Investigation of parameters of the three phase high-voltage alternating current plasma generator with power up to 100 kW working on steam

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Abstract. The paper presents the results of experimental investigation of parameters of the three-phase high voltage alternating current plasma generator with power up to 100 kW operating on steam with gas protection of the electrodes. Researches were carried out over a range of arc current from 25 to 50 A and range of steam consumption of 3-5 g/s. Current-voltage and volt consumable characteristics, operation oscillograms and dependence of power versus the flow rate of steam and protective gas are presented.

1. Introduction

Steam-and-water plasma consists of hydrogen and oxygen acting as active reagents in many chemical reactions. There is no ballast like nitrogen is in air plasma. For many processes nitrogen is inert and, moreover, is harmful, as it is a source of toxic NOx.

According to forecasts, the future of power engineering during, at least, XXI century will be connected with use of various types of organic fuel of wood, municipal waste and mainly coal which stocks are great enough. However, significant emissions of CO2, oxides of sulfur and nitrogen of coal-consuming plants, huge scales of slag yield and non-cultivated grounds demand basic revision of methods of further use of coal as a fuel. Recently in the world the concept of complex processing of coal with production of high-calorific synthesis gas (mixture CO and H2) [1-6] and accompanying saleable material (from slag) is examined: aluminum, iron carbide, etc. The basis of this strategy is the process of coal gasification. In the future coal gasification is the most significant the practical application of steam-and-water plasma. A basic element of systems of plasma gasification and pyrolysis of coal and various organic containing waste are electric arc plasma generators. As it has been noted above, for many of these processes steam-and-water plasma is the optimum environment. Therefore problems of development and research of electric arc generators of steam-and-water plasma are rather actual.

Plasma torches generating oxygen-hydrogen plasma with temperature from 2000 up to 5000 K are necessary for technologies of plasma production of liquid synthetic fuels from coals, slates or peat. The designs using water or steam as a plasma forming environments are related to such type of plasma generators.
As a result of the researches carried out in this area by different collectives, various designs of electric arc plasma generators using water [7 - 14] or steam [15 - 20] as a plasma forming environment have been created.

The review of existing designs of electric arc plasma generators intended for generation of low temperature (up to 10000) plasma has shown the following:

Basically the presented designs are direct current plasma generators with steam supply and protection of one of electrodes (cathode or anode) by inert gas (mainly argon). A part of designs represent highly enthalpy direct current plasma generators with argon arc squeezing by a water vortex and arc closing on the external rotating electrode.

Researches have shown the increased erosion of electrodes in electric arc plasma generators, using water as a plasma forming environment. For this reason at creation of industrial steam-and-water electric arc alternating current plasma generators it is necessary to apply gas protection of electrodes. Thus the most promising protective gas environment is air, owing to such qualities as cheapness and abundance.

In the majority of designs the arc voltage drop does not exceed 300 - 400 V. That is why the increase in power is reached due to increase in arc current that negatively affects on operating time of electrodes.

As steam-and-water plasma represents a mixture of hydrogen plasma with oxygen in the ratio 2:1, its properties are closer to properties of hydrogen as in its content in the mixture is higher. Heat conductivity of steam-and-water plasma is significantly higher, and viscosity considerably lower, than at other kinds of plasma. Owing to this at arc burning in a vortical stream of steam-and-water plasma the arc column is subjected to not so strong lateral cooling, as in the environment of pure hydrogen, but to much more intensive, than in the environment of other gases. It, in a combination with a high specific thermal capacity of steam-and-water plasma, leads to greater intensity of the electric field in the arc column and to greater enthalpy of steam-and-water plasma at the same arc current that imposes essential requirements of the power supply system and constructional features of the electric discharge chamber.

Based on the carried out preliminary researches the decision to develop a design of a resource electric arc plasma generator (200 hours of continuous work) for generation of water plasma using the principles incorporated in designs of high-voltage electric arc alternating current plasma generators [21] - increase in power of plasma generator due to increase in arc voltage was made.

2. Description of the experimental plant
The power supply for single-phase or three-phase load comprising the electric arc has been constructed for the tests. The schematic of the power supply source is shown in Figure 1.

![Figure 1. The electrical schematic.](image-url)
power source: no load voltage is 6000 or 10000 V, short circuit current 30, 40 and 50 A in dependence on the scheme of the reactor connection.

The experimental design of the electric arc plasma generator has been created for carrying out tests. This design has an electric arc chamber optimized for operation with steam at temperature of 250°C. It allows supply into the electric-discharge chamber of various plasma forming media. Figure 2. shows the external view of the experimental plasma generator.

![Experimental steam-air high-voltage alternating current plasma generator.](image)

**Figure 2.** Experimental steam-air high-voltage alternating current plasma generator.

The experimental plasma generator consists of chambers for protective gas supply, steam, nozzle apparatus (conicity 40%), electrode system of water-cooled rod electrode (water pressure in the cooling system is 1.2 MPa). Electrodes with 8 mm diameter are made of a ceramic-metal alloy. Steam pressure can vary from 0.2 up to 1 MPa, temperature is 200°C. Specific wear of electrode material is \(10^{-6}\) g/C. Electrode lifetime is more than 200 hours. Plasma generator efficiency measured on thermal balance \(W_{\text{arc}}/W_{\text{cons}}\) is about 0.75-0.92 depending on parameters of gas supply.

