Water vapor thermal plasma generation

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Abstract. The results of studies of an electric arc plasma torch for heating water vapor are presented. For the first time, a structural diagram of a steam-water thermal plasma generator with copper electrodes was implemented. The energy characteristics of the plasma torch and erosion of the electrodes reflect the features of their behavior during combustion in a plasma-forming medium of water vapor. The results obtained indicate the promise of the developed design of the steam-water plasmatron.

1. Introduction

The low-temperature water vapor plasma has several unique properties: high enthalpy, environmental friendliness, and wide availability. Therefore, the fields of its application are quite extensive: from energy to plasma chemistry and from metallurgy to mechanical engineering. The data (Fig. 1) on the enthalpy of various plasma-forming gases depending on temperature, borrowed in [1], show that in terms of enthalpy, the steam-water plasma exceeds the air, argon, nitrogen, and oxygen plasma, and second only to hydrogen plasma.

Figure 1. Enthalpy of various plasma-forming media depending on temperature.
An analysis of the known methods of thermal processing of carbon-containing wastes of various morphological composition shows that in recent decades, plasma gasification has attracted the most attention. The high-temperature level in the flow of the electric arc plasma (3500–5000 K) provides a significant yield of synthesis gas (CO + H₂ mixture) up to 90% vol., required environmental and technological safety. It has been found that the level of synthesis gas yield is the highest in the presence of water vapor plasma. Water vapor is a heat carrier and an active reagent in reduction and oxidation processes.

Gasification of the organic component of municipal solid waste, sawdust, rice husk, and biological sludge in the air plasma produces synthesis gas from 80 to 93% (by volume) with a ratio of H₂/CO=1.5–3.0 [2]. Specific energy consumption is 0.6–1.2 kW×h/kg. Replacing air plasma with steam-water plasma increases the combustion heat of synthesis gas from 10 to 18–20 MJ/nm³.

To implement plasma technology in the industrial production of synthesis gas (or fuel gas), powerful and reliable electric arc steam-water plasma generators are required. Existing plasmatrons for heating water vapor structurally contain a tungsten thermal cathode, which requires a protective medium in the form of argon or pure nitrogen [1]. Firstly, these are expensive gases, and secondly, they significantly pollute the steam-water plasma. At the same time, it is difficult to carry out numerical calculations of real technological processes based on steam-water plasma. Therefore, the transition to the design of a plasma torch for heating water vapor with copper tubular electrodes was very relevant.

The main problem in the development of a steam-water plasmatron is to prevent droplet formation on the water-cooled surfaces of the electric discharge chamber. Otherwise, in these places an uncontrolled breakdown in the gap between an arc discharge and a solid wall is possible. Therefore, it will be impossible to obtain continuous stable arc burning in the technological process. Also, the ingress of water or its vapors at the points of attachment of the supporting spots of the arc on the working surface of the electrodes leads to their rapid destruction.

2. Experimental setup
The basis of the developed and studied single-chamber steam-water plasma torch is made up of two hollow copper electrodes of a stepped configuration, separated by an insulator [3], fig. 2.

![Figure 2](image)

**Figure 2.** The design of the steam-water plasma torch. 1 – internal electrode-anode; 2 – output electrode-cathode; 3 – insulator; 4 – spin ring; 5 – steel shell.

To exclude the condensation of the vapor of the water-cooled elements of the discharge chamber, it is necessary to observe the conditions of vaporization above its saturation temperature. In this design, this is done with indirect cooling of copper electrodes due to a cylindrical shell 5 made of stainless steel with a thickness δ along the length of the inner electrode and on the initial section of the inner electrode.

The dimensions of the electrodes D₁ / d₁ are 1.4-1.6, and the lengths l₁ and l₂ were variable during the experiments to ensure the burning of the arc behind the steps. The geometry of the steel shell was calculated using PC ANSYS. The calculation is performed for experimental heat fluxes in the electrode and the temperatures of the electrodes at the entrance and exit from it. [4].
To obtain water vapor with a temperature of 300 ± 50 °C, a steam generator with forced ventilation of water has been developed. It consists of a coil of the variable cross-section made of stainless steel and a damper to smooth out the hydrodynamic pulsations that occur in the evaporative section of the steam generator. The coil is heated from a controlled current source APR-404. The flow rate of generated steam from $2 \times 10^{-3}$ to $5 \times 10^{-3}$ kg/s was determined by the flow rate of water. The vapor temperature at the entrance to the discharge chamber of the plasma torch is measured by a chromel-aluminum thermocouple and an M-838 digital multimeter with an accuracy of ± 2%.

