High voltage AC plasma torch operating on vapours of organic substances

A V Surov1, S D Popov1, E O Serba1, V A Spodobin1, Gh V Nakonechniy1, A V Pavlov1, A V Nikonov1, D I Subbotin1,2,3, V E Popov1, N V Obraztsov1,4

1Institute for Electrophysics and Electric Power of Russian Academy of Sciences (IEE RAS), Dvortsovaya emb. 18, 191186, St.Petersburg, Russia
2Saint-Petersburg State Institute of Technology, Moskovsky pr. 26, 190013, St. Petersburg, Russia
3Saint-Petersburg State University, Universitetskaya emb. 7-9, 199034, St. Petersburg, Russia
4Peter the Great St. Petersburg Polytechnical University, Polyteknicheskaya 29,195251, St.Petersburg, Russia
alex_surov@mail.ru

Abstract. The article deals with a three-phase high-voltage AC plasma torch with separate supply of gases and vapours during its operation on a mixture of steam, carbon dioxide, methane and organic vapours. Increase in flow rates of organic vapours and methane leads to increase in the arc voltage drop from 875 to 1150 V and electric power from 80 to 102 kW.

1. Introduction

Plasma torches have found wide application in metal cutting, heat treatment of surfaces, solid waste processing, reforming of natural gas, and also processing of toxic substances. The most complex task of plasma chemistry is a high conversion of organic matter due to high temperature, good mixing of reaction components and the formation of active radicals [1]. In this case, air direct current plasma torches are most often used [2]. In addition, the processing of waste by nonequilibrium plasma is investigated: gliding discharge [3], DBD [4], RF plasma [5]. Particular interest is plasma processing with steam, which leads to the decomposition of complex heteratomic organic substances (e.g., chlorinated) with the formation of an appropriate hydride (e.g., hydrogen chloride) [6]. Steam plasma torches were used for gasification of municipal solid waste [7], treatment of polychlorinated biphenyls [8], perflourinated compound [9], reforming natural gas [10], etc.

The atmospheric pressure electric arc plasma torch was used to obtain active plasma radicals (O, H, OH) from steam for reforming glycerin [11]. The power of the plasma torch is from 45 kW to 61 kW (current 200 A, voltage 225 - 305 V), steam flow rate is 2.4-4.5 g/s at 500 K.

Another water-argon DC plasma torch was used for processing toxic substances. This plasma torch is about 110 kW with a W-Th cathode, in which the arc is stabilized by argon and a vortex of liquid water. The flow rate of argon is 22 l/min, the flow rate of evaporating water is about 18 g/min [12]. The anode of the plasma torch is a rotating disk with water cooling, which is located outside the arc chamber.

Also, a CF₄ decomposition system including a steam atmospheric pressure DC plasma torch was investigated. The anode was a copper nozzle, and the cathode was made from a hafnium rod 1.0 mm in diameter [13]. In the plasma torch there are two inputs: liquid water, which evaporates, forms a
plasma-forming gas in the anode region; \(\text{CF}_4\) and \(\text{O}_2\) are fed to the end of the nozzle. The electric current of the arc was from 7 to 9 A, and the voltage was from 110 to 150 V, the mass flow of water and \(\text{CF}_4\) was 75 mg/s and 3.75-15 mg/s, respectively.

However, at the moment there is no information on plasma torches operating on vapours of organic substances. Those plasma torches will be most effective for the decomposition of organic substances, because in them all the reaction components will pass through the high-temperature zone.

The article deals with a new three-phase AC plasma torch operating with a mixture of steam, carbon dioxide, methane and organic vapors as a plasma-forming medium.

### 2. Investigated plasma torch

The investigations were carried out on the facility consisting of a high-voltage three-phase AC plasma torch (Fig. 1), a steam generator with a superheater and a power system with an electrical measuring circuit (Fig. 2). The plasma torch is three cylindrical discharge channels with two injections of plasma-forming gases and three rod electrodes [14]. A shielding gas (carbon dioxide) is supplied to the near-electrode zone, and steam, methane and vapors of a mixture of organic substances are fed into the arc burning zone. The composition of the mixture of organic substances is presented in Table 1.

![Figure 1 The three-phase AC plasma torch](image)

1 - electrode; 2- arc channel; 3 — electric arc; 4 — shielding gas (carbon dioxide); 5 - plasma-forming gas (steam, methane, the mixture of organic substances).

