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Numerical simulation of DC air plasma torch modes and plasma jet instability for thermal spraying technology

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Abstract. The article is dedicated to nonstationary simulation of DC air plasma torch. The mathematical model for the analysis of plasma jet instability is developed. The proposed 2D axisymmetric model demonstrates the physical processes taking place inside and in the outer region of the plasma torch. The influence of the power source parameters and anode geometry on voltage and plasma jet fluctuation is described. Simplified mathematical model is developed in order to assess the effect of the flow behavior on heat transfer processes. The developed model can be used for the design of plasma torches and their operation modes. The results of mathematical model verification are based on experimental studies.

1 Introduction

Application of thermal plasma technology is widespread in modern electro-technological processes related to the effective heat transfer to materials. The plasma spraying technology is one of the main examples of arc discharge, where the plasma flow generated by the plasma torch is used as a tool. Melting of material is carried in the formed flow for deposition on a work surface.

The main trend of plasma spraying technology development is increasing the productivity of the spraying process and providing specified characteristics of the sprayed coating (porosity, adhesion, etc.)[1]. The efficiency of plasma spraying technology and the quality of the applied coating mainly depend on the properties of powder materials and the characteristics of the plasma flow. That is why the main task in the technological development of new plasma torches for spraying is to obtain optimal flow parameters and operation modes of the plasma torch, providing high service life of the plasma torch's constructive elements [2-5].

The main problem in the design of plasma torches is a lack of hydrodynamic processes understanding and stabilization of the arc inside the plasma torch's channel. Attempts to stabilize the arc and plasma jet led to the development of the new plasma torch's geometry (see. Fig.1).

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A modern study of physical processes in a plasma torch is based on the development and verification of magneto-gas dynamics mathematical models [6-8]. Because the application of numerical simulation methods reduces the development costs of plasma torches and can predict the optimum operation modes. But there are some difficulties of non-stationary mathematical model creation and one of them is the consideration of instability phenomena. The instability phenomena of the plasma flow can be divided into two categories (separation conditionally):

- Force instability (associated with momentum fluctuation).
- Thermal instability (associated with Joule heating fluctuation).

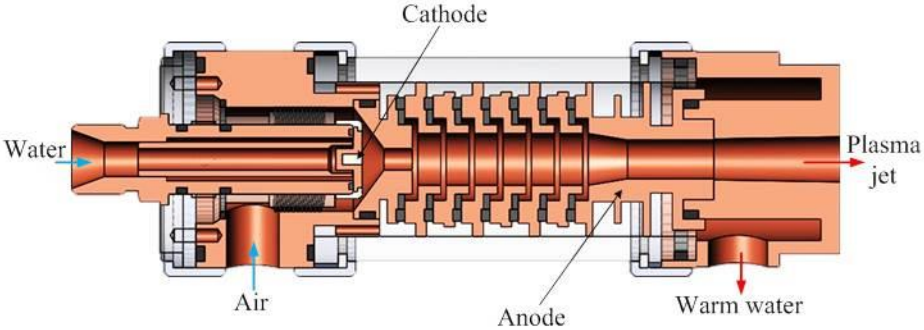


Fig. 1. The construction of PN-V1 plasma torch (with inter-electrode sections).

Force instability phenomenon of thermal plasma is due to the presence of a high temperature gradient and velocity shear (Kelvin-Helmholtz instability) and density-difference (Rayleigh-Taylor instability). The development of instability leads to changing of plasma flow behavior (laminar/turbulent).

Thermal instability phenomena is due to arc attachment in the plasma torch channel and characteristics of power sources used. The period of the temperature field fluctuation is comparable to the melting time of the powder inside plasma flow and it is the determining factor of spraying process efficiency.

Basic criteria of the sprayed coating quality are porosity and adhesion [9-13], and these depend on conditions of plasma flow directly [3, 11].

