Modeling the gas and liquid flow in the channels of the microplasmatron that is a plasma unit for applying fine coatings

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Abstract. This article describes a mathematical model of the flow of working gas and coolant in the channels of the microplasmatron of an industrial unit for the plasma application of fine coatings to confirm the performance of the installation. The unit is designed for applying protective coatings that make it possible to strengthen the surface of a certain part, which subsequently makes it possible to increase its service life. For convenience, the study is carried out in the universal Ansys Fluent software module, which has a wide range of capabilities for modeling the flow of liquids and gases, allowing one to identify the dominant physical phenomena occurring in the installation. As a result, calculation results were obtained in the form of distributions of temperatures, velocities and pressures within the volume of the working area of gas and liquid, and the operability of the installation element was confirmed.

1 Introduction

Modern industry is developing rapidly in all areas. New technologies are constantly emerging that make it possible to obtain quickly and cost-effectively a high-quality product. But this is not enough; the final product must have high durability while keeping its original properties. That is why efficient use of resources is becoming a priority direction for industrial development. Product wear resistance enhancement can be done in various ways. In mechanical engineering, the application of protective coatings with specific properties, depending on the task at hand, is a promising direction for increasing the working life [1,2]. One of these coating methods is plasma spraying [3, 4].

To ensure the safe operation of various technological systems, strict requirements are imposed on their operational characteristics, one of which is durability. Increasing this parameter is an urgent task for all industries. It is especially important to increase the durability of equipment operating in aggressive environments, vacuum, etc. Applying protective coatings to the most loaded parts of the device will increase their final wear resistance [5,6].

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During the spraying process, wear-resistant, anti-corrosion, anti-friction and other types of reinforcing coatings are applied to surfaces of varying degrees of complexity. In order to apply protective fine coatings, an electric industrial device for plasma application of fine coatings (hereinafter referred to as EPU PNMP device) was developed.

Currently, there is little convenient coating equipment available. For example, at work [7] industrial ion-plasma equipment for applying protective coatings is presented. The disadvantage of such device is the low rate of coating deposition and a possibly high level of voltage. Or at work [8] the analysis of various devices, with possible disadvantages, is considered. The goal of the work is to create an improved industrial PNMP installation to increase certain mechanical properties of various structures.

Today, science is becoming more accurate due to the mathematical description of the studied objects and phenomena. Modeling from a scientific point of view is logically proved using a minimum number of assumptions accepted as hypotheses based on observations of the modeled object. The main advantage of mathematical modeling is saving materials and resources, reducing research time. The objective of the paper work is mathematical modeling of the flow of working gas and coolant in the channels of the microplasmatron of the developed installation.

2 Methods

2.1 Design of the developed PNMP PU

Using the developed installation (Figure 1), it is possible to perform technological operations of applying a finely dispersed plasma coating to various parts of technical equipment in order to strengthen them and increase the final durability.

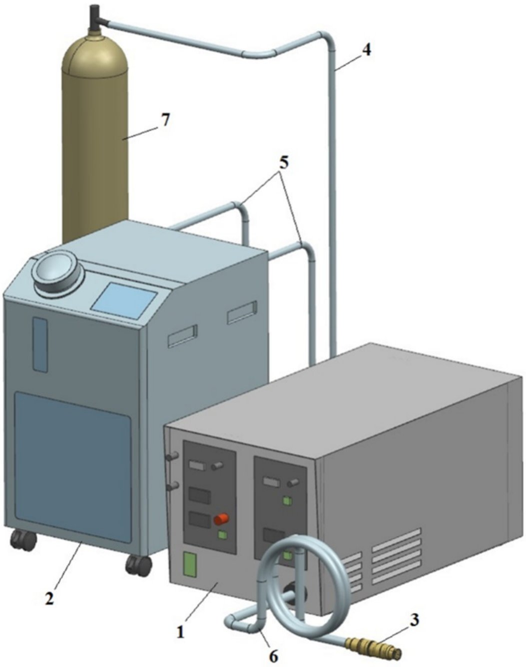

Fig. 1. Design of the PNMP PU: 1 – service unit, 2 – cooling unit, 3 – microplasmatron, 4 – gas hose, 5 – water hose, 6 – microplasmatron supply hose, 7 – gas cylinder.

