AC plasma torch operating on a mixture of air and methane

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Abstract. The article considers a high-voltage AC plasma torch for air reforming of natural gas. It has two inputs of plasma-forming gases: the electrode zone (for shielding gas) and the arc zone (for the main plasma-forming gas). The voltage drop on the arc increases with increasing methane flow rate due to the formation of hydrogen and intensification of heat transfer.

1. Introduction

Hydrogen is the largest chemical product. It is used in petrochemistry, for production of methanol, ammonia and alcohols, as well as energy. With the development of methods for producing hydrogen and reducing oil production, the share of liquid hydrocarbons produced by Fischer-Tropsch method will increase. The main method for obtaining hydrogen is reforming of natural gas with steam or oxygen [1]. The first process (steam reforming) is endothermic:

\[ \text{CH}_4 + \text{H}_2\text{O} = \text{CO} + 3\text{H}_2 \] (1)

The second process, due to the partial oxidation of natural gas, becomes exothermic:

\[ 2\text{CH}_4 + \text{O}_2 = 2\text{CO} + 4\text{H}_2 \] (2)

At the same time, H2/CO becomes less than 2. However, for the production of organic compounds by the Schiffer-Tropsch method, a molar ratio of H2/CO = 2 or more is required. Therefore, the produced mixture of hydrogen and carbon monoxide (synthesis gas) undergoes additional catalytic conversion with steam:

\[ \text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2 \] (3)

This problem can be solved by supplying the electrical energy necessary to heat the mixture to the required process temperature. Reforming methane with thermal plasma was considered in a number of works.

Steam-carbon dioxide reforming using the AC plasma torch [3] was carried out with selectivity for hydrogen of more than 98% and energy consumption of 104.7 MJ/kg of hydrogen. The main disadvantage of the method is high energy consumption for the endothermic process.

Air-plasma reforming under the action of sliding arcs is presented in the article [4]. The plasma torch was powered by an AC power source (maximum power is 2 kW) with a high voltage transformer (up to 20 kV) and a frequency of 5-20 kHz. At the same time, the energy consumption for hydrogen
production was 154 - 440 MJ/kg, which is explained by high losses when operating at a high frequency.

The best results for the air reforming of natural gas were obtained by L. Bromberg et al. [5]. The pilot plant consisted of a direct current plasma torch with a power of up to 10 kW, a power source (maximum current of 75 A at voltages of ~120-160 V), the plasma catalytic reactor (nickel oxide catalyst). In this case, the selectivity for hydrogen reached 90-100% at specific energy consumptions of 45-55 MJ/kg of H₂. The authors noted the importance of creating more powerful plasma torches for industrial applications. The article deals with the plasma torch of higher power, operating on a mixture of air and methane.

2. Experimental part
The investigations were held out on the experimental facility consisting of a three-phase AC plasma torch, a high-voltage power system, and the system for measuring electrical parameters.

The three-phase power supply consists of current-limiting inductors, reactive power compensators and the step-up transformer with an output voltage of 10 kV (Figure 1). The high-voltage power supply system of such plasma torches is described in more detail in [6]. The AC plasma torch has separate injections of a plasma-forming gas: air (shielding gas and oxidant) was supplied into the electrode zone, and methane was fed into the arc zone. As a result, the chemical process proceeds according to the reaction (2). A scheme of such a plasma torch working on a mixture of carbon dioxide, steam, and methane is described in [7].

![Diagram of the three-phase plasma torch power source.](image)

**Figure 1.** Diagram of the three-phase plasma torch power source.
A, B and C – terminals for connection to the power line, L1 – L3 – current-limiting reactors; T – step-up transformer; C – reactive power compensator

The effective value of alternating current and voltage is determined on the basis of the same amount of heat released according to the Joule-Lenz law at the same resistance at equal intervals:

\[ I \approx \frac{1}{\sqrt{n}} \sum_{k=1}^{n} i(k)^2, \]  

(4)

\[ U \approx \frac{1}{\sqrt{n}} \sum_{k=1}^{n} u(k)^2, \]  

(5)

where \( i(k), u(k) \) – instantaneous values of current and voltage at intervals of time \( \Delta t, n = T/\Delta t \) – the number of values for the measurement interval.