2 Experimental and theoretical investigations

The development of modern computer systems radically changed the direction of new technologies development towards numerical simulation in the industry in order to reduce time and money costs. The development of a plasma torch mathematical model is a combination of electromagnetic, gas dynamics and heat transfer tasks [13-19], thereby representing a multi-physical task.

2.1 Investigation of the plasma torch

The following assumptions are used for creation of two-dimensional non-stationary mathematical model:

- Plasma is optically thin.
- Plasma is in local thermodynamic equilibrium (LTE).
- Plasma is considered as a single-phase flow.
- Pressure and viscous dissipation work is not taken into account.
- Near-electrode processes are not taken into account.

The computational domain is shown in Figure 2. It corresponds to the real geometry of the plasma torch (PN-V1).

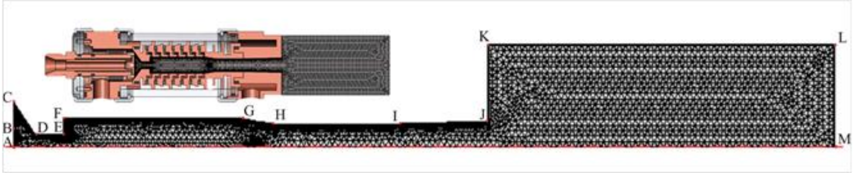


Fig. 2. The computational domain for numerical simulation.

The boundary conditions for computational domain are shown in Table 1.

Table 1. Boundary Conditions.

A-B cathode	**B-C inlet**	**C-G wall**	**G-H anode**	**H-J wall**	**J-M outlet**	**M-A**
T_{cath}	T_{inlet}	$q=h(T_{ext}-T)$	T_{anode}	$q=h(T_{ext}-T)$	$T_{,n}$	Axial symmetry
$\upsilon=0$	$\upsilon=\upsilon_{in}$	$\upsilon=0$	$\upsilon=0$	$\upsilon=0$	$p_{,n}=0$	
$-\sigma\varphi_{,n}=J_{cath}$	$\varphi_{,n}=0$	$\varphi_{,n}=0$	$\varphi=0$	$\varphi_{,n}=0$	$\varphi_{,n}=0$	
$A_{,n}=0$	$A=0$	$A_{,n}=0$	$A_{,n}=0$	$A_{,n}=0$	$A_{,n}=0$	

Air properties were used as properties of the plasma forming gas (depending on the temperature). Properties of sprayed materials are not included in the calculation. Basic equations of the non-stationary mathematical model:

– Heat balance equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{\upsilon} \nabla T - \lambda \nabla T = Q_s - Q_{rad}, \tag{1}$$

where T – plasma flow temperature; $\rho = f(T)$ – temperature-dependent plasma density; $C_p = f(T)$ – temperature-dependent plasma heat capacity; $\lambda = f(T)$ – temperature-dependent thermal conductivity; $\boldsymbol{\upsilon}$ – plasma velocity vector; $Q_{rad} = f(T)$ – temperature-dependent radiation power density; Q_s – heating source density (Joule heating).

– Maxwell's system of equations:

$$\begin{cases} \boldsymbol{J} = \left(\sigma + \varepsilon_0 \varepsilon \frac{\partial}{\partial t}\right) \boldsymbol{E} \\ \boldsymbol{E} = -\nabla V \\ \sigma \frac{\partial \boldsymbol{A}}{\partial t} + \nabla \times \mathbf{H} = \boldsymbol{J} \\ \boldsymbol{B} = \nabla \times \mathbf{A} \end{cases}, \tag{2}$$

where $\sigma = f(T)$ - temperature-dependent electrical conductivity; $\varepsilon = 1$ – plasma relative permittivity; ε_0 – absolute permittivity.

– Momentum equation:

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho(\boldsymbol{v}\nabla)\boldsymbol{v} = \boldsymbol{F} + \nabla[-pI + \mu(\nabla \boldsymbol{v} + (\nabla \boldsymbol{v})^T)], \tag{3}$$

where $\boldsymbol{F}$ – forces acting on the plasma flow (Lorentz force); I – identity matrix; $\mu = f(T)$ – temperature-dependent plasma viscosity.

