https://doi.org/10.37434/tpwj2020.11.08

DIAGNOSTICS OF HYDROGEN-OXYGEN PLASMA JET FOR APPLICATION IN THERMAL SPRAYING

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The problem of obtaining a low-temperature plasma jet, where the plasma-forming gas is a hydrogen-oxygen mixture produced by electrolysis-water generators, was considered. The aim of the work is to determine the size of the active zone of the jet, along the length of which the melting and heating of the particle takes place, and to control it by changing the nature of the flow. In the course of diagnosing the plasma jet, the distribution of temperature, velocity and effective thermal power depending on the nature of the jet flow was determined. It was determined that the sizes of the active zone of the plasma jet can be 1.4 times larger at a laminar nature of the flow than at a turbulent one. The maximum temperature is observed in the arc part of the plasmatron and amounts to 8400 ± 1000 K, in the jet of hydrogen-oxygen plasma the average temperature is 5000 ± 500 K. Taking into account the results of the diagnostics, the material for plasma spraying and distance can be chosen. 19 Ref., 1 Table, 2 Figures.

Keywords: hydrogen-oxygen plasma jet, laminar, turbulent nature of flow, sizes of active zone of the jet, plasma spraying

The use of high-enthalpy gases and mixtures as a plasma-forming medium in the technologies of thermal coating is one of the modern research directions. It is known that to produce coatings with a high-quality performance applying thermal methods of deposition, the preference is given to the jets with high kinetic and thermal parameters, because an increase in these parameters leads to a more intense heat exchange between the plasma jet and sprayed particles.

The ability to control the power and specific energy characteristics of the plasmatron by changing the composition of the plasma-forming gas allows predicting the characteristics and comparative sizes of plasma jets obtained from different plasma-forming media. As a determining factor of efficiency of applying such a jet, the sizes of an active zone of a plasma jet can be chosen, in which heating, melting and acceleration of particles of the material during thermal spraying is possible.

Such a source can be a plasma jet using a hydrogen-oxygen mixture (HOM) as a plasma-forming medium, which is produced by electrolysis-water generators. Obtaining plasma-forming gas directly at the workplace makes the technological process of thermal treatment of materials mobile and the absence of cylinder, transport and storage facilities reduces the cost. In addition, in terms of influence on environment and human health, such a mixture during flaring and plasma generation reduces the amount of harmful substances.

One of the components of the hydrogen-oxygen mixture is hydrogen, which during ionization has high thermophysical properties and is a highly efficient converter of electric energy into heat.

Analysis of the technical literature showed that the use of hydrogen-oxygen plasma in the processes of thermal treatment of materials is almost absent, and the use of hydrogen as a plasma-forming additive in the amount from 10 to 30 % in plasma-forming gases is an outdated information, more modern is the use of steam-water plasma [1–4].

Dissociation of hydrogen starts at a temperature of 2000 K, 90 % occurs at a temperature of 4700 K and ends completely at a temperature of 6000 K. In this temperature range, hydrogen has an extremely high thermal conductivity [5].

The temperature and enthalpy of hydrogen plasma under standard conditions are presented in Table. Depending on changes in physical conditions, these indices can increase significantly. During electric arc heating, the hydrogen-oxygen mixture as a plasma-forming gas can decompose into 23 neutral and charged components [6]. To simplify the determination of thermophysical properties, such dissociated products can be used as H_2, H, O_2, O, OH, H_2O + H. By theory, the dependence of enthalpy on plasma temperature of different gases can be determined using the reference literature [7, 8]. In practice, these physical characteristics and other may differ significantly,

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taking into account changes in pressure, consumption and composition of the gas mixture.

The use of diatomic gases leads to a sharper increase in arc voltage (Table). In this case, the energy of the arc is also used to dissociate gas molecules into atoms. The arc voltage increases significantly while using a gas that has a high heat capacity and thermal conductivity.

The peculiarity of HOM is featured by the ratio between the volume of oxygen VO_2 and hydrogen VH_2 in the mixture obtained by electrolytic decomposition of water $2H_2O = 2H_2 + O_2$, constant and equilibrium $\beta = VO_2/VH_2 = 0.5$. At this ratio of components in the mixture, the plasma jet has an oxidizing potential.

A positive factor may be the fact that the presence of oxygen in hydrogen volume in the ratio 2:1 increases kinetic characteristics of the jet by increasing the density of the plasma-forming mixture.

