Numerical simulation of hydrodynamic flows in the jet electric

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Abstract. On the basis of concepts from magnetic hydrodynamics the mathematical model of hydrodynamic flows in the stream of electric arc plasma, obtained between the rod electrode and the target located perpendicular to the flat conductive, was developed. The same phenomenon occurs in the welding arc, arc plasma and other injection sources of charged particles. The model is based on the equations of magnetic hydrodynamics with special boundary conditions. The obtained system of equations was solved by the numerical method of finite elements with an automatic selection of the time step. Calculations were carried out with regard to the normal plasma inleakage on the solid conducting surface and the surface with the orifice. It was found that the solid surface facilitates three swirling zones. Interaction of these zones leads to the formation of two stable swirling zones, one of which is located at a distance of two radii from the axis and midway between the electrodes, another is located in the immediate vicinity of the continuous electrode. In this zone plasma backflow scattering fine particles is created. Swirling zones are not formed by using the plane electrode with an orifice. Thus, the fine particles can pass through it and consolidate.

1. Introduction

Investigation of the interaction of electromagnetic fields, flows of particles, plasma with a solid body and its application in various areas of technology and production evokes interest to the problems associated with the study of electrical gas discharges. For practical application of the gas discharge device it is necessary to determine the dependence of plasma characteristics on external controlled parameters (pressure, type of gas and its consumption, electric current, voltage, geometric dimensions, incoming power of the electromagnetic field, etc.): to control processes of plasma maintenance and generation; select optimal operating conditions according to specific plasma technologies. Solution of these problems is possible through a comprehensive experimental study and mathematical modeling of electrical discharges. Basics of theoretical description of the physical processes, occurring in the gas-discharge plasma, are described in [1], where it is noted that magnetogasdynamic (MGD) description of plasma is effective within the limits of applicability of the continuous medium approximation as well as the fundamental kinetic approach. The technology of plasma arc is most widely used in engineering, especially in metallurgy, powder spraying, welding, etc. In the process of welding by consumable electrode a conductive thermal plasma is formed. Its properties, mode parameters greatly affect the processes of formation of the metal bath of the substrate, where the properties of the
modified surface are formed. Therefore, the numerical modeling of hydrodynamic and thermal fields is an important tool in the creation of surface modification technologies [2]. In [3 – 8] numerical studies with regard to the above mentioned processes are carried out. In [3] the influence of the cathode shell on the temperature field is studied. It is found that different potential boundary conditions on the back surface of the anode plate do not substantially affect the heat flow in the cathode or within the arc but influence the current density and the temperature distribution near the anode plate. When a single computational domain comprises cathode and anode arcs, additional conditions at the boundary “plasma-electrode” to account the energy flows through it should be used. For the electric current of 200 A calculation of isotherms gives a satisfactory agreement with the experiment. In [4] the formation of self-organizing structures of electrodes is studied. As a result a three-dimensional two-temperature simulation model is developed, which shows gradual emergence of a point structure alongside the increasing level of anode cooling; from one blurred spot for low levels of cooling to subsequent coating of the anode zone by small spots for intensive cooling. Paper [5] is devoted to comparison of turbulent flow models for a free burning of a high-intensity argon arc. Navier-Stokes equations are modified in the paper by taking into account the radiation transport, electric power consumption and electromagnetic forces. For modeling of turbulence, which has a value for the arc boundary due to the sharp temperature gradient between the arc column and the surrounding gas, zero- and two- viscosity equation is used. It is found that this model best describes the temperature profiles in the arc.

Works [6 - 8] are devoted to the study of processes occurring in the molten bath during plasma exposures. In [6] the problem of investigation of heat transfer and the fluid flow during pulsed arc welding of stainless steel is solved by the method of finite elements. The proposed model allows to study evolution of the weld pool in time at a constant and pulsed current. In [7] the numerical simulation was supplemented by experiments using high-speed shootings of the weld pool surface in the infrared. Processing and analysis of the images showed good agreement with the numerical model.

In [8] on the basis of the equilibrium magnetogasdynamic model the calculation of the flow and heating of gas (argon) in the diaphragmatic plasmatrone’s channel depending on the diaphragm position and size, consumption and gas swirling intensity is performed. Peculiarities of changes of the arc characteristics in the channels of variable section for swirling and non-swirling flows are revealed. It is shown that diaphragming of the channel in the conditions of an intensive gas swirling ensures in the area up to the diaphragm localization of plasma flow in the narrow near-axial zone having a clear thermal interface with an external gas flow (effect of the swirling thermal insulation of plasma); the length of the stabilization area depends on the sizes of the diaphragm aperture and its position in the channel. In [9] a numerical study of the microwave discharge in the argon flow, axially injected into the coaxial with a shortened inner electrode, was performed. It was established that an important role in the formation of a microwave discharge plays the inner electrode’s section, and the cold gas “blown” through its channel cooling the wall, stabilizes burning of the microwave discharge and contributes to the formation of a sharp leading heat edge.

Thus, we must conclude that at present time the modern trends of modeling of plasma effects target creation of a unified mathematical model that describes the processes in the area adjacent to the cathode as well as in the molten bath. Therefore, the aim of our work is to simulate hydrodynamic flows in the diaphragmatic electric arc.

2. Problem formulation

The model based on the equations of Navier-Stokes, thermal conduction and Maxwell’s equations is used for the simulation of the plasma flow and temperature distribution in it.