In a microplasmatron, a plasma flow is generated and the ionization of the sprayed coating occurs. The movement of working gas and coolant occurs in it. These movements can be described using mathematical models presented later in the paper work.

2.2 Mathematical model

2.2.1 Model of the flow of liquids and gases

First, let's have a look at the basic ideas used to model gas and liquid flows.

When describing the flow of liquids and gases, people do not describe the movement of each particle due to their large number and the lack of initial data about them. For these purposes, the procedure of averaging all measured quantities, such as density, speed, temperature, is used.

Let us consider the basic equations of continuum mechanics, with the help of which the flows of gases and liquids are described.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + div\left(\rho \upsilon\right) = 0 \tag{1}$$

This scalar equation contains 4 functions, the form of which is unknown: ρ – scalar density function, υ – spatial velocity vector having 3 coordinates.

Equation of motion:

$$\rho \frac{d\upsilon}{dt} - \rho F - divT_{\sigma} = 0 \tag{2}$$

This tensor equation contains 3 scalar equations and in general 13 unknowns: ρ – scalar density function, υ – spatial velocity vector having 3 coordinates, stress tensor T_{σ} – 9 functions. F is a given vector of external mass forces.

Symmetry of the Cauchy stress tensor:

$$T_{\sigma} = T_{\sigma}^{T} \tag{3}$$

Energy equation:

$$\rho \frac{du}{dt} - T_{\sigma} D + divh - \rho q = 0 \tag{4}$$

where u is the specific internal energy, q is the energy supply per unit time per unit mass of the continuous medium (mass energy source), h is the energy flow vector,

D– velocity deformation tensor, defined as:

$$D = \frac{1}{2}\left(div\upsilon + div\upsilon^{T}\right) \tag{5}$$

Entropy equation:

$$\rho \frac{d\eta}{dt} + div\frac{h}{T} - \frac{\rho q}{T} - \omega^{*} = 0, \omega^{*} \geq 0 \tag{6}$$

where T is the absolute temperature, η – specific entropy; ω^{*} – dissipation function.

Let us write the equations above in a conservative form.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + div\left(\rho \upsilon\right) = 0 \tag{7}$$

Equation of motion:

$$\frac{d\rho\upsilon}{dt} - \rho F + div\left(\rho\upsilon\upsilon - T_{\sigma}\right) = 0 \tag{8}$$

Energy equation:

$$\frac{d\rho e}{dt}+div\left[\left(\rho eE-T_{\sigma}\right)\upsilon+h\right]-\rho\left(F\upsilon+q\right)=0 \tag{9}$$

where E is the unit matrix tensor, e is the specific total energy, defined as follows:

$$e=u+\frac{\upsilon\upsilon}{2} \tag{10}$$

Entropy equation:

$$\frac{d\rho\eta}{dt}+div\left(\rho\eta\upsilon+\frac{h}{T}\right)-\frac{pq}{T}-\omega^{*}=0 \tag{11}$$

2.2.2 Turbulence models

Calculation of numerical values of turbulent flows requires supplementing the system of Reynolds equations with a description of the turbulence hypothesis. In this way, the pulsating velocity component will be obtained. In general, turbulence models are divided into: the turbulent viscosity model, the Reynolds stress model, and the large eddy model.

Below, in Table 1 we present the main models included in finite element packages and their features.

Table 1. Turbulence models.

Turbulence model	**Short description**
Spalart-Allmaras	The model uses only one additional transport equation for the turbulent viscosity coefficient. Best suited for aerospace applications. (flow around aircraft wings, turbine blades). Recommended for use for plane problems.
Standard k-ε	This model takes into account the influence of turbulent kinetic energy and its reduction due to viscosity. The model introduces 2 additional equations describing the transport of kinetic energy of turbulence and dissipation of turbulence. Allows you to solve problems with strong turbulence, contains coefficients determined experimentally.
RNG k-ε	It is a continuation of the Standard k-ε model. Allows you to determine the coefficients involved in equations analytically. Has worse convergence compared to Standard k-ε, not recommended for use with areas with vortex.
Standard k-ω	Unlike the Standard k-ε model, instead of the dissipation equation, the equation for the dissipation rate of turbulent energy is solved. The model places high demands on the quality of the mesh, as well as on the correct initial approximation.
RSM	The model adds 7 Reynolds equations. Used in volumetric tasks with a high degree of turbulence, as well as with rotation. Has a high consumption of computer time.

