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Original Article

Development of a Plasma Fine-Particle Coating Unit

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Abstract *- This study aims to increase the durability of the elements of peristaltic pumping units (PPU) by modifying the most loaded parts of the rotor with fine-particle coatings applied to them. To achieve this task, a fine-particle coating unit is designed, the flow of plasma-forming gas and coolant is analyzed in the plasma torch channels by simulating the flow structure, the thermal state of the elements is studied, and the reliability index is calculated. As a result, a comprehensive unit is obtained, which makes it possible to apply protective coating from various metals. Analysis of the results of simulating the distribution of temperatures, velocities and pressures, and the current line paths inside the volume of the working area of gas and liquid, makes it possible to conclude that the structure is operable and correct. At this stage, the values of the reliability indicators are obtained, which enable us to evaluate the considered systems of the plasma fine-particle coating unit and establish the compliance of this indicator with the technical requirements. The developed coating method is unique because, at a high temperature of the plasma jet and a high speed (up to 500 m/s) of particle motion, the heating of the sprayed surface is small and does not exceed 200°C, which does not lead to deterioration of the sprayed substrate material properties. Thus, strengthening the peristaltic pumping unit rotor, which is the most loaded structural element, is achieved to ensure the trouble-free operation of this system.*

Keywords *- Fine particle coatings, Finite element method, Peristaltic pumping units, Plasma torch, Strength analysis.*

1. Introduction

Pumping units are widely used in various areas of human life: utility systems, treatment facilities, production cycles of enterprises, nuclear power engineering, and space technology [1–4]. According to the type of the working chamber and the nature of its connection with the inlet and outlet, these devices are divided into dynamic and volumetric, while among the latter, hose devices, namely peristaltic ones, are widely used.

The peristaltic pump unit (PPU) is a machine whose main operating component is an elastic hose pinched by rotating rollers. This design enables the pumping of various liquid media, which differ in various temperature ranges, density, viscosity, chemical activity, and the presence or absence of impurities and solid particles [5]. The transported substance, contacting only with the hose, is isolated from the pump's mechanical parts, which makes it possible to protect it from additional contamination. Such pumps can be used as dosing pumps in various technological processes installed on pipelines.

Modern mechanical engineering tends to increase the parameters of durability and reliability of mechanisms, and PPU structural elements are no exception [6-8]. The service life of a peristaltic pump can be increased by standardizing maintenance procedures, timely modernization, early detection, and elimination of defects during operation [9, 10]. Another option for increasing durability is associated with an integrated approach based on simulation and modification of structural surface elements.

To date, many surface-hardening methods have been developed. However, after a detailed analysis of the literature and proposals presented on the equipment market, it is possible to formulate a problem that consists of the lack of a sufficient number of model range of units that enable hardening materials in the required way [11–14].

Thus, the developed design of an industrial plant is the object of the research, and the analysis of the flow structure in the plasma-forming gas channels and the plasma torch coolant and the study of the thermal state of its components constitute the subject of the research. Accordingly, this research aims to develop an industrial fine-particle coating unit (IFPCU), which is the best way to improve the durability and reliability of PPU operating mechanisms.

2. Literature Survey and Analysis

The materials and methods section should contain sufficient detail so that all procedures can be repeated. It may be divided into headed subsections if several methods are described. The protective wear-resistant coating is one of the effective ways to increase the service life of the critical structural elements of the PPU [15–21]. Applying coatings on an industrial scale requires units whose operating principle must be based on the appropriate coating method. In this regard, various coating methods were analyzed.

According to the methods of obtaining the coating methods are divided into mechanical, physical, chemical, and electrophysical; according to the type of technological process – they can be galvanic, vacuum, and depositing. The methods also differ in the materials used: metals, ceramics, polymers; according to the type (state) of the materials used – coatings can be applied in the solid (or solid dispersed) state; from the liquid phase (emulsions, suspensions, varnishes, slips); from electrolytic solutions; melt coating; and deposition of coatings from gases or gas mixtures [22, 23].

According to the environment in which the coating process is conducted, the following methods are distinguished:

- solid (thermal diffusion methods);
- liquid (chemical and electrochemical methods);
- gaseous (gas-thermal and gas dynamic spraying methods);
- vacuum (thermal, electron beam, ion, and laser deposition).

The thermal diffusion method for applying metal coatings consists of treating the protected surface with liquid, solid (in powder form), or gaseous metal at high temperatures [24]. Thermal diffusion is a process of zinc atoms penetration into the metal surface layer, which occurs under the influence of high temperature in reducing or inert gas medium. The operating temperature depends on the thickness of the coating and varies between 280 and 470°C, with penetration into the crystal lattice of the metal. As a result, the coating is distributed evenly, with the possibility of adjusting the coating thickness in a wide range. The disadvantages of this technology include a limitation in the size of products.

Electrochemical coatings are deposited on products in the form of metal ions from an electrolyte using an electric current [25]. Depending on the purpose, electrochemical coatings can be thick, from fractions of a micron to tenths of a millimeter. Chemical methods apply chemical coatings as a result of the recovery of coating metals from solutions or a gaseous medium without external electric current. Chemical coatings usually do not apply more than 10 microns thick. The advantages of these methods are that, without using high temperatures, it is possible to create coatings from pure metals and compounds and form multilayer coatings by successive deposition. The disadvantages include the low adhesion strength of the coating and the product and the difficulty of applying uniform coating on products of complex shapes and surfaces inside the product.

Table 1. Advantages and disadvantages of gas-thermal methods for coating formation

Method	Advantages	Disadvantages
gas-flame spraying	– the possibility of obtaining coatings from most materials melting at temperatures up to 3000°C; – high process performance with a high coefficient of material utilization; – low level of noise and light radiation; – ease of maintenance, low cost, and mobility of equipment.	– limitation of sprayed materials by melting temperature; – insufficient strength of coating adhesion to the substrate; – high porosity of coatings, preventing their use in corrosive environments without additional treatment; – low coefficient of using the gas flame jet energy for heating the powder material.
electric arc spraying	– the possibility of obtaining coatings with higher adhesion compared to flame spraying.	– possibility of overheating of the sprayed material; – formation of coatings with a large number of oxides and high porosity; – the low adhesion strength of coatings to the substrate for some operating conditions; – significant losses of the sprayed material due to the large spray cone.
detonation method of spraying	-a method of obtaining a coating with excellent adhesion strength; -the simplicity of the unit design.	-high noise level; -technological restrictions on the processing of non-rigid parts caused by high pulse pressures when a jet of detonation products acts on the substrate; -restrictions on the sprayed surface hardness

The gas-thermal method for coating formation consists in heating the initial coating material to a liquid or plastic state and spraying it with a gas jet [26]. The sprayed material enters the treated surface in the form of a stream of liquid droplets or plasticized particles which, upon impact, are fixed on the part's surface, forming a coating. Based on the thermal energy sources, this method can be classified into several more, the advantages and disadvantages of which are presented in Table 1.

The essence of the gas-dynamic spraying method [26] is applying solid particles of metal or a mixture of materials ranging in size from 0.01 to 50 μm, accelerated to the required speed in air, nitrogen or helium, and fixing them on the surface of a product or part. These are particles of aluminum, tin, nickel, babbits of different grades, or a mixture of aluminum powder with zinc. The medium with which the material is moved can be cold or heated to a temperature not exceeding 700°C. The advantages of this method include a slight thermal effect on the coated product, which eliminates the occurrence of internal stresses in the products, their deformation, and the oxidation of coating materials and parts; when exposed to a high-speed flow of sprayed particles, the surface is cleaned from contaminants. The main disadvantage is the narrow choice of materials that can be applied.

