Development of the computer model of the plasma installation

R A Okulov$^{1,2}$, E V Popov$^1$, B R Gelchinsky$^3$ and A A Rempel$^1$

$^1$ Institute of Metallurgy, Ural Branch of the Russian Academy of Sciences, Amundsen street 101, Ekaterinburg, 620016, Russia
$^2$ Federal State Autonomous Educational Institution of Higher Education «Ural Federal University named after the first President of Russia B.N. Yeltsin», Mira street 19, Ekaterinburg, 620002, Russia

E-mail: okulov.roman@gmail.com

Abstract. Mathematical model of a plasma installation for the production of metal powder and coating has been developed. The problem of creating an objective mathematical model of the plasma jet flow is solved, which adequately describes the real process and allows predicting the parameters of the plasma jet. The value of the temperature of the plasma jet at a characteristic point located on its axis is investigated. The computer model was verified by carrying out a full-scale experiment. Comparative analysis of the results of numerical and field experiments showed satisfactory convergence. It is shown that the temperature of the plasma jet flow obeys the normal Gaussian distribution. The research results can be used to improve processes and technological equipment.

1. Introduction

Improvement of technology and equipment, allowing the production of powders used as raw materials for additive technologies, is an urgent scientific and technical task [1]. Plasma spraying is widely used. A review article describing the advantages and disadvantages of the plasma method and a description of the proposed development of the technology is described in [2]. The method makes it possible to obtain powders with a dispersion of 20 to 100 microns from a wide range of metals, including refractory steels, stainless steels, titanium alloys, etc. [3]. An overview of the use of plasmatrons in additive technologies in which an in-depth analysis of existing technologies is presented and designs are described is presented in [4].

Plasmatrons have also found wide application for the deposition of protective coatings [5]. Plasma spraying of coatings has proven itself due to its advantages - high intensity, direct impact of the energy source, localized zone of impact, speed, efficiency, productivity [6-9].

A number of factors influence the outcome of the powder production and coating processes. Factors such as the temperature of the plasma jet play a special role. The value of the temperature at each point of the plasma jet is different and changes along the axis of the flow and with distance from its core in the perpendicular direction relative to the axis of the jet.

In the production of powder, metal rods or wires are used as a workpiece, which are fed into a plasma jet. The entry point of the workpiece and the feed angle relative to the axis of the plasma jet have a significant effect on the spraying result - the shape of the powder. In the coating process, powder materials are used as raw materials, which are fed into the plasma flow. The degree of heating...
depends on the point of entry, as a result, and the quality of the applied coatings. Developers and consumers of technological equipment need to take into account the temperature distribution in the space of the plasma jet to select an acceptable area for the input of raw materials. Therefore, the determination of the temperature of the plasma jet flow is an urgent task and determines the scientific significance of the presented study.

The purpose of this article is to create an objective mathematical model of a plasma installation that allows an adequate description of the plasma jet flow. The developed mathematical model is planned to be used to predict the jet parameters affecting the processes of coating and powder production. The presented mathematical model can be guided by the development of the units of the plasma installation - the device for introducing raw materials, the cooling system, the shape of the parts that form the inner channel of the plasmatron, this determines the practical significance of the results of scientific research. Based on the data of the carried out numerical experiment, it is possible to work out the processes at the stage of equipment design, which makes it possible to reduce the costs that arise as a result of commissioning, as well as to reduce the time spent in the development of the technology.

In the literature, the use of finite element analysis for solving such problems is described quite fully. There are known articles on the formation of powders by the finite element method [10]. The study [11] describes the application of a numerical study carried out to determine the growth mechanisms and the effect of the silicon fraction in a powder material for metal-silicon binary systems. In article [12], the features of the construction of plasmatrons are considered. The problem of modeling the system of gas vortex stabilization of electric arc plasmatrons was solved [13]. Despite the existing scientific groundwork, the predecessors have not solved the problem facing the presented research.

2. Description of the mathematical model and numerical experiment
As a prototype for creating a mathematical model, a laboratory plasma installation was adopted, which is used both for the production of powders and for applying coatings. The composition and a detailed description are presented in works [14-16]. The installation includes a plasmatron, the profile section of which is presented with a description in figure 1.

![Figure 1. Scheme of the section along the axis of the head of the plasmatron.](image)

- 1, 4 - gas swirl; 2 - cathode; 3 - interelectrode insert; 5 - anode.

The problem is solved numerically using the ANSYS software package, which implements the finite element method. The accuracy of the computer experiment is influenced by the size of the finite element mesh. Within the framework of this scientific study, the size of the element is chosen so that
in the most critical areas of the design model, the minimum number is 4 elements. The rationale for the choice of the size of the finite element mesh is described in detail in the article [17, 18].