2.2.3 Convective heat transfer model

Now let's look at the basic concepts and relationships related to heat transfer.

Convection is the transfer of heat associated with the movement of macroparticles of liquid or gas to different temperature regions. Convective heat exchange is the heat exchange that occurs between a body and the liquid or gas that flows around this body.

Heat flow q in a moving fluid is defined as:

$$q=q_{t}+q_{k} \tag{12}$$

Where $q_t=-\lambda grad\left(T\right)$ – heat flow due to thermal conductivity; $q_k=\rho\upsilon i$ – heat flow in the orthogonal direction with respect to the velocity vector; c_p – specific heat capacity at constant pressure; υ, λ – coefficient of thermal conductivity of the flowing medium; T – temperature, $i = c_p T$ – enthalpy.

To calculate the amount of heat transferred during convective heat transfer, Newton's law for heat transfer is used:

$$dQ = \alpha\left(T_l - T_S\right)dF \tag{13}$$

Where α – heat transfer coefficient, T_l, T_S – temperature of the liquid and body surface, respectively, dF – elementary surface area, dQ – amount of heat passing through the elementary area dF.

Let us write the differential equation of convective heat transfer for a homogeneous isotropic liquid using constant physical parameters (density, heat capacity, thermal conductivity, etc.). If the work of external forces and kinetic energy are small compared to the enthalpy of the medium, the heat transfer equation will be written as:

$$\rho\frac{di}{dt} = -divq + q_\upsilon \tag{14}$$

For incompressible fluid $\rho = const$, the enthalpy value can be determined from the integral $i = \int_0^T c_p dT$. Taking this into account, equation (14) will take the form:

$$\frac{dT}{dt} = \frac{\lambda}{c_p\rho}\nabla^2 T + \frac{q_\upsilon}{c_p\rho} \tag{15}$$

To solve this equation, it is necessary to know the components of speed. The change in speed in time and space is described by differential equations of motion, which can be written in vector form:v_x, v_y, v_z.

$$\rho\frac{d\upsilon}{dt} = \rho g - divp + \eta\nabla^2\upsilon \tag{16}$$

where g is the acceleration of free fall, p is pressure, η – coefficient of dynamic viscosity.

2.2.4 Formulation of the problem

The study of the form of fluid and gas flow in the plasmatron will determine the thermal load during operation on the constituent elements of the plasmatron. The study examines the flow of plasma through the working channel of the plasma torch, the flow of coolant through the cooling channel, heat transfer from the working gas to the elements of the plasma torch and to the coolant; the study also models the boundary layer for plasma and liquid flows. The study is carried out in a software product for FE analysis. The FE mesh is constructed in such a way that it is possible to simulate the boundary layer. As a result, the dominant physical phenomena that occur in the design of the plasma torch will be highlighted.

3 Results and discussion

3.1 Calculation scheme

During the calculation process, the plasmatron model was simplified by excluding elements that did not make a significant contribution to the final values.

The model of the computational domains was compiled on the basis of models of the working channel and cooling channel of the plasmatron. The models were developed by filling the internal cavities of the channels. For the model corresponding to the working gas, a computational domain located immediately after the working channel was also constructed. This is necessary for modeling the processes occurring at the exit from the plasmatron.

Since the simulation determines the thermal state of the plasmatron elements, their models also need to be included in the calculation. Figures 2-4 show the complete model, which contains both models of the computational regions of the working gas and liquid, where the hydro- and gasdynamics were calculated, and models of the plasmatron elements, for which the thermodynamics were calculated.

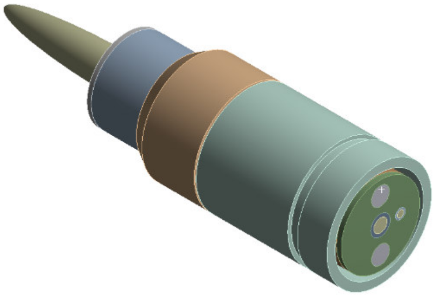

Fig. 2. Full calculation model.