The plasma method related to thermal gas spraying turned out to be the most effective for the task set. With this method, the powder material is supplied to the plasma jet at a given temperature, and the particles falling on the target surface condense and fuse together [27]. As a result, the original component receives new, improved technical and operational characteristics [28]. The features of this method are the accelerated deposition of the coating due to the instantaneous transfer of particles with a plasma jet and the possibility of creating combined protective layers on the surface [29, 30]. Powder metals and alloys serve as working materials; polymer and composite materials are also used [31-34]. The coatings are of high quality, have good adhesion to the substrate, and can form a single whole with the latter [35, 36]. Compared to other presented methods, it is not limited by the dimensions and complexity of the shape of the hardened product. To create protective coatings with this method, materials of various nature can be used. Another significant advantage is the absence of influence on the final coating, its material, and the original product by external factors of the deposition process. Plasma-based equipment is the most versatile and mobile in use and has a lower price compared to devices of other application methods. This method makes it possible to vary the quality indicators of the final coating in a wide range of values and characteristics. The disadvantages include the low efficiency of plasma jet energy for heating the powder and the high equipment cost.

As a result, it can be concluded that, in accordance with the requirements, plasma methods for applying protective coatings are the most suitable for further designing a fine-particle coating unit.

3. Materials and Methods

3.1. Coating Technique

The principle of operation of IFPCU is based on the method for plasma spraying of anti-corrosion, anti-friction, wear-resistant and other coatings on small-size substrates, including those of complex shapes. Spraying is performed with metal or ceramic powders using a microplasma torch.
IFPCU performs the following processes:

1) Activation treatment of the substrate surface;
2) Ionization of sprayed particles;
3) Spraying of coating particles on the pre-prepared substrate.

The deposition occurs as follows: an arc appears between the cathode and the anode, which heats the operating gas to the state of a plasma jet. Nitrogen, argon, and hydrogen – inert gases – are the operating gas media. In parallel with this process, a powder is fed into the nozzle, which turns into a substance that can penetrate the workpiece's surface layer under the influence of plasma. Further, the melting material settles on the substrate.

Plasma spraying is a fully controlled process that allows adjustment of plasma feed rate, power and shape of the jet.

3.2. Description of the Unit Design

The design of the developed industrial unit for plasma application of finely dispersed coatings consists of the following components (Figure 1):

- maintenance section;
- cooling section;
- microplasma torch;
- gas hose;
- water hose;
- plasma torch supply hose;
- gas cylinder.

The maintenance section is used to power the coating unit; it is a control device with a control panel for controlling the spraying process. The cooling section is a device for water circulation intended for cooling the microplasma torch. There is a filler neck for filling the coolant and a liquid level indicator on the front part of the cooling section. A control panel is located on the front part of the cooling section to control the cooling process. For ease of transportation, handles are provided on the side walls, and the cooling section itself is mounted on wheel supports.

The cooling section is connected to the maintenance section through a water hose to organize a water-cooling system. The argon gas cylinder reducer is connected to the maintenance section through a gas hose to organize the gas system. The electrical, hydro, and gas systems are connected to the microplasma torch from the maintenance section through the plasma torch supply hose.

A microplasma torch is designed to generate a plasma flow, and; it provides the ionization of the sprayed particles of the coating raw material. The microplasma torch structure can be conditionally divided into anode section 1, cathode section 2 and bottom section 3 (Figure 2).

The design of the anode section of the microplasma torch is shown in Figure 3.

The anode and cathode sections are connected using a union nut, providing a quick disconnect coupling, which simplifies the assembly and disassembly of the anode part of the microplasma torch.

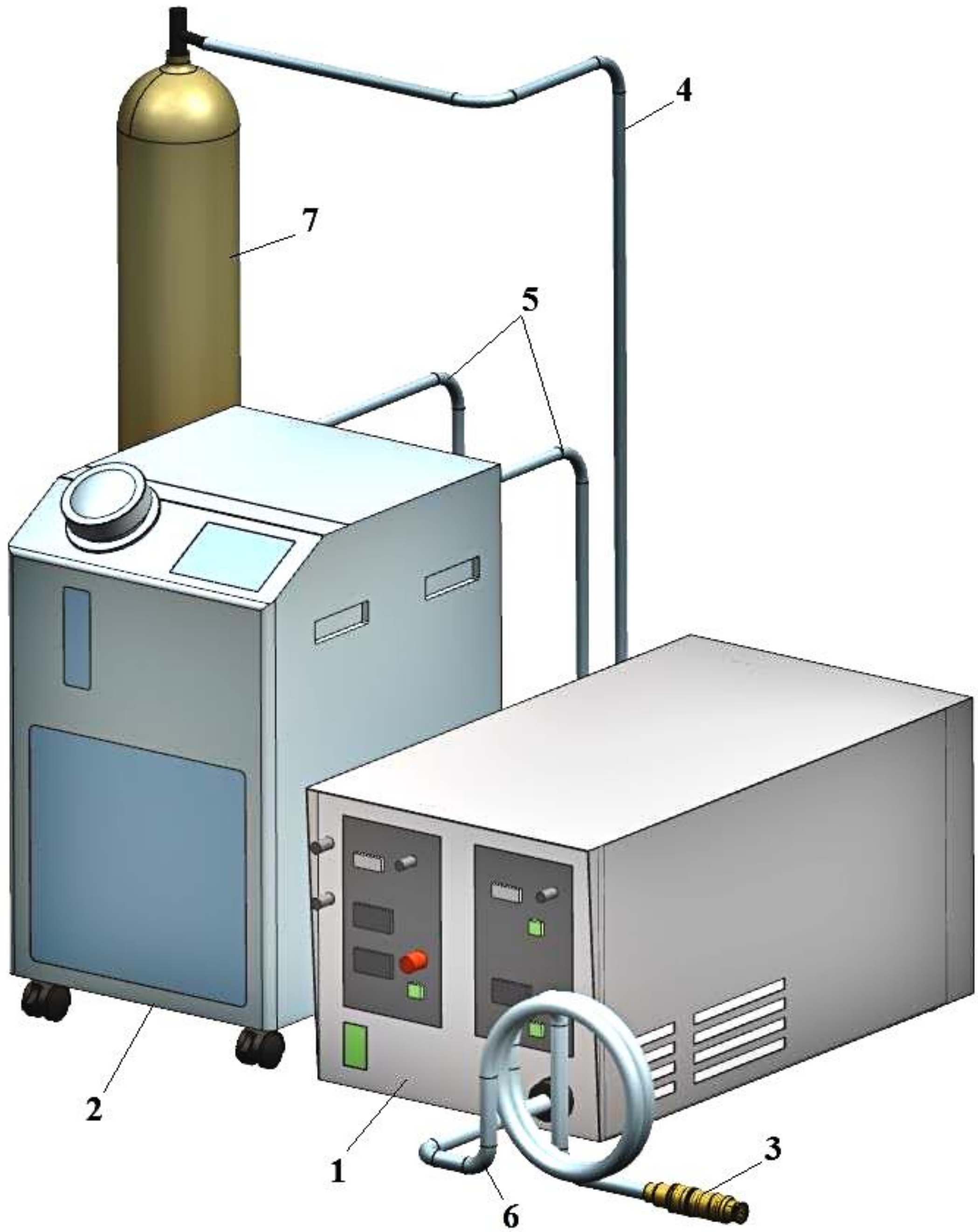


Fig. 1 The IFPCU design: 1 – maintenance section, 2 – cooling section, 3 – micro plasma torch, 4 – gas hose, 5 – water hose, 6 –plasma torch supply hose, 7 – gas cylinder