– Continuity equation:

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \nabla(\rho \boldsymbol{v}) = 0 \tag{4}$$

The calculation is carried out using Comsol Multiphysics software. The distributions of temperature, velocity and etc. are obtained. It is revealed in the course of the analysis that one of the main destabilization factors affecting the efficiency of the spraying process is Joule heating fluctuation. These fluctuations can be compensated by changing the diffuser angle of the existing plasma torch PN-V1 design (see Figure 3).

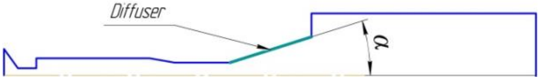


Fig. 3. Demonstration of the diffuser angle (geometry of the plasma torch PN-V1 channel).

The simulation results for different diffuser angles are shown in Figure 4.

The estimation of numerical simulation results correctness is carried out by comparing experimental studies and simulation results. Verification of the mathematical model is carried out using experimental data on arc voltage and the methods of spectral diagnostics (for more information see[20-23]). Radial temperature distributions at different distances from the output of the plasma torch are obtained from the results of spectral diagnostics. Experimental and numerical studies results comparison for the plasma torch operating mode with gas consumption 0.55 g/s and arc current 180 A is shown in Figure 5.

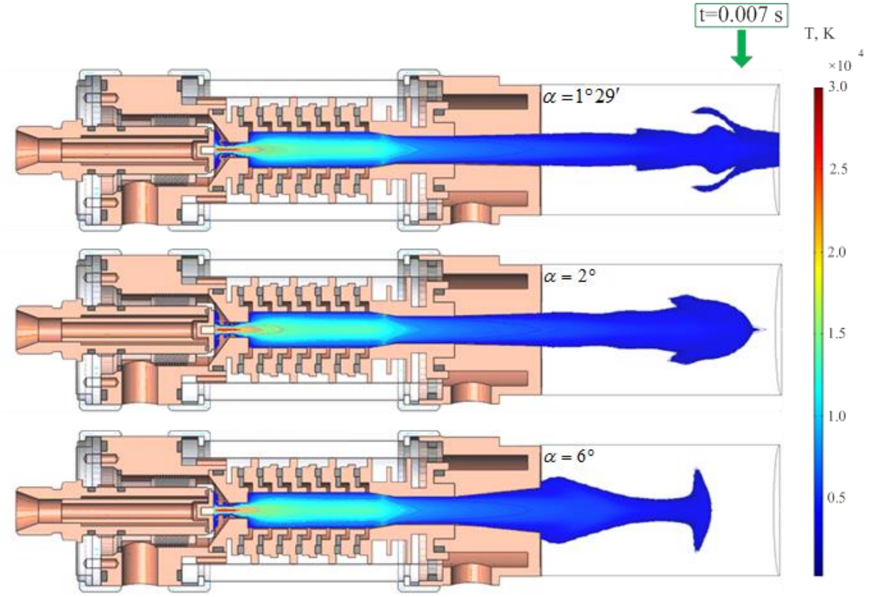


Fig. 4. Temperature distribution for different diffuser angles at the same simulation time.