3. **Experiment results**
A series of experiments, where the following parameters have been varied, are carried out: characteristics of the power supply (current); steam flow rate; air flow rate; proportion of a steam-air mixture. Steam flow rate varied from 1 up to 4 gram per second. The range of change of the steam and protective gas flow rate for this model of the plasma generator was selected from a condition of steady arc burning. The protective gas (air) flow rate varied over the range from 0.5 up to 5 g/s. The short circuit current of the power supply varied from 12 up to 33 A. Figure 3. shows the photo of plasma jet of the experimental plasma generator.
Arc intensity $E \approx 50 - 100$ V/cm depending on mode of supply of plasma and protective gas. The dependence of voltage arc drop variation from component composition and mass flow rate of plasma gas was investigated during experiments. For the investigated high-voltage steam-air alternating current plasma generator the arc voltage drop depends not only on the total flow rate of plasma environments, but also from a relation of protective air and steam flow rate. Figure 4 shows the character of variation of voltage drop on the plasma generator arc versus the flow rate of the mixture of plasma gases.

Figure 3. Steam-air plasma jet

Figure 4. Volt-flow rate characteristics of the single-phase electric-arc plasma generator operating on steam-air mixture.
Researches have shown that dependence of voltage variation on the mass flow rate of steam-air mixture essentially differs from results obtained at use of air in plasma generators of similar design [21,22,23] or carbonic gas, where with increase in the mass flow rate of plasma gas it is observed growth of arc voltage drop in connection with compression of arc column by gas stream. For air-steam mixture the tendency of change of arc voltage drop is different. With increase in total air flow rate from minimal at constant steam flow rate, arc voltage drops and only at attainment of the air flow rate comparable with the steam flow rate it is observed the tendency of growth of arc voltage drop (similarly to high-voltage electric arc alternating current plasma generators working only on air).

It is necessary to note, that the arc current practically does not change over all range of flow rates (it is stabilized by the power supply system), the current density remains constant as the cross-section of the arc column is limited by the nozzle device. Hence, for change of the arc voltage drop (arc intensity) is responsible the conductivity of the arc column. As conductivity in these conditions is defined by a relation of sections of electron-nuclear and electron-ionic interactions and at achievement of critical concentration of electrons, when section of electron-ionic collisions becomes determining, conductivity practically does not change, as a rule, at electron concentration \( \geq 10^{15} \, \text{cm}^{-3} \) [24]. In the examined case, considering complex plasma composition, these relations are varied. And the task of the further researches is definition of critical concentration for a concrete mixture of plasma forming environments, that, apparently, determined the character of dependence of intensity versus the flow rate.

On the basis of the obtained results the multi-phase high-voltage alternating current plasma generator was designed and created. It is intended for operation on mixture of steam and air or carbon dioxide. The external view of the plasma generator and photo of the plasma generator operation on the steam-air mixture are shown in Figure 5.

\[\text{Figure 5. The experimental industrial steam-air three-phase high-voltage AC plasma generator. External view}\]

Figure 6 and Figure 7 show the characteristics of this plasma generator working on a steam-air mixture.
As is seen from the presented graphs the highest arc voltage drop and the highest power are achieved at the minimal air flow rate.

The efficiency of three-phase electric-arc steam-air plasma generator at relation of flow rates 3 g/s steam, 1 g/s air power 68 kW is 93%.
Photos of the experimental start up of this model of the plasma generator operating on mixture of steam and carbon dioxide are shown in Figure 8. The experimental results are presented in Figure 9 and Figure 10.

**Figure 8.** Three-phase high voltage AC plasma generator operation on the mixture of steam and carbonic gas. At the left and on the right above - photos of a flame and arcs of the working plasma generator accordingly; on the right below - a photo of the switched-off plasma generator with supplied steam.

Figure 9 shows the dependences of variation of the arc voltage drop versus carbon dioxide flow rate at constant flow rate of steam.

**Figure 9.** Volt-flow rate characteristics of the three-phase electric-arc plasma generator operating on steam-carbon dioxide mixture. Steam flow rate is 3 g/sec.
Figure 10 shows the dependences of variation of power of the electric arc multiphase high-voltage plasma generator operating on mixture of steam with carbon dioxide.

![Figure 10](image-url)

**Figure 10.** Dependence of power of the three-phase electric-arc plasma generator versus the parameters of the power source and flow rate of the carbon dioxide. Steam flow rate is 3g/sec.

The obtained values of variation of power versus the relation of consumption parameters of plasma agents and parameters of the power source allow the use of the created model of the plasma generator in the pilot plasmachemical reactor.

### 4. Conclusion

As a result of the carried out work the complicated dependence of ranges of steady-state work of the plasma generator, arc voltage drop and power from parameters of the power supply and flow rates of plasma gases have been obtained.

Values of arc voltage drop are achieved at work on a steam-air mixture 3400 V for single-phase experimental installation and 1550 V for the multiphase industrial pilot device.

The design of an experimental multiphase AC plasma generator working on a mixture of steam with air or carbon dioxide as a plasma gas has been created for the realization of the processes of plasmachemical processing of hydrocarbonic raw material.

Experiments have shown the existence of complicated dependence between the mass flow rate of steam-gas mixture, relation of steam to the second gas and electric arc voltage drop for the given configuration of the plasma generator.

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