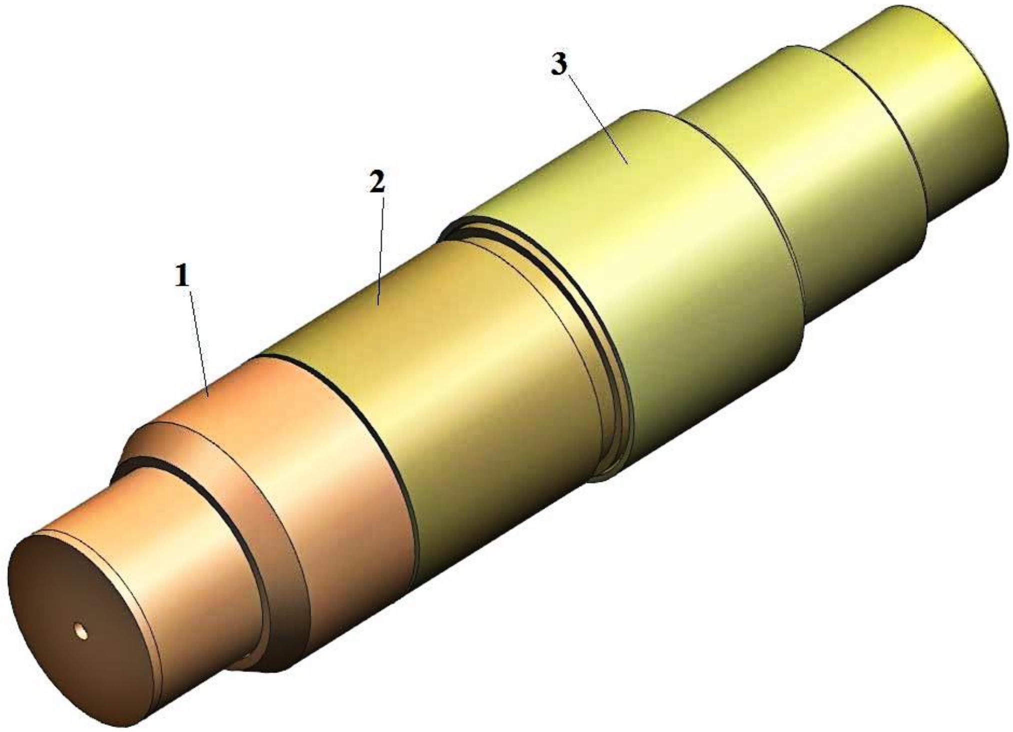


Fig. 2 The microplasma torch: 1 – anode section, 2 – cathode section, 3 – bottom section

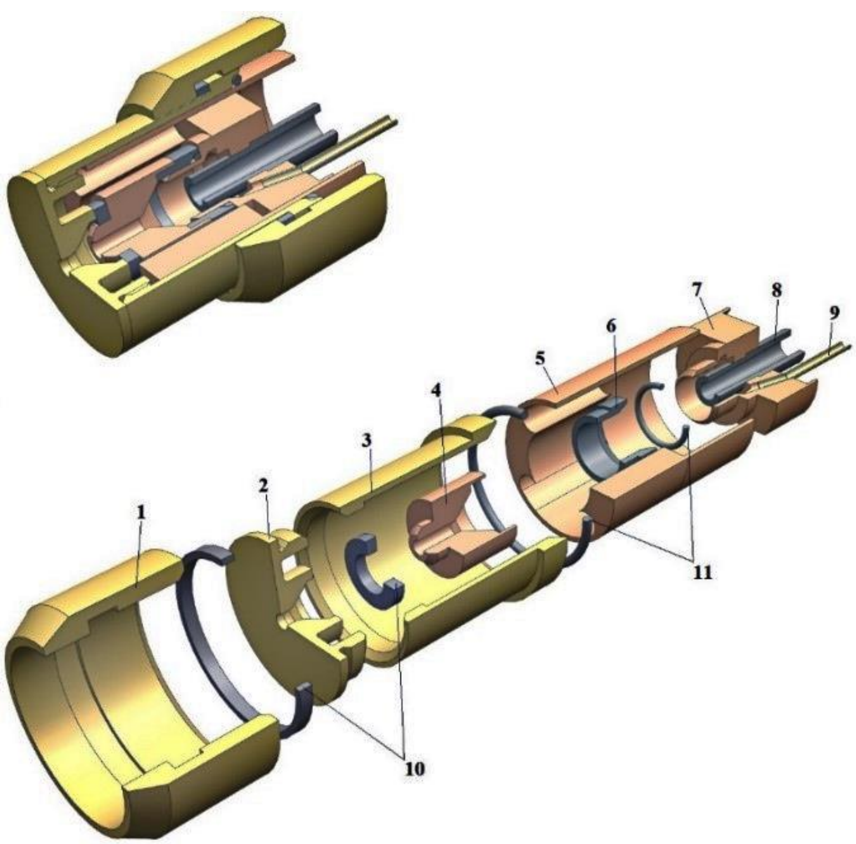


Fig. 3 The anode section: 1 – union nut, 2 – anode holder, 3 – anode body, 4 – output section of the interelectrode insert (IEI), 5 – insert insulator, 6 – IEI bushing, 7 – IEI input section, 8 – bushing, 9 – tube, 10 – insulating rings, 11 – sealing rings