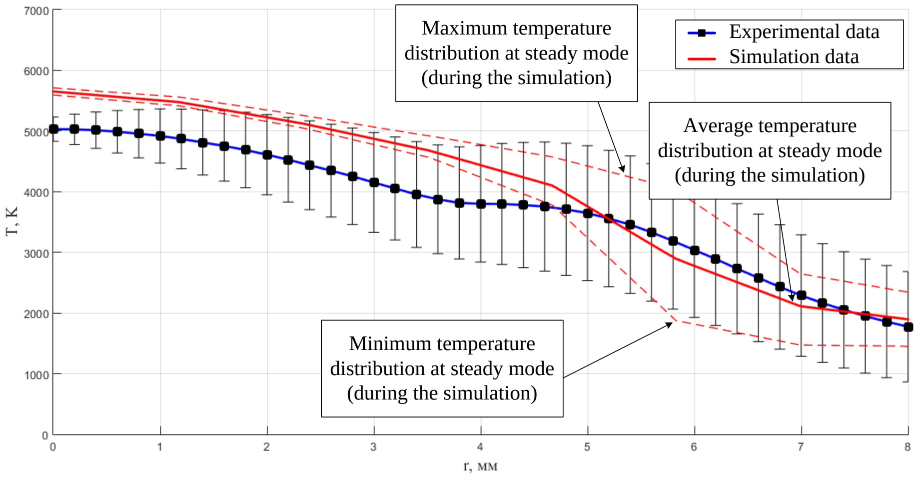


Fig. 5. Radial temperature distributions at the distance 11mm from the output of the plasma torch.

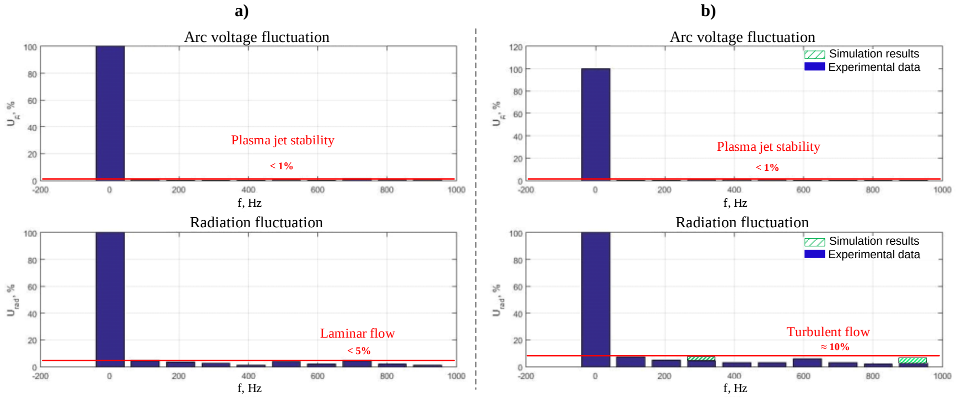
2.2 Research of the plasma torch operating modes

The experimental bench was designed to conduct research and verify the mathematical model. In the course of the experimental study of the plasma torch PN-V1 (using various power sources) the following characteristics are obtained:

- Arc voltage.
- Radiation power fluctuation.
- Arc current.
- Pressure fluctuation.

The characteristic the plasma torch operating modes were established using this experimental bench. An optical sensor (allowing to register the fluctuation data with frequency up to 30 kHz) was used to identify temperature fluctuation (radiation power fluctuation) at the plasma torch output. The data obtained make it possible to estimate the stability of the plasma jet. Sensors of increased sensitivity were used to identify the behavior of the plasma flow. The plasma torch operating modes corresponding to the laminar and turbulent flows were established by the results of the study. The data post processing was carried out with the discrete Fourier transform algorithm.

The results of the experimental study corresponding to stable (power fluctuation) laminar flow are shown in Figure 6a. The results of the experimental study corresponding to stable (power fluctuation) turbulent flow are shown in Figure 6b.



Gas consumption 0.55 g/s Gas consumption 1.25 g/s

Fig. 6. Experimental results of the plasma torch PN-V1.