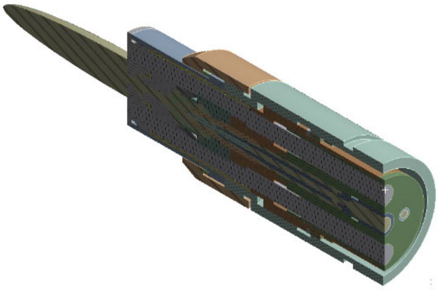

Fig. 3. Full calculation model in section A.

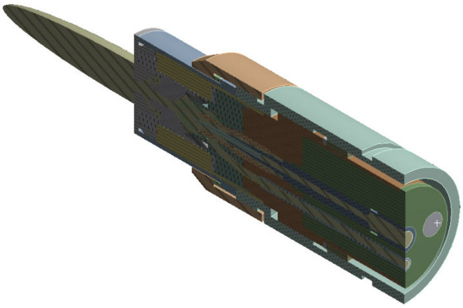

Fig. 4. Full calculation model in section B.

In the process of modeling processes in the plasmatron, a calculation scheme was developed, presented in Figures 5-7.

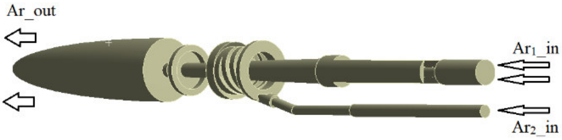

Fig. 5. Calculation scheme describing the behavior of the working gas.

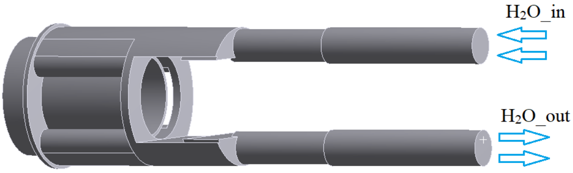

Fig. 6. Calculation diagram describing the behavior of the coolant.

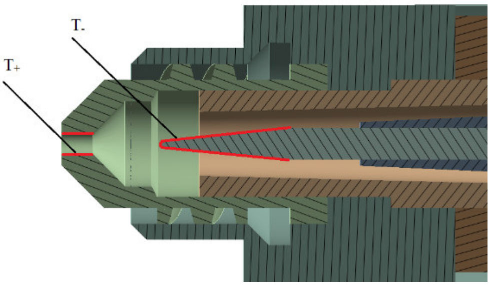

Fig. 7. Calculation diagram describing temperature distribution.

Design diagram – a model of the computational domain for the working gas, coolant and parts of the plasmatron, as well as a description of the properties of materials and boundary conditions.

When calculating, argon was chosen as the working gas, and water was chosen as the coolant.

3.2 Calculation of flow parameters of working gas and liquid and thermal state of plasmatron elements

The purpose of the finite element calculation is to study the structure of the flow in the channels of the working gas and coolant of the plasmatron, as well as to study the thermal state of its elements. The results of the calculation are the distributions of velocities, temperatures and pressures within the volume of the working area of gas and liquid. Also, the result of the calculation is the temperature distribution inside the plasmatron elements.

Figures 8-13 show the distributions of temperatures, velocities and pressures in cut planes A and B in the plasmatron model.

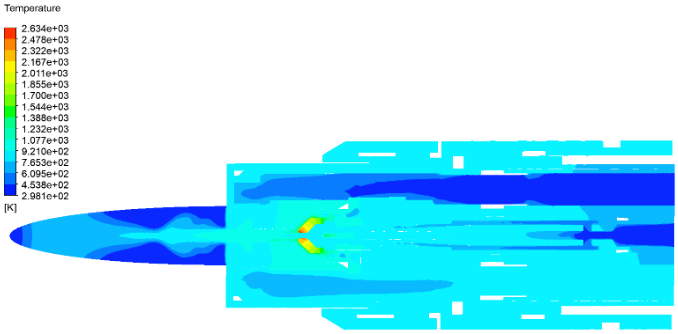

Fig. 8. Section A, temperature distribution.

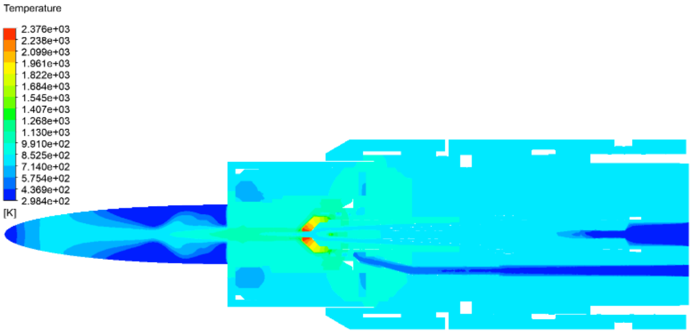

Fig. 9. Section B, temperature distribution.