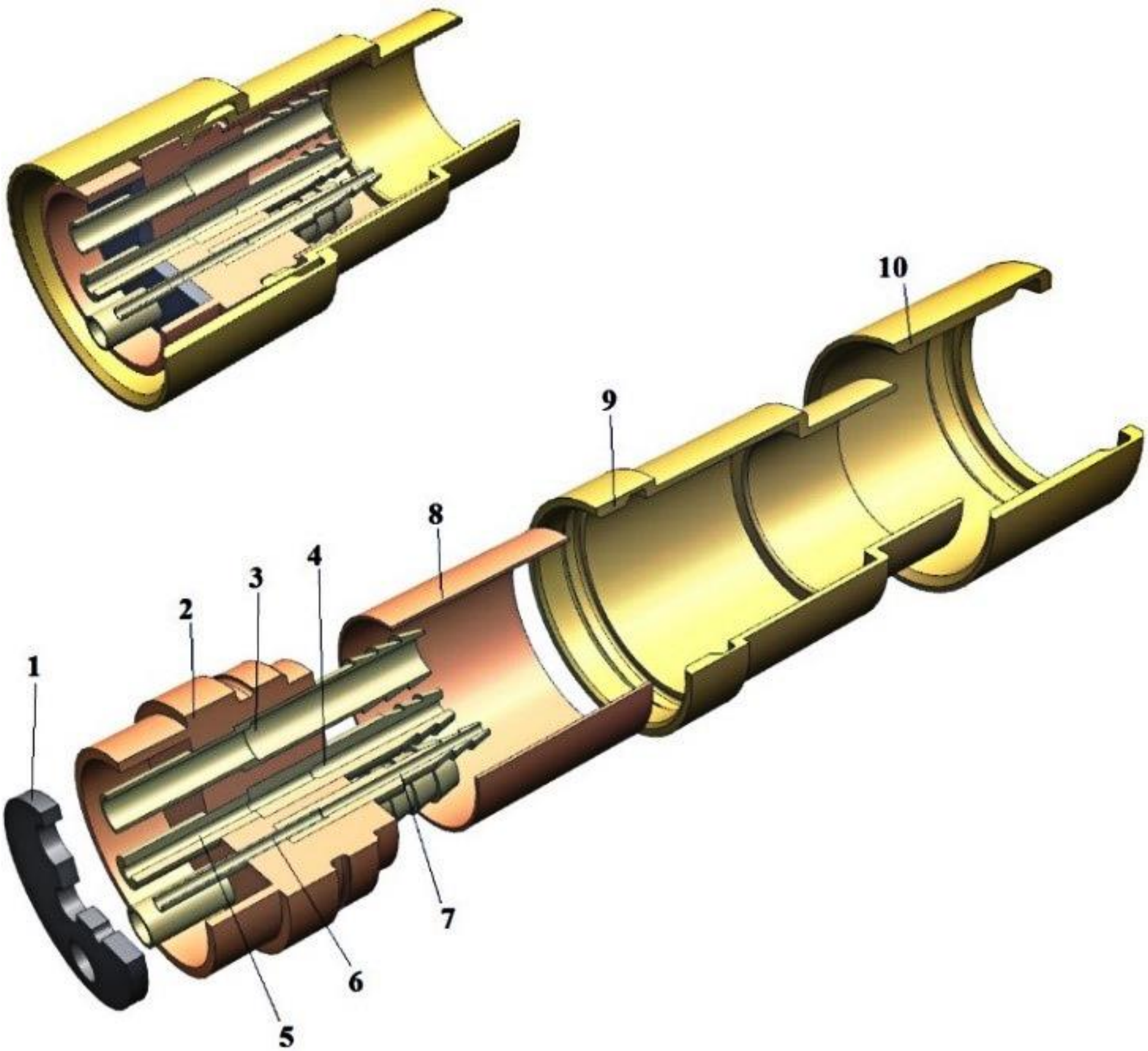


Fig. 4 The bottom section: 1 – gasket, 2 – base plug, 3 – water cooling fitting, 4 – gas supply fitting, 5 – gas supply fitting tube, 6 – powder supply fitting tube, 7 – powder supply fitting, 8 – tube, 9 – housing, 10 – cup

The interelectrode insert (IEI) is an insulated sectioned insert between the cathode and the anode. IEI is designed to increase the voltage on the arc and thus increase the power of the plasma torch. The insert insulator is made with channels for the coolant.

The design of the bottom section of the microplasma torch is shown in Figure 4.

The bottom and cathode sections are connected using a threaded coupling - a cup, providing a quick disconnect coupling, which simplifies the assembly and disassembly of the bottom part of the microplasma torch.

Water supply and discharge hoses of the water-cooling system are connected to the water-cooling fittings, providing circulation of the coolant in the water-cooling circuit of the microplasma torch.

A gas hose is attached to the gas supply fitting, providing the supply of plasma-forming gas–argon to the interelectrode cavity of the microplasma torch. The powder supply fitting supplies the sprayed particles of the coating raw material.

The design of the cathode section of the microplasma torch is shown in Figure 5.

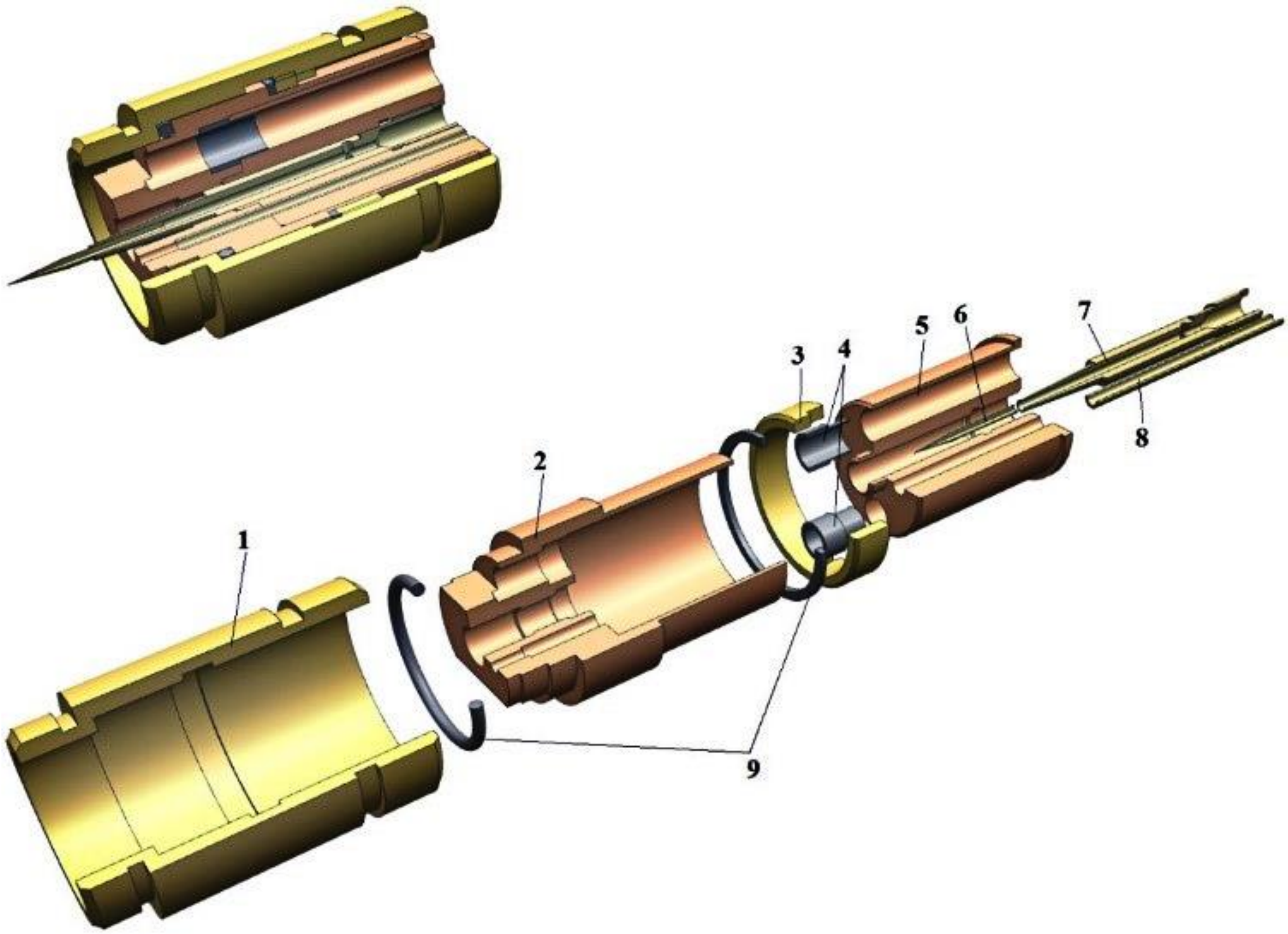


Fig. 5 The cathode section: 1 – micro plasma torch body, 2 – cathode insulator, 3 – internal nut, 4 – water sleeve, 5 – cathode body, 6 – tip, 7 – cathode holder, 8 – powder supply tube, 9 – O-rings

The cathode body and insulator are made with channels for cooling liquid and supplying gas and powder. Water sleeves ensure the tightness of the butt joint of the body cooling channels and the cathode insulator.

The cathode holder is made in the form of a hollow tube with a closed (tip) outlet end and two side holes. When supplied, the plasma-forming gas flow is divided into two parts and fed tangentially into the IEI channel at the anode section of the microplasma torch, creating a vortex flow, as a result of which the efficiency of the plasma flow formation process increases.

3.3. Research Methodology

The geometric model was partitioned by a finite element mesh to obtain a numerical solution. The need to model the boundary layer is considered when constructing a finite element mesh. The model of the computational domain for the operating gas has a refined mesh near the walls for modeling the near-wall boundary layer.