However, oxygen as a plasma-forming gas has a lower ionization potential than nitrogen, so due to the lack of electrons, the oxygen atom will seek to compensate for it by electrons couple bound with hydrogen. As a result, HOM may have a lower ionization potential and a higher degree of dissociation than hydrogen, respectively, and the values of arc voltage will be lower than the values given in Table.

The choice of the mixture as a plasma-forming gas medium is determined by the possibility of its use in the existing plasmatron and a reliable operation of the anode and cathode units of this plasmatron, as well as the process technology.

The efficiency of using depends on the design of the plasmatron that generates plasma from the plasma-forming mixture. The main directions of improvement of typical designs of plasmatrons are oriented on modification of their separate units and elements to increase their efficiency factor [11].

Due to the fact that HOM is explosive, high safety requirements should be provided in the development of equipment and technological processes. Lack of information and investigations on the thermophysical characteristics of low-temperature hydrogen-oxygen plasma and evaluation of their impact on thermal processes hinders the development and implementation of HOM in the production.

The aim of the work was to generate low-temperature hydrogen-oxygen plasma of atmospheric pressure obtained by electric arc heating and to diagnose the thermophysical properties of the jet in relation to application in the plasma coating method.

For this purpose the following equipment was used: electrolysis-water generator of monopolar type A1803UKhLCh with the maximum efficiency on HOM production — 1.6 m^3/g; power source of inverter type CUT-40 for plasma cutting with an open-circuit voltage of 300 V and the maximum current of 40 A [12]. As the basis for the design of the plasmatron the cathode unit of the microplasma torch OB-1160A was used in the system MPU-4 [13].

Data on plasma formation in different gases [9, 10]

Gas	Energy supplied to the plasmatron, kW	Plasma temperature, °C	Plasma heat capacity, kcal/kg	Voltage on the arc, V	Energy utilization factor for gas heating, %
Ar	48	14000	4670	40	40
He	50	20000	51100	47	48
N_2	60	7300	9950	65	60
H_2	62	5093	76600	120	80

The thermochemical cathode represents a water-cooling copper electrode containing a hafnium insert. The geometry of the plasmatron nozzle had a narrowing shape, the initial diameter was 3 mm. A safe operation, initiation and production of hydrogen-oxygen plasma were carried out with the help of starting gas mixtures, such as air. The start and receiving the plasma jet took place in air mixture, into which HOM was introduced, gradually the air mixture overlapped and a hydrogen-oxygen jet was formed. When the work is finished, the actions occur in reverse order. At a stable operation of the plasmatron on HOM, the operating voltage was 100 V.

Procedure of investigations and results. The geometric sizes of the plasma jet were fixed. The transition limits from a laminar to a turbulent nature of the flow were determined by maximum and minimum lengths of the plasma jet with the control of the mixture consumption. At a laminar nature of the flow, the consumption of the gas mixture was 0.4 m^3/g and at a turbulent one more than 0.6 m^3/g at a pressure of 0.08–0.1 MPa. As investigations of the geometry of a hydrogen-oxygen plasma jet with a laminar nature of the flow have shown, when the jet flows into the surrounding atmosphere, it behaves like a hydrogen-oxygen flame, the opening angle of the jet is small and can be 2–5°, and the length is more than 200 mm (Figure 1, *b*). With an increase in flow rates of the mixture and the transition of the jet into a turbulent nature of the flow, the opening angle increases and the plasma flame is reduced to 70 mm. As is seen from Figure 1, *a* (through a red light filter), the structure of the plasma flame resembles a gas flame, where the core and the near-core zone are visible.

To determine the effective thermal power of plasma jets of different flow nature, an experimental installation with a water calorimeter was used. The amount of heat emitted by the plasma jet was re-