The focus of the studies was on the internal electrode – the anode. Firstly, erosion of a copper tubular anode is noticeably less than cathode erosion under the same conditions. Secondly, when switching to the melting plasmatron mode, it is easier to achieve a long electrode life if it is an anode.

### 3. Research results

Comparative current-voltage characteristics of the arc during the operation of a steam-water plasma torch in air and water vapor at the same gas flow rates showed that the average field strength in the pair along the discharge length was 18–20 V/cm, while in plasma torches with air-arc stabilization – 12–14 V/cm. Thus, the presence of a hydrogen-containing medium in the discharge chamber of the plasma torch significantly affects the magnitude of the voltage drop across the arc.

Figure 3 shows the current-voltage (I – V) characteristics of the arc in water vapor. In the studied ranges of current strength and steam flow rates, they have a falling shape. The power of the plasma torch was 50–100 kW; with increasing steam flow, the arc voltage at constant current increases (Fig. 3, b; I = 200 A).

The obtained I – V characteristics of the arc are generalized in a criterial form (all values in the SI system):

$$ U = 2280 \left( \frac{I^2}{G \cdot d_2} \right)^{0.17} \left( \frac{G}{d_2} \right)^{0.2} \cdot (p \cdot d_2)^{0.25}. $$

Due to the small range of determining parameters, the accuracy of the formula is small (± 10%), but it is useful for evaluating calculations of the discharge chamber of steam-water plasmatrons of different power.

Heat fluxes to the electrodes are shown in Fig. 4. As can be seen, most of the heat fluxes are concentrated at the output electrode-cathode. They are almost the same in size for air and water vapor. Calculation of the thermal efficiency $\eta_t$ based on the measurement results showed that for water...
vapor-operating plasma torch, $\eta_t = 0.55-0.70$ which exceeds the data for the air-operating torch since the power deposited in the arc discharge is greater than in air. Similar efficiency values were obtained for steam-water plasmatrons with an end thermal cathode [1].

![Figure 4. The dependence of heat loss in the electrodes on the arc current, $G = 4.1 \times 10^{-3}$ kg/s.](image)

1 – anode; 2 – cathode; 3 – total heat fluxes.

Optimization of the length of the output electrode-cathode and the flow rate of the plasma-forming gas in the jet operation will increase the efficiency of the plasma torch to 0.8, and in the melting mode – to 0.85–0.9.

The characteristic of the rate of destruction (erosion) of the electrodes is the value of their specific erosion $\overline{G} = \Delta m / I \times t$, kg / C, where $\Delta m$ is the mass of the eroded material determined by weighing.

The experiment lasts from 20 minutes to 2 hours arc discharge currents $I = 180–200$ A. The flow of water vapor was constant and amounted to $4 \times 10^{-3}$ kg/s.

An analysis of the experimental results for the internal electrode-anode and the output electrode-cathode shows that the $\overline{G}$ value for the anode in the steam-water plasmatron is almost an order of magnitude higher for similar conditions of an air plasma torch and is $10^{-8}$ kg/C, and for the cathode – $(3–5) \times 10^{-9}$ kg/Cl. This is due to various reasons.

Conclusions
Firstly, the high temperature of dry superheated steam of 300 °C. An increase in the temperature of the electrode leads to an increase in its erosion. This will positively affect thermal efficiency and the speed of movement of the arc spot. Third, a partial change in the configuration of the steel shell based on numerical calculations [4] due to the improvement of its cooling led to a noticeable decrease in the $\overline{G}$ of the anode ($\overline{G} = 1.7 \times 10^{-9}$ kg/C). That is, due to the optimization of the water cooling system of the composite electrode, it is necessary to bring the temperature of the working surface to a minimum temperature above saturated steam (about 110°C).

Subject to the above conditions, it is possible to obtain $\overline{G}$ anode values at the level of $10^{-10}–10^{-9}$ kg/C to implement the long-term operation of the electrodes. For the investigated structural scheme of the steam-water plasma torch (Fig. 2), taking into account the experimental data, the electrode life can be estimated at 250–300 hours at arc discharge currents of 180–250 A.

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