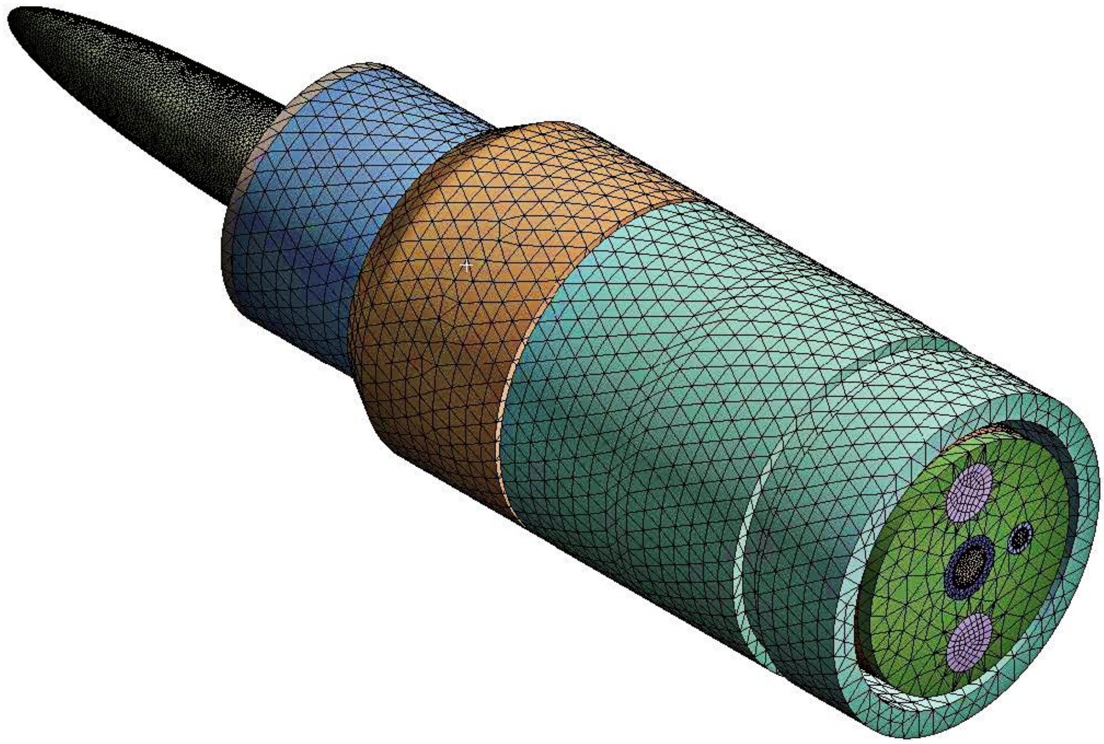
Graphical representations of the automatic distribution of finite elements in the volume of the plasma torch model are shown in Figure 6.

During the work, the reliability indicators were calculated in the format of approximate calculation of the IFPCU PPU. The following qualitative indicators were determined: mean time to failure, the probability of failure-free operation, and failure rate.

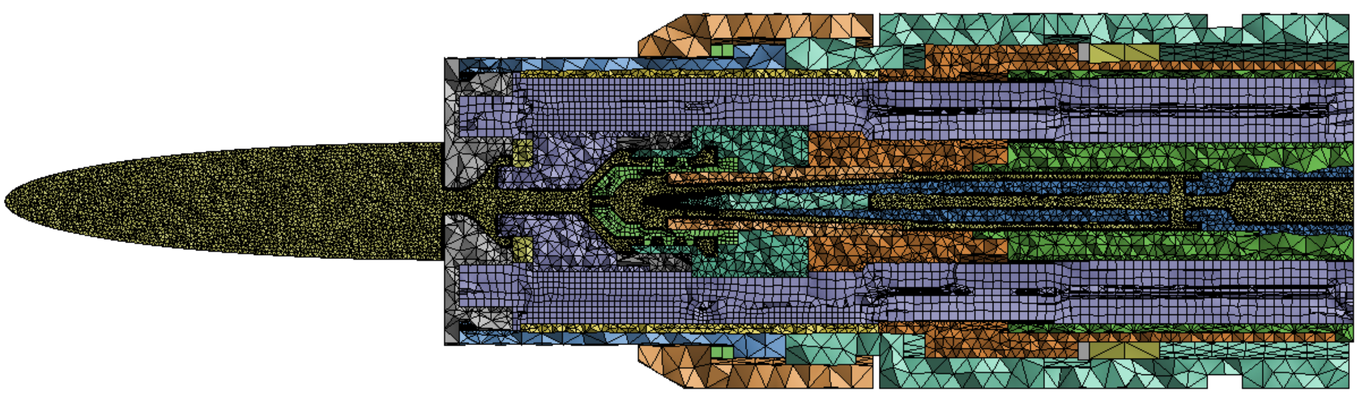
Analytical dependencies interconnect quantitative characteristics of reliability. In practice, the failure rate of individual components of products is most often a constant (nominal) value. In this case, the following equation is true:

$$P(t) = e^{-\lambda t} \tag{1}$$

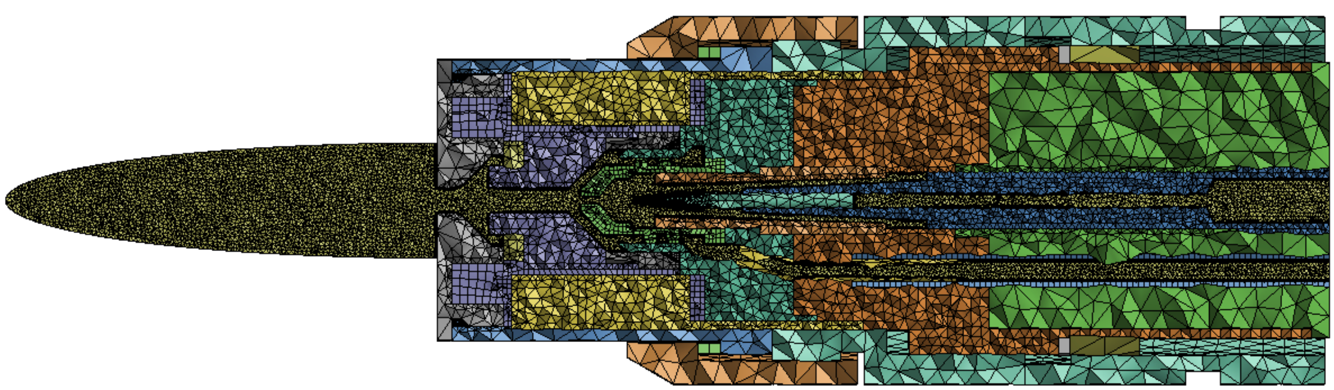
where e is the base of the natural logarithm; λ – is the part failure rate, [p^{-1}]; t – is the preset operating time in hours.



(a)



(b)



(c)

Fig. 6 A finite element mesh in the volume of the plasma torch model created in the automated mode (a) and parametrized considering the part features (b) and (c)

Failure rate λ(t) is the number of failures of n(t) object components per unit of time, related to the average number of components Nt of the object, operable at time Δt:

$$\lambda(t) = \frac{n(t)}{Nt \cdot \Delta t}, \quad (2)$$

Where Δt is a preset time interval.

The failure rate of components during operation under real conditions λ_i is equal to the nominal failure rate λ_0 multiplied by the correction factors K_1, K_2, K_3, ..., K_n, a_i considering the impact of mechanical factors (shaking, vibration) and operating environment conditions – humidity, temperature, pressure, etc.