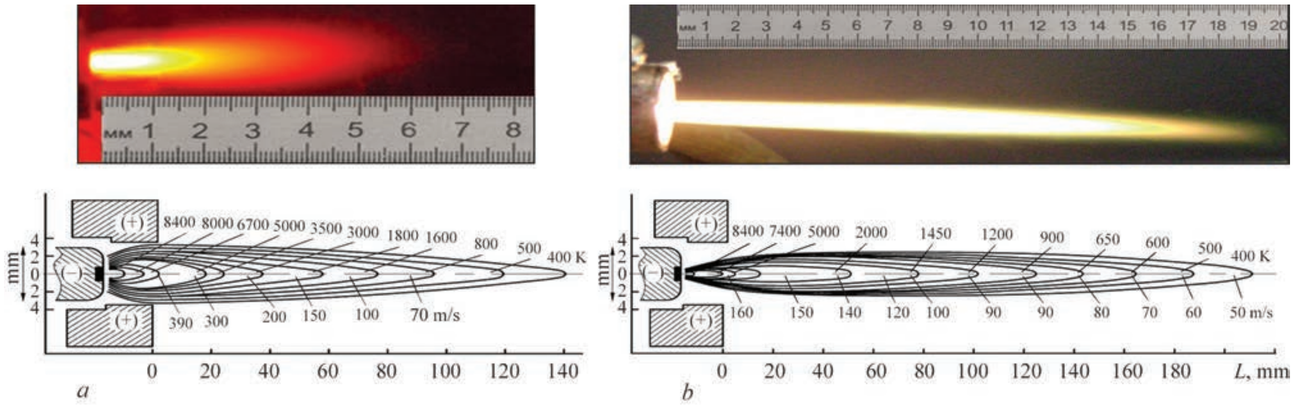

Figure 1. Distribution of temperature and velocity along the length of the plasma jet with different flow characteristics: *a* — turbulent $V = 1$ m^3/g; *b* — laminar $V = 0.4$ m^3/g

corded by heating the copper plate. At this time, the heating time, temperature of liquid in the calorimeter were determined, the measurement was performed by special Beckman thermometer, and calculations were performed according to the standard method [14].

The studies showed that the effective thermal power at a consumption of HOM being 0.4 m^3/g, which corresponds to a laminar nature of the flow, amounted to 30 mJ at an applied electric power to the plasmatron of 4 kW. At perturbation of a flow and transition to a turbulent state of a flow with a consumption of the mixture being 0.6–1.0 m^3/g, the effective thermal power amounted to 54–60 mJ.

The hydrodynamic method was used to determine the velocity distribution along the jet length applying a probe based on a Pitot-Prandl tube with a diameter of 1.5 mm and inner holes of 0.5 mm. To calculate the velocity, an equation known from technical thermodynamics based on the Bernoulli equation was used, which takes into account the pressure and plasma temperature in the jet region [15].

To study the temperature distribution along the length of the plasma jet, the jet was divided into three intervals of effective temperatures. Three methods of measurement were used: in the temperature range of 8000–4000 K — spectral one, 3300–2200 K — pyrometric one and 2000–500 K — thermocouple one.

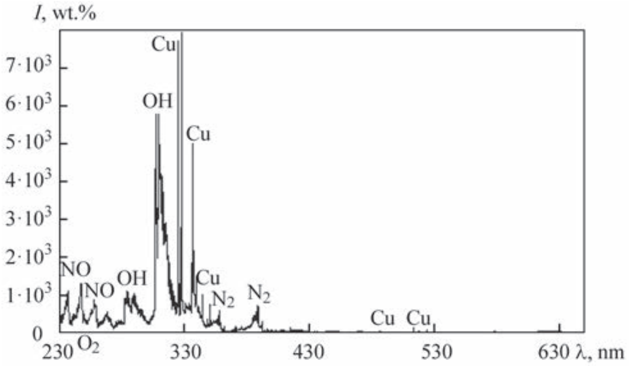

Figure 2. Spectra of plasma flame radiation at $z = 15$ mm, $h = 5$ mm in the wavelength range of 200–650 nm

To determine the temperature in the first range based on the components of the plasma jet, the noncontact method of emission spectroscopy was used. To study the second temperature range, an optical pyrometer LOP-78 was used based on the temperature of the heated body, where as a body a tungsten rod with a diameter of 3 mm was used, the absolute temperature was calculated according to the standard procedure [16]. In the third range, a tungsten-rhenium thermocouple VR-5/20 with a diameter of 0.5 mm was used. To prevent oxidation and burnout, the thermocouple was placed in a protective shell of quartz glass. The thermocouple was calibrated, the error of thermocouples amounted to 1 % of the electromotive force measurement, and the admissible error of the measuring device was 0.2 %. To determine the temperature of the plasma jet components, the noncontact method of emission spectroscopy was used. The temperatures and concentrations of the components of the plasma jet were studied along its length (*z*), at a deviation from the central axis (*h*), taking into account the fact that the torch is axisymmetric.

The emission spectra of the plasma flame were recorded using a spectrometer based on the CCD line Solar TII (S-150-2-3648 USB), which operates in the wavelength range of 200–1080 nm and has a triangular hardware function with a half-width of 0.2 nm, in the wavelength range of 200–650 and 0.3 nm in the range of 650–1080 nm. The radiation was recorded on the rays of vision perpendicular to the axis of the plasma flame [17, 18]. Figure 2 shows typical spectra of plasma radiation in the case of using HOM at $z = 15$ mm and $h = 5$ mm. The spectra are multicomponent, containing components of the electrode material, namely, atomic copper lines, components of the atmosphere, into which the jet flows, and the working gas, oxygen multiplet and molecular bands OH, NO, O_2 and N_2.