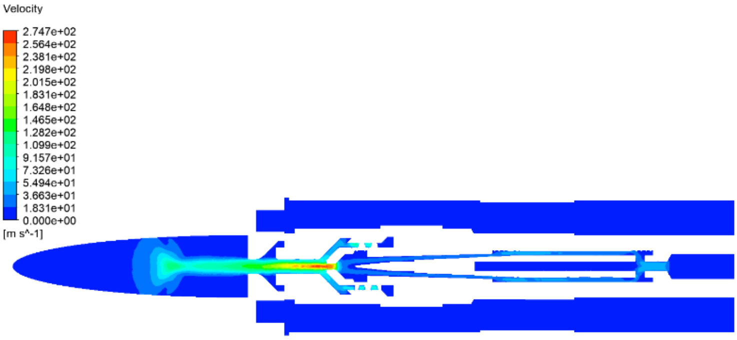

Fig. 10. Section A, velocity distribution.

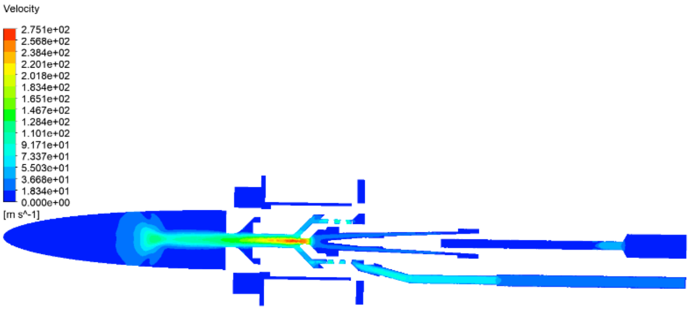

Fig. 11. Section B, velocity distribution.

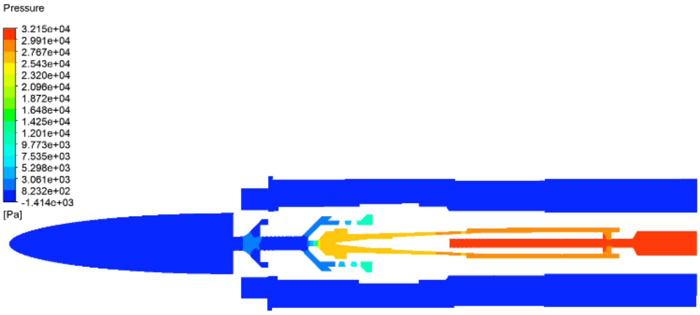

Fig. 12. Section A, pressure distribution.

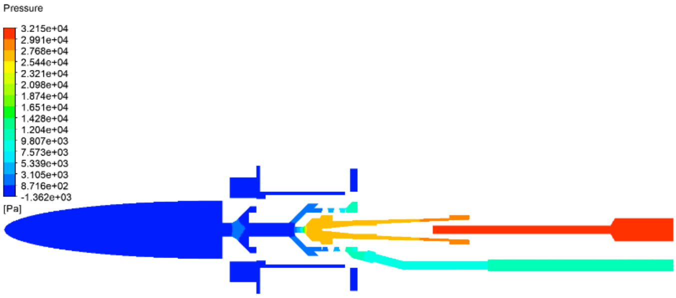

Fig. 13. Section B pressure distribution.

Thus, in plane A the maximum temperature is 2634 K; maximum speed 274.7 m/s; maximum pressure 32.150 kPa, minimum pressure -1.414 kPa.In plane B the maximum temperature is2376TO; maximum speed 275.1 m/s; maximum pressure 32.150 kPa, minimum pressure -1.362 kPa.

4 Conclusion

As a result of the research, simulation modeling of gas and liquid flow in the channels of the plasma torch was carried out in order to analyze the elements of the plasma torch during its operation. The obtained values do not exceed the maximum permissible values established in the technical requirements for the installation, which allows us to conclude that the required level of strength necessary for the safe operation of the structural element has been achieved.

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