In this case, the failure rate increases and is defined as follows:

$$\lambda_1 = k_1 \cdot k_2 \cdot k_3 \cdot \ldots \cdot k_n \cdot a_i \cdot \lambda_{0i} = a_i \cdot \lambda_{0i}, \quad (3)$$

For automation equipment and electronics, the assumption of random and independent failures is possible because non-random failures can be foreseen and eliminated, and dependent ones will not affect the reliability of a device with the main connection of components since, by definition, such a system loses its operability with the failure of the first inoperative component, i.e., with independent failure. The failure rate of the entire device can be determined as follows:

$$\lambda_y = \sum \lambda_i \quad (4)$$

The mean time to the first failure and the probability of failure-free operation of the device is determined through the failure rate of the entire device:

$$T_{av.y} = \frac{1}{\lambda_y}, P_{y(t)} = e^{-\lambda_y t} \quad (5)$$

where $T_{av.y}$ is the average time to the first failure, in hours; $P_{y(t)}$ is the probability of failure-free operation of the device; t – preset operating time, in hours; λ_y – device failure rate, 1/hour.

The reliability indicators are calculated based on the data presented in Table 2.

4. Results and Discussion

Figures 7-16 illustrate the distributions of temperatures, velocities and pressures, and current paths in the plasma torch model. The results are shown for two planes – section plane A and section plane B. Comparative Table 3 presents the simulation results, namely, the maximum temperatures, velocities, and maximum and minimum pressures in the considered section planes.

The results obtained during the calculation by FEM (Table 3) meet the technical requirements for the coating unit. Calculation of the reliability indicators resulted in the following values: the average time of failure-free operation is 18,832 hours, and the probability of failure-free operation is 0.96 during one month of continuous operation (720 hours).

Table 2. Initial data for an approximate calculation of reliability

Component	Number of components n_i, pcs	Failure rate $\lambda_i \cdot 10^{-6}$, 1/h	Product $n_i \cdot \lambda_i$ 10^{-6}, 1/h
Maintenance section	1	17.8	17.8
Cooling section	1	13.5	13.5
Microplasma torch	1	21.0	21.0
Gas cylinder	1	0.5	0.5
Conveying hoses	6	0.05	0.3
Cumulative failure rate of the IFPCU			53.1

Table 3. Computation results

Object of consideration	Maximum temperatures, K	Maximum velocities, m/s	Maximum pressures, Pa	Minimum pressures, Pa
Maintenance section	2634	274.7	32150	-1414
Cooling section	2376	275.1	32150	-1362