The values of the excitation population temperatures of the electronic T_e^* levels were determined using the software code Spec Air [19].

The calculations and experiments showed that the temperatures determined on copper are T_e^* (Cu) = = 6700 ± 1000 K. The temperature of atomic oxygen on the axis of the plasma flame is twice higher as compared to the random deviation from the axis, i.e. at $h = 0$ mm T_e^* (O) = 8400 ± 1000 K, and at $h = 5$ mm T_e^* (O) = 4100 ± 1000 K. The population temperature of the excited oscillatory and rotational levels of hydroxide within the error is the same and equals to T_r^* (OH) = T_v^* (OH) = 5000 ± 500 K. The excitation population temperatures of the electron T_e^* oxygen levels, determined by the method of Boltz charts, have a lower value as compared to the use of the software code Spec Air, but these differences do not exceed the error value. The temperatures that were determined by the molecule (OH) and by the atomic components (O and Cu) differ, which indicates that the plasma is nonisothermal. The reason for the temperature difference may be a nonuniform spatial distribution of radiating particles and exothermic processes in the flame. As was shown by estimation of the population temperatures of the excited electronic levels along the length of the hydrogen-oxygen plasma jet, as the average mass temperature of the jet the value of the OH molecule, which represents 5000 ± 500 K, can be taken, and as the maximum atomic mass O = 8400 ± 1000 K, which coincide with the literature data.

A study in the temperature range of 3300–900 K showed that the distribution largely depends on the nature of the flow, and at a laminar nature of the flow (Figure 1, *b*), this area can be 1.4 times larger in relation to a turbulent one (Figure 1, *a*). At the turbulence of a flow the tendency changes, a more high-temperature interval 8000–4000 K is larger at a turbulent nature of a jet flow.

The maximum values of the plasma jet velocity grow in the case of increased flow rates at a constant nozzle diameter, which is characteristic of a turbulent nature of the flow, but as the flame length shortens, the range of effective velocities also decreases. With a decrease in the flow rates of the mixture and the transition to a laminar nature of the flow, the maximum values of the velocities are lower, but the length of the interval of effective velocities is larger.

Taking into account the effective temperature and velocity intervals of the plasma jet using HOM as a plasma-forming gas, it is possible to set the sizes of the active zone of the jet, in which melting and a sufficient velocity of particles are possible, to determine one of the important technological parameters of the process of thermal coating, spraying distance and to produce a quality coating. This distance for such process parameters can be 80 mm for a turbulent and 140 mm for a laminar nature of the jet flow.

Accordingly, the velocity values of the jet can be significantly increased by increasing the flow rate of the plasma-forming mixture, initial diameters and profiling of geometric sizes of the nozzle part of plasmatrons. Meantime, the lengths of the plasma jet as well as the sizes of the active zone may change. However, the regularity of the temperature distribution in the jet of a hydrogen-oxygen plasma may correspond to the results of our investigations.

For application of the plasma method of spraying functional coatings using HOM as a plasma-forming gas, the following approach can be defined. At a laminar nature of the flow, it is possible to apply coatings from metals and alloys. At a turbulent nature it is more effective to spray heat-resistant, heat-protective and other coatings based on oxides, borides, etc., with a high melting point.

Conclusions

1. The distance of spraying while using HOM can be 1.4 times larger during a laminar nature of the jet flow than during a turbulent one. The angle of opening of the jet is 2–5°, which allows concentrating the heat flux density on the treated product by reducing the heating spot.

2. The effective thermal power of the plasma jet at a flow rate of HOM being 0.4 m^3/g, which corresponds to a laminar nature of the jet flow, was 30 mJ, at a supplied electric power to the plasmatron being 4 kW. At a turbulent nature of the plasma jet flow at a flow rate being 0.6–1.0 m^3/g, the power was 54–60 mJ.

3. The maximum temperature of the hydrogen-oxygen plasma is observed in the arc part of the plasmatron and at the nozzle-anode section of 9–12 mm and amounts to 8400 ± 1000 K, the average mass temperature of the hydrogen-oxygen plasma jet is 5000 ± ± 500 K.

4. The presented results can be used in the development of technological processes of plasma method of coating using HOM as a plasma-forming gas.

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Received 12.10.2020

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