#### Table 1. Composition and properties of the mixture of organic substances.

| Parameters            | Units  | Value |
|-----------------------|--------|-------|
| Toluene               | % wt   | 50    |
| Butanol               | % wt   | 15    |
| Butyl acetate        | % wt   | 10    |
| Ethanol               | % wt   | 10    |
| Acetone               | % wt   | 7     |
| Ethyl cellosolve      | % wt   | 8     |
| Initial boiling point | °C     | 59    |
| The auto-ignition temperature | °C | 403   |

The selected composition of the mixture of organic substances complicates the production of vapours, so the heating of this mixture was carried out in two stages in different heat exchangers: heating to the boiling point and evaporation of the mixture.
The plasma torch is connected to the power supply and the measuring circuit (Figure 2). The electrical circuit of the power supply system consists of a circuit breaker (SF), a contactor (KM), capacitive reactive power compensators, current-limiting reactors (LL), a step-up transformer (T), measuring transformers of current (TI) and voltage (TU) and secondary converter of sensor (DI and DU) [15]. Losses from ohmic heating in this system do not exceed 2-3% of the total power. The open-circuit voltage of the power source is constant and equal to 10 kV.

3. Results and discussion

The dependence of the parameters of the plasma torch operation on the flow rate of a mixture of organic substances is studied. CO\textsubscript{2} was supplied to the near-electrode zone, and a mixture of organic substances was fed into the arc burning zone together with steam and CH\textsubscript{4}. The steam flow rate is 2.9 g/s, the CO\textsubscript{2} flow rate is 2.9 g/s, the CH\textsubscript{4} flow rate is 0.3 g/s, the flow rate of the mixture of organic substances is varied from 0 to 3 g/s. The plasma torch worked on the environment at atmospheric pressure. Figure 3 shows the dependences of the voltage drop on the arc and the power of the plasma torch on the flow rate of a mixture of organic substances. The effective current value in the arcs was \( \sim 52 \) A.

![Figure 2](image)

**Figure 2** The electric scheme of the power supply system for the three-phase AC plasma torch.

![Figure 3](image)

**Figure 3** Dependences of the power of the plasma torch and the voltage drop on the electric arc on the flow rate of the mixture of organic substances (at constant flow rates of other components of plasma forming mixture)

Also, the dependences of the operation parameters of the plasma torch on the CH\textsubscript{4} flow rate into the arc burning zone with a constant flow rate of a mixture of organic substances were obtained. The steam flow rate was 2.9 g/s, the CO\textsubscript{2} flow rate was 2.9 g/s, the CH\textsubscript{4} flow rate varied from 0.3 to 1.2 g/s, the organic matter flow rate was 3 g/s. Figure 4 shows the dependences of the voltage drop on the arc and the power of the plasma torch on the flow rate CH\textsubscript{4}.
Figure 4 Dependences of the power of the plasma torch and the voltage drop on the electric arc on the methane flow rate (at constant flow rates of other components of plasma forming mixture)

As can be seen from Figures 3 and 4, the voltage drop of the arc of the plasma torch increases with increasing flow rate of mixture vapors of the organic substances and CH₄. This is due to the formation of hydrogen during the reforming of organic substances by steam and carbon dioxide at high temperature:

\[
\begin{align*}
\text{C}_6\text{H}_5\text{CH}_3 + 6\text{H}_2\text{O} &= 6\text{CO} + 10\text{H}_2 \\
\text{C}_6\text{H}_5\text{CH}_3 + 6\text{CO}_2 &= 12\text{CO} + 4\text{H}_2
\end{align*}
\]

In comparison with carbon dioxide hydrogen has a high heat capacity and thermal conductivity, which leads to an increase in heat losses from the arc. The change in the power of the plasma torch is also important for the processing of organic substances. Depending on the composition of the mixture of organic substances, different energy inputs are required. This value can be changed by feeding vapours of organic substances into the plasma torch or into the plasma chemical reactor located behind the plasma torch. In addition, the steam plasma produced in the plasma torch effectively decomposes the soot formed in the colder parts of the plasma chemical reactor. This fact is confirmed for the most thermally stable hydrocarbon (methane) [16]. Due to the protective gas (CO₂), hydrogen does not interact with the material of the electrodes. In this case, its service life can significantly increase.

4. Conclusion
During the tests it was found that the developed plasma torch operating on a mixture of carbon dioxide, steam, methane and vapours of the mixture of organic substances has a power of 80-102 kW. The power can be changed by changing the flow rates of a mixture of organic substances (80-96 kW) and methane (96-102 kW). This plasma torch is suitable for plasma steam reforming of various organic substances, including their mixtures. Carbon dioxide protects rod electrodes from aggressive steam and participates in reforming. Therefore, the process proceeds without the formation of by-products. The plasma torch operates in a wide range of flow rates of plasma-forming media, which allows achieving of a low concentration of soot in reaction products.

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