕСТ 4.140-85 «Өнім сапасының көрсеткіштер жүйесі. Электр дәнекерлеу жабдықтары. Көрсеткіштер номенклатурасы» бойынша реттелетін плазматронның оңтайлы конструкциясын жасауға мүмкіндік берді.*

Кілт сөздер: *плазматрон, турбиналық қалақтарды қалпына келтіру, газ-ауа арнасы, газды тасымалдау, газ-динамикалық процестер, плазмалық газ, плазмалық алауды жаңғырту, бөліктің фазалық құрылымы, стандартты емес турбиналық қалақтар, ұнтақ қоспасы, турбиналық қалақтар, плазмалық алаудың жұмыс сипаттамасы, үш жақты құйынды араластырғыш, бүрку, оңтайлы технологиялық режимдер.*

Исследование газодинамических особенностей конструкции газовоздушного тракта плазмотрона

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Аннотация. *Целью исследования является рассмотрение метода повышения энергоэффективности технологического процесса плазменного восстановления лопаток турбин ТЭЦ за счет разработки и внедрения в конструкцию плазмотрона трехзаходного вихревого смесителя. Изменяя эксплуатационные параметры смесителя возможно адаптивно управлять не только режимами восстановления, но и физико-механическими свойствами покрытия. Установлено, что конструктивные изменения технологических элементов плазмотрона существенно изменяют его структурные характеристики, что приводит к изменению газодинамических процессов, происходящих в нем. Изменения заключаются в появлении дополнительных гидравлических и газовых сопротивлений потока транспортирующего газа с порошковой смесью. Модернизация плазмотрона и оптимизация технологических режимов требует проведения газодинамического расчета каждого элемента газовоздушного тракта на стадии проектирования. Исследования принципов распределения давления, скорости потока, изменения расхода транспортирующего газа и порошковой композиции позволили спроектировать оптимальную конструкцию плазмотрона, сохранив его технические характеристики, регламентированные стандартом ГОСТ 4.140-85 «Система показателей качества продукции. Оборудование электросварочное. Номенклатура показателей».*

Ключевые слова: *плазмотрон, восстановление лопаток турбин, газовоздушный тракт, транспортирующий газ, газодинамические процессы, плазмообразующий газ, модернизация плазмотрона, фазовая структура детали, некондиционные лопатки турбин, порошковая смесь, рабочие лопатки турбин, эксплуатационные характеристики плазмотрона, трехзаходный вихревой смеситель, напыление, оптимальные технологические режимы.*

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