Let us consider the cylindrical electrode with one of its ends having a hemispherical shape, another electrode we shall assume to be flat (Figure 1). On the border of GD (plasma/anode) the heat flow for the anode is set by the sum of the heating from plasma, heating from electron condensation \( \mathbf{j} \cdot \mathbf{n} \varphi_a \) (where \( \varphi_a \) is the work function of anode electrons) and radiation losses \( \alpha \sigma T^4 \) (where \( \varepsilon \) – anode
emissivity, $\sigma_B$ – Stefan-Boltzmann constant). At the border of EB (plasma/cathode) the heating from plasma, ion heating $j_i V_i$, radiation losses $\sigma_T B^4$ and thermoionic cooling $j_e \varphi_c$ (energy required for electron emission from the cathode, which is given by the product of electron current density and work function of cathode material) contribute into the heat flow. The boundary conditions for Maxwell’s and magnetohydrodynamic equations are provided in Table 1. The material properties accepted for calculations are given in Table 2. Kinetic parameters of plasma (specific heat, thermal conductivity, viscosity, conductivity) depend on the temperature and are given in a tabular format.

![Figure 1.](image)

**Table 1.** Boundary condition

| AB | BC, CD | DE | EF | AE, FG | EG |
|----|--------|----|----|--------|----|
| $T, q$ | $-\vec{n} \cdot \vec{q} = 0$ | $T_0$ | $T_0$ | $T_0$ | $\vec{n} \cdot \vec{q} = 0$ |
| $(u, v, w)$ | $p = p_0$ | $-\vec{n} \cdot \vec{v} = 0$ |
| $(V, \vec{A})$ | $\vec{j} \cdot \vec{n} = \frac{I_c}{\pi R_c^2}$ | $\vec{j} \cdot \vec{n} = 0$ | $\vec{j} \cdot \vec{n} = 0$ | $V = 0$ | $\vec{j} \cdot \vec{n} = 0$ |

**Table 2.** Material properties of the cathode, anode and gas

| Symbol | Nomenclature | Value |
|--------|--------------|-------|
| $\rho_m$ | Density anode and cathode metal | 7500 kg m$^{-3}$ |
| $C_m$ | Specific heat of metal | 602 J kg$^{-1}$ K$^{-1}$ |
| $k_m$ | Thermal conductivity of metal | 26 W m$^{-1}$ K$^{-1}$ |
| $\sigma_m$ | Electrical conductivity of metal | $7.7 \times 10^5 \Omega^{-1}$ m$^{-1}$ |
| $\varphi_c$ | Surface work function of cathode | 4.52 V |
| $V_i$ | Plasma’s ionization potential | 15.68 V |
| $\varphi_a$ | Surface work function of anode | 4.65 V |
| $\varepsilon$ | Surface emissivity | 0.9 |
3. Results and discussion

System (1), (2) with regard to the boundary conditions is solved by the finite element method for the case of aperture’s absence and its presence. The cathode is a cylinder limited by hemisphere of the same radius, the radius is 0.8 mm, the anode in the first case is a plane and in the second case – a plane with an aperture of 2 mm radius. Distance from the cathode to the anode (EG) is 3.8 mm. On the cathode the current density is set, so that the total current is 100 A. On the anode it is assumed that the potential is zero. The initial conditions correspond to the quiescent gas and electrode material. The temperature at the initial time for the entire area is constant and equals to 300K. The initial density is chosen to be constant for each zone: for the cathode and anode – steel density, for the interelectrode gap – air density. Step on the spatial coordinate is 0.1 mm. The time step is automatically chosen basing on the Courant-Friedrichs-Lewy condition.

First, we shall analyze the case of diaphragm’s absence. In moments of times up to 1 μs the flow in the plasma jet is non-stationary. From the cathode to the anode propagates the temperature wave and in the flow zone three swirling zones are generated (Figure 2 a). One of them, in the vicinity of the cathode and the symmetry axis, is due counter-propagating jets. These jets are generated because of the action of the radial component of the electromagnetic force directed toward the axis. Near the symmetry axis approximately at the midway between the cathode and the anode the second swirling zone is located. In the subsequent moments the interaction of these zones results in the formation of one stable swirling zone at a distance of two radii from the axis. The third swirling zone is formed near the anode at the moment of time 0.1 μs and is observed during the calculation time.

Thus, the plasma transits from essentially non-stationary state into a quasi-stationary. It is induced by the viscous and electrodynamic forces. The flow has a complex structure and includes the zones: close to the electrode, the near-axial flow with a shock transition, two swirling zones. The velocity distribution on the axis is shown in Figure 2 b, which implies that the velocity of plasma arc, starting from zero speed (E – cathode surface) reaches maximum ~500 m/s at a distance of 1 mm from the cathode surface, and then drops to zero and changes the sign. Analytical models and numerical calculations with large spatial steps do not reveal these features.

![Figure 2. Velocity field of arc. (a) – streamlines at t=1.1 μs; b – streamlines at diaphragm](image-url)
particles 100 nm from the molten material. The second, the swirling zone near the anode creates a plasma counter-current, which does not allow the fine particles to reach the anode surface and participate in the coating formation. Therefore, we propose to use an orifed anode. The calculations with an orifice are given in Figure 2b, which shows that the swirling zones are not formed and it can be used to develop welding technology.

4. Conclusion
Mathematical model of hydrodynamic flow in the plasma during electric arc welding is developed. It is shown that at times $t < 1 \mu s$ three swirling zones are formed. Formation of the first swirling zone, and its existence $\sim 1 \mu s$, create conditions for generation of fine particles. However, the presence of plasma backflow near the anode does not allow them to get on the surface of the modified material. The diaphragm in the electrode leads to the fact that the swirling zones are not formed and the fine particles can be consolidated.

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