Strong temperature gradient near the surface of the particle during gas-dynamic interaction (accompanied by heat transfer processes between the plasma and the body) is the thermal boundary layer. The thickness of the thermal boundary layer exceeds the thickness of the gas-dynamic boundary layer (see [3, 4, 10]). The thickness of the boundary layer and the behavior of the plasma flow exert a significant influence on the heat transfer processes between the plasma and the body. Heat transfer is mainly due to the mechanism of thermal conductivity in the laminar plasma flow. The coefficient of air plasma thermal conductivity does not exceed 6 W/(m·K), then the thermal boundary layer is a significant thermal resistance. The value of thermal resistance decreases due to active mixing of the medium inside the boundary layer in the transition from laminar to turbulent flow. Simplified mathematical model is developed in order to assess the effect of the flow behavior on heat transfer processes, which is a non-isothermal laminar and turbulent flows with a solid body inside (properties of Al_2O_3).

Analysis of turbulent flow simulation results demonstrates chaotically occurring velocity and pressure pulsations, which leads to intensive mixing of the medium and more efficient heat transfer. The efficiency of heat transfer processes in laminar and turbulent flows can be estimated from the average temperature of the heated body (see Figure 7).

More intensive heating of the particle is carried out in the turbulent flow due to the destruction of the boundary layer by impulsive action and active heat transfer due to the mixing of the flow layers. This is an important factor in the use of refractory materials in thermal spraying technology. In addition, the results of this analysis indicate the need for a laminar flow inside the plasma torch (to increase the service life) and turbulent flow at the output of the plasma torch for more intensive heating of the particles.

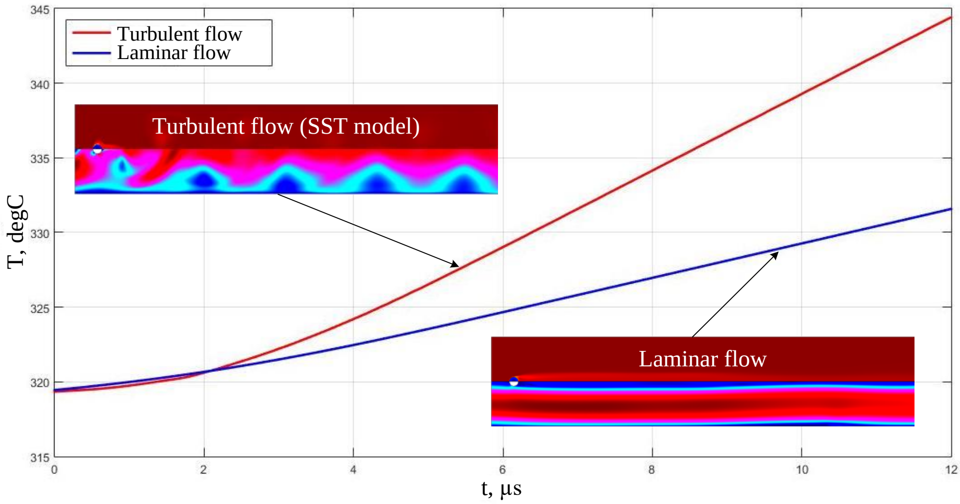


Fig. 7. Dependence of the average particle temperature on time.

3 Conclusions

Nonstationary mathematical model of DC plasma torch is developed based on the generally accepted laws of physics.

The mathematical model is verified by the comparative analysis of results taking into account the nonstationary plasma flow and the post processing error of numerical simulation and experimental studies.

The analysis of the plasma torch elements effect with inner-electrodes sections on the stability of the plasma flow is presented. According to the results of the study, the optimal value of the diffuser angle is from 2° to 6°. The diffuser angle increasing leads to a "shortening" of the plasma jet and the formation of detached flows at the angle value more than 6°. Analysis of the numerical simulation results of heat transfer processes demonstrates more intense heating (almost 2 times) of the sprayed particle in the turbulent plasma flow.

The plasma torch operation modes (provide a stable plasma flow with an efficiency increasing of heating process at the expense of turbulent plasma jet) were established based on the experimental study results.

The efficiency of the particle heating process increases when passing from a laminar flow to a turbulent flow (almost 2 times). These results make it possible to increase the spraying process productivity the refractory material from 4 kg/h to 7 kg/h without reducing the quality of the applied coating.

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