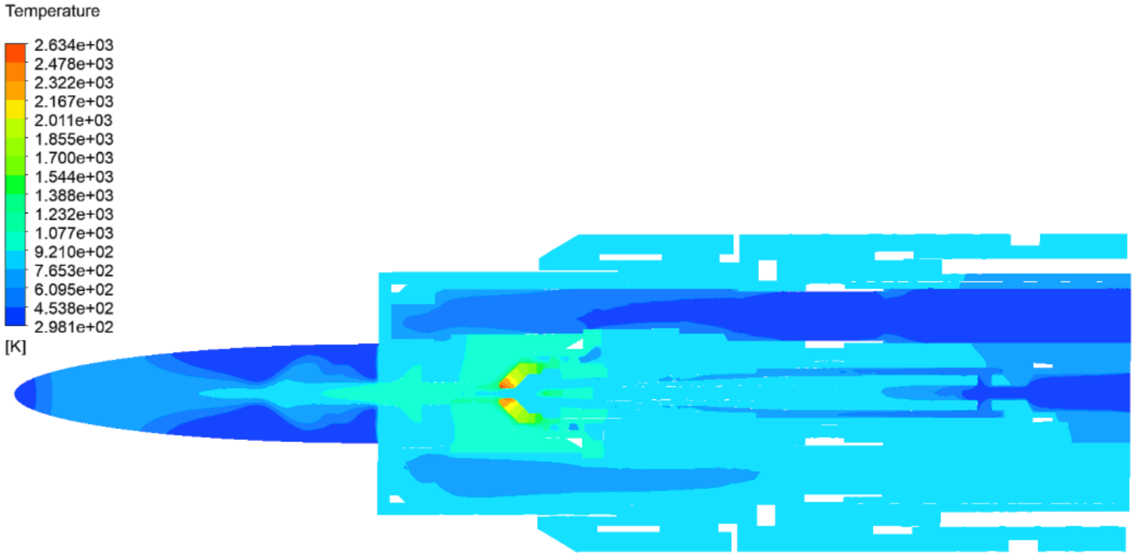


Fig. 7 Distribution of temperatures in the plasma torch model in section plane A

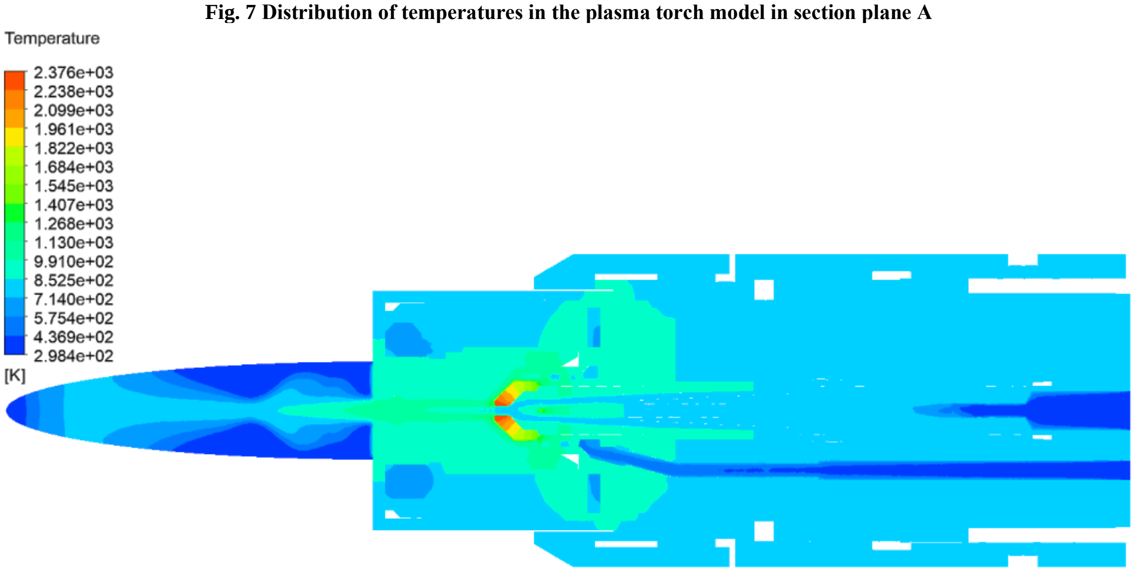


Fig. 8 Distribution of temperatures in the plasma torch model in section plane B

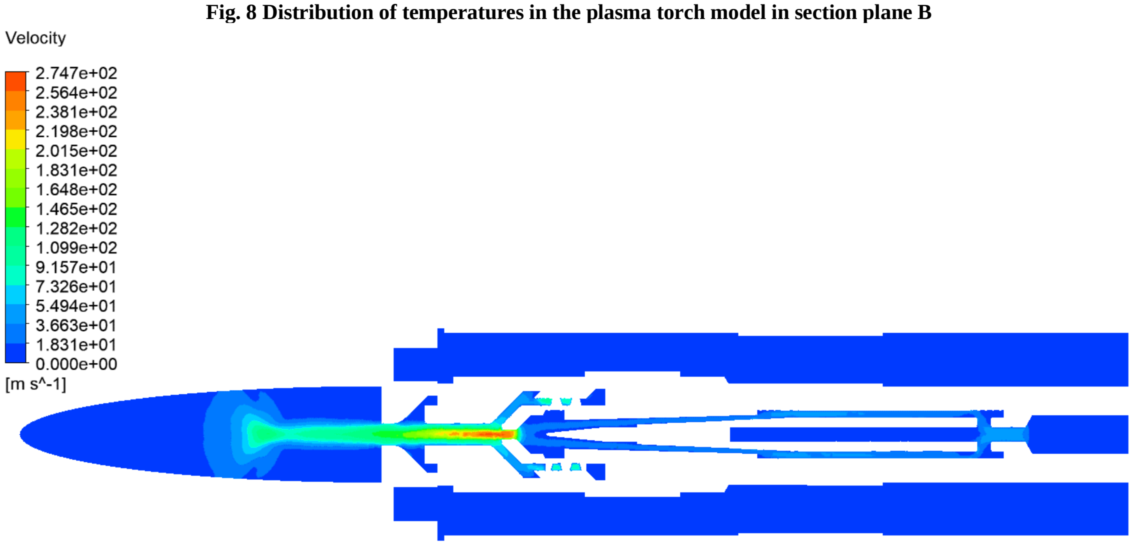


Fig. 9 Distribution of velocities in the plasma torch model in section plane A

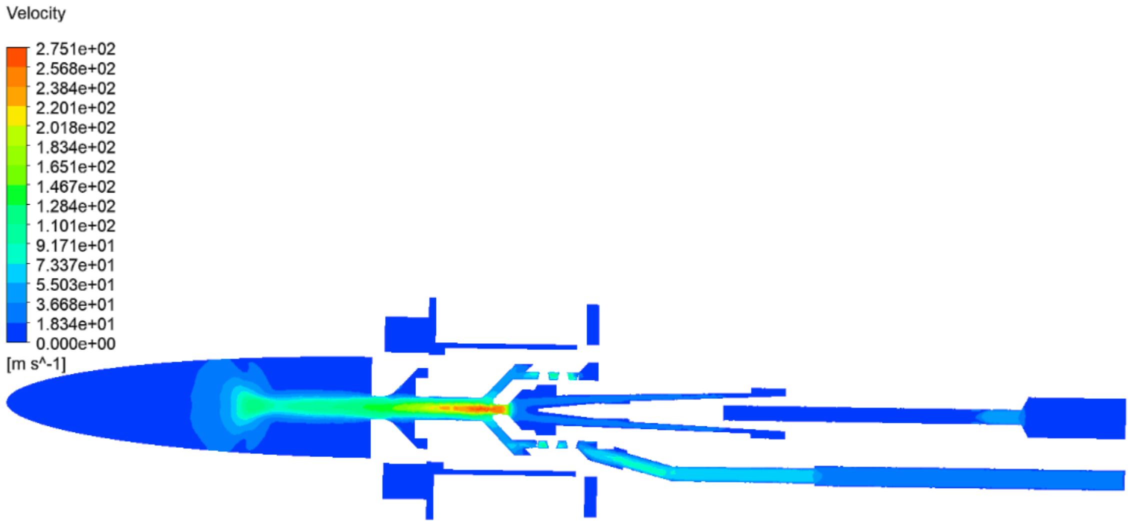


Fig. 10 Distribution of velocities in the plasma torch model in section plane B

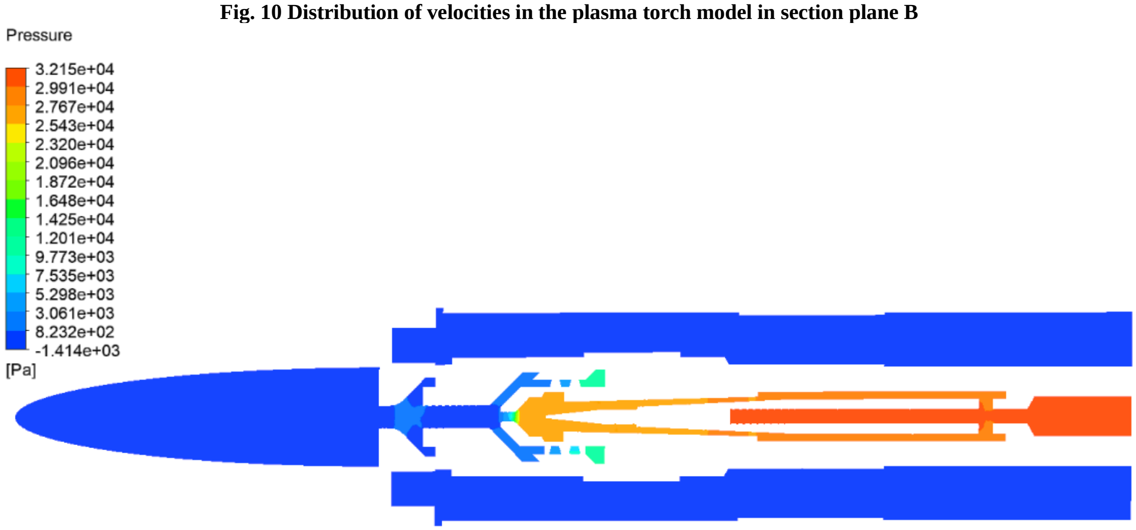


Fig. 11 Distribution of pressures in the plasma torch model in section plane A

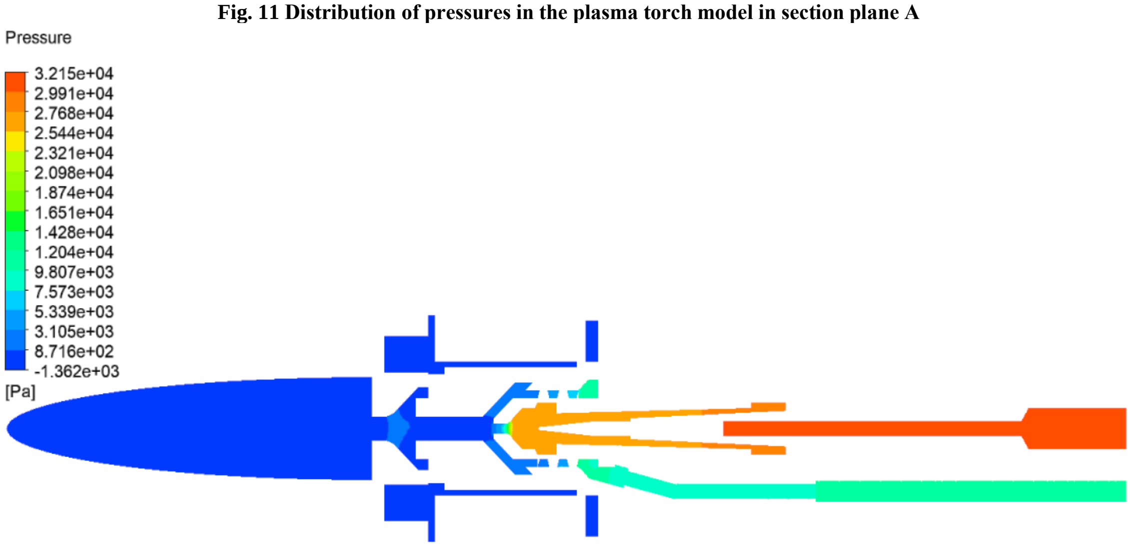


Fig. 12 Distribution of pressures in the plasma torch model in section plane B

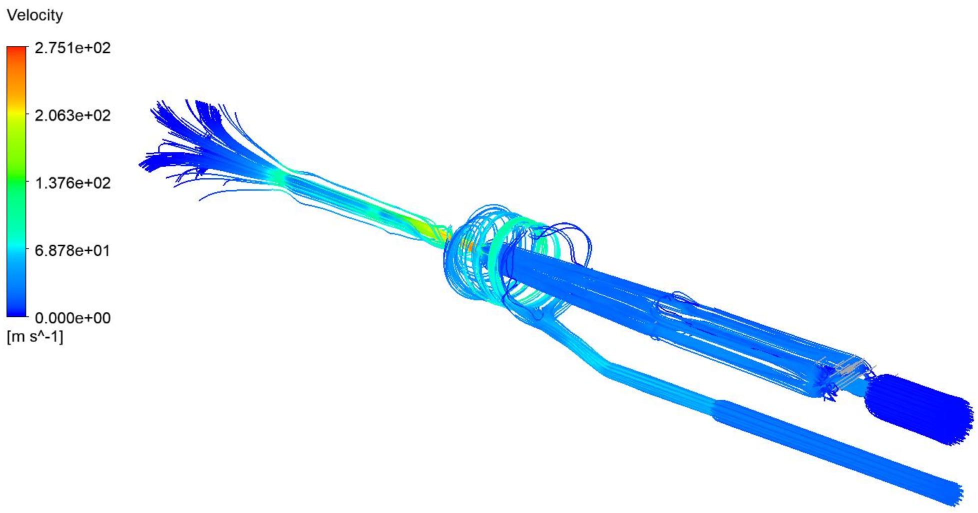


Fig. 13 Current paths in the computational domain of the operating gas

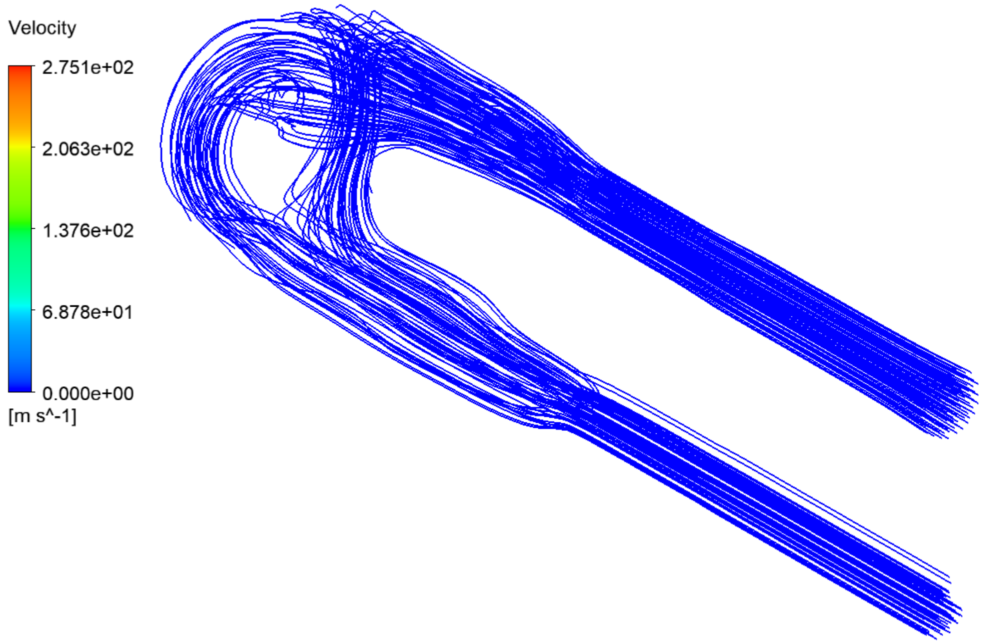


Fig. 14 Current paths in the computational domain of the coolant

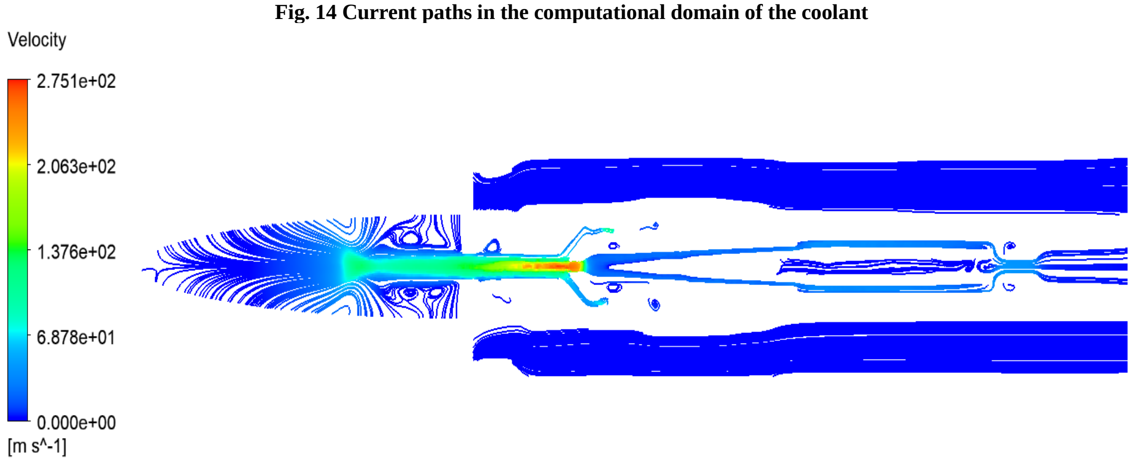


Fig. 15 Current paths in section plane A

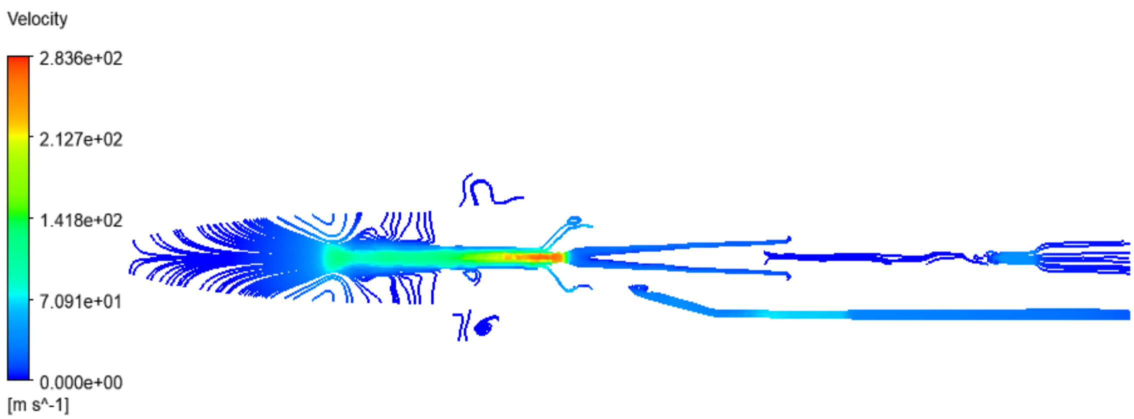


Fig. 16 Current paths in section plane B

5. Conclusion

The research results have determined that gas-thermal methods of spraying protective coatings are the most promising and currently developing techniques. This method is the best way to harden the loaded surfaces of the components of peristaltic pumping units. The method is quite promising in the context of restoring the shapes and sizes of parts that, for objective reasons, have undergone wear that can be eliminated.

Analysis of the obtained simulation results for distributing temperatures, velocities and pressures, and the current paths inside the volume of the working area of gas and liquid makes it possible to conclude that the developed design is working and correct. The simplicity of the operation schemes and equipment design and the high potential for making modifications to the equipment are the advantages of the developed industrial unit compared to the existing ones.

Values of the reliability indicators at this stage of the work enable us to evaluate the IFPCU systems under consideration and establish the compliance of the reliability with the technical requirements, which makes it possible to conclude that the installation is operational, ready for production and further implementation at the enterprise, which will further confirm the operation of the coating unit in practice.

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