Active power is calculated by two-wattmeter method:

\[ P_{xy} = \frac{1}{T} \int_{0}^{T} (u_{ac} i_a + u_{ac} i_b) dt \approx \frac{1}{n} \sum_{k=1}^{n} (u_{ac}(k)i_a(k) + u_{ac}(k)i_b(k)). \]  

(6)

where \( P_{xy} \) – active power; \( u_{xy}(k) \) – instantaneous voltage drop across the arc between phases; \( i_x(k) \) – instantaneous current flowing through the phase. Because the plasma torch is an asymmetric load, the following calculations are also carried out:
The current sensor (LA 55-P) parameters: the measuring range of is 0 – ±70 A, accuracy is ±0.65%, non-linearity is < 0.15%, delay time at 90% of the maximum value of the measuring range is <1 mks, frequency range is 0 – 200 kHz. The voltage sensor (LV 100/SP51) parameters: measuring range is 100 - 4500 V, accuracy is ± 0.7%, non-linearity is <0.1%, delay time at 90% of the maximum value of the measuring range is 20 - 100 mks, frequency range 3 kHz. Signals from the current and voltage sensors are processed by 12-bit A/D (500 kHz) (National Instruments Corp.) with a sampling frequency of 32 kHz on all channels.

3. Results and discussion

In the course of experimental studies of the plasma torch, the plasma-forming gases were as follows: air into the electrode zone of 6 g/s, air into the arc zone of 6 g/s, methane into the electrode zone 0 to 1 g/s. Figure 2 shows dependence of plasma forming gases flow rate and the power vs time. Figures 3 and 4 show the arc voltage drop and the plasma torch power, depending on the methane flow rate fed into the electrodes zone. The average effective value of the current was ~ 46.8 A.

![Figure 2. Flow rate of plasma forming gases and the power vs time.](image-url)
The growth of arc voltage drop is caused by several factors. First, the endothermic process of hydrogen formation takes place, which consumes the energy of the electric arc. At the same time, as the amount of produced hydrogen increases, the temperature in the electric arc reduces, which leads to a decrease in the arc electrical conductivity. Secondly, hydrogen has a high heat capacity and thermal conductivity, which intensifies heat exchange between the arc and the cold gas vortex stabilizing it. In addition, the total flow rate of the plasma-forming mixture increases, which leads to an increase in the linear velocity of the gas in the arc channel of the plasma torch. These factors make it possible to change the plasma torch power and the temperature in the plasma-chemical reactor, which can ensure efficient processing of organic substances.
The plasma torch was tested on a plasma-chemical installation described in previous studies [7]. It consists of the plasma torch, a lined reactor, the system for supplying plasma-forming media and the system for sampling reaction products. Table 1 shows the composition of the gaseous products of air plasma methane reforming and the comparison of this composition with a thermodynamically equilibrium mixture at the same experimental temperatures.

Table 1 Comparison of the experimental and calculated compositions of products

| Substance                        | Experimental data,% vol. | Estimated data,% vol. |
|----------------------------------|--------------------------|-----------------------|
| CH4                              | 0.05                     | 0                     |
| H2                               | 39.81                    | 36.91                 |
| CO2                              | 0.35                     | 0.47                  |
| CO                               | 18.29                    | 19.36                 |
| N2                               | 40.85                    | 42.75                 |
| Ar                               | 0.65                     | 0.51                  |
| Specific energy consumption, MJ/kg of methane | 71.3          | 9.3                   |
| Specific energy consumption, MJ/kg of hydrogen | 265.3        | 38.9                  |

As can see, plasma reforming allows to achieve the thermodynamic equilibrium by the high temperature of the reaction mixture. This suggests that other hydrocarbons and their mixtures (for example, associated petroleum gas) can be processed in the same way.

4. Conclusions

Investigation of a high-voltage electric arc plasma torch operating on a mixture of air and methane in various ratios was carried out. Dependences of the arc voltage drop and the plasma torch power on the flow rate and composition of the plasma-forming mixture were obtained.

The power of the plasma torch during the experiments increased by an increase in methane flow rate from 40 to 96 kW, the arc voltage drop changed from 500 to 1300 V.

The increase in the arc voltage drop and, consequently, the power with increasing methane flow rate is associated with the intensification of heat exchange between the arcs and the plasma-forming mixture. This is due to the increase in the total flow rate of the mixture, as well as the increase in the concentration of hydrogen in the arc zone. Thus the increase in the concentration of hydrogen in the arc discharge zone is the determining factor. Air plasma reforming allows to almost completely convert methane to hydrogen and carbon monoxide, so the proposed processing method can be applied on an industrial scale.

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