Table 1 presents the initial data for the numerical experiment.

| Parameter name                                      | Value   |
|-----------------------------------------------------|---------|
| Gas type                                            | Argon   |
| Plasma-forming gas consumption (l / min)            | 50      |
| Plasma jet core temperature (K)                     | 7000    |
| Chiller cooling capacity (kW)                       | 135     |
| Plasma-forming gas pressure (atm.)                  | 1.5     |
| Average size of the finite element mesh (mm)        | 0.24    |
| Length of the confuser section of the anode (mm)    | 58      |
| Anode inlet diameter (mm)                           | 11      |
| Anode outlet diameter (mm)                           | 8       |

To estimate the error of a numerical experiment using the method described in [19], direct multiple equal-accuracy measurements of the same physical quantity - the temperature of the plasma jet flow at a characteristic point were carried out. A point located on the axis of the plasma flow, at a distance of 19 mm from the end surface of the anode, was chosen as a characteristic point.

As a result of 25 parallel computer experiments, the temperature value was measured at a characteristic point and a number of values were obtained: 3657.20; 3654.93; 3653.32; 3650.14; 3647.02; 3660.40; 3648.22; 3661.50; 3658.55; 3653.73; 3655.79; 3661.41; 3656.82; 3659.44; 3644.75; 3660.67; 3653.19; 3646.74; 3656.08; 3657.82; 3659.43; 3659.87; 3659.2; 3662.1; 3661.8 K.

After processing the measurement data, it was found that the mathematical expectation \( \mu \) is 3656.01 K; the root-mean-square deviation \( \sigma \) is 5.17 K. Figure 2 shows a histogram.

![Figure 2](image.png)

The results of multiple measurements in the presence of random errors are formed under the influence of a large number of independently acting factors. On this basis, we can assume that in the absence of any dominant influence, the results of direct multiple measurements obey the Gaussian normal distribution.

3. Verification of the results of a numerical study and description of a full-scale experiment

In order to verify the results of the theoretical experiment, a full-scale experiment was carried out to establish the temperature value at a characteristic point. For this, a rod with a diameter of 3 mm made of lanthanum tungsten TU 48-19-27 was used, the melting temperature of which is 3653 K. trapped in the manipulator. The manipulator was located at a distance of 0.5 m from the plasmatron. Further, the
manipulator with the rod fixed in it was gradually moved at a constant speed of 20 mm/min parallel to the axis of the plasma flow towards the plasmatron. The distance from the rod to the end plane of the anode was recorded. Also in the full-scale experiment, an optical pyrometer (type EOP-66 No. 240 GOST 5.278) was used, which was used to measure the surface temperature of the free end of the bar. At the moment when the melting process begins on the bar surface, the data from the pyrometer scale and the distance from the bar to the plasmatron were recorded. A description of a full-scale experiment is presented in more detail in [20-23].

The parameters of the gas flow rate and its type corresponded to the data used in the computer experiment. Conducted three parallel full-scale experiments. The results were averaged and compared with the results of a numerical experiment (table 2). It was found that the actual melting temperature of the bar material deviates from the theoretical insignificantly and fluctuates within the root-mean-square deviation \( \sigma \).

| Numerical experiment (mm) | Full-scale experiment (mm) | Measurement error (%) |
|--------------------------|----------------------------|-----------------------|
| 19                       | 20                         | 5                     |

The results of the comparative analysis showed satisfactory convergence.

4. Recommendations and practical significance of research results

The practical significance of the results of the work performed lies in the creation of a mathematical model, the use of which allows predicting the temperature distribution of the plasma jet. Based on the data of a numerical experiment, it is possible to predict the temperature of the plasma jet, which makes it possible to choose the most rational point of input of raw materials for the processes of powder production and coating. The presented results can be useful for improving technological equipment, as well as in its design.

5. Conclusions

Mathematical model of a laboratory plasma installation designed for coating and powder production has been created. To assess the statistical error, a number of parallel experiments were carried out and methods of statistical data processing were used. A histogram of the distributions of the results of measurements of the numerical experiment was constructed and it was demonstrated that the distribution of the studied quantity at the characteristic point obeys the normal Gaussian distribution law.

A full-scale experiment was carried out to confirm the results of the computer experiment. The results of the comparative analysis showed satisfactory convergence. It is confirmed that the mathematical model objectively describes the flow of a plasma jet. It was found that the actual melting temperature of the bar material deviates from the theoretical insignificantly and fluctuates within the root-mean-square deviation.

The results are of practical importance, since they make it possible to predict the temperature of the flow, which is required when determining the point of entry of raw materials.

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