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Electric Arc Methods of Production Hydrogen from Hydrocarbons

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Abstract—The article discusses methods for producing hydrogen based on the thermal impact of arc plasma on natural gas. A high-voltage alternating current plasma torch with a power of up to 120 kW and an open circuit voltage of the power supply source of 10 kV is used for this purpose. Experiments were carried out on plasma pyrolysis of natural gas in the presence of argon and thermal reforming in the presence of water vapor and carbon dioxide. The methane conversion exceeded 86% during pyrolysis and 99.8% during reforming.

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INTRODUCTION

Hydrogen is a valuable chemical raw material with a wide range of applications. It is used in metallurgy, chemical, petroleum refining, pharmaceutical, and food industries. Global hydrogen production has already reached 70 million tons per year, and it is expected that hydrogen consumption will only increase. Hydrogen is also being considered as the energy carrier of the future, and the transition to a carbon-neutral economy is being linked to it.

Currently, the following technologies are most commonly used for hydrogen production:

—steam methane reforming (SMR) of natural gas [1];

—water electrolysis [2].

All large-scale hydrogen production facilities operate based on the SMR technology. The cost of hydrogen produced by this process is the lowest, but this technology has serious drawbacks, such as high carbon footprint, incomplete methane conversion, and high-temperature steam heating in tubular furnaces [3].

The production of one kilogram of hydrogen results in the emission of up to 11 kg of carbon dioxide into the environment.

In the technological process of hydrogen production by electrolysis, there are no carbon dioxide emissions, but the process itself has low productivity and high energy consumption [4]. To obtain one kilogram of hydrogen, it is necessary to expend 55–60 kWh of electrical energy (data is provided for alkaline electrolyzers). Hydrogen produced this way can be considered “green”, but it should be noted that 70% of the world’s electrical energy is produced from fossil fuels. In this case, “green” electrolytic hydrogen becomes “gray”. The resulting carbon dioxide emissions from the production of one kilogram of electrolytic hydrogen can reach 24 kg.

PLASMA PYROLYSIS

The process of pyrolysis allows for a reduction in carbon dioxide emissions during the production of hydrogen from hydrocarbons. In this process, methane is heated above 1000°C and decomposes into hydrogen and carbon. The process of pyrolysis of hydrocarbons has been known for a long time, but the deposition of carbon on the heating elements of equipment has prevented its wide implementation in practice. Modern tubular furnaces are not suited for pyrolysis of hydrocarbons without a system of removing carbon from the surface of the tubes. Plasma pyrolysis of hydrocarbons allows for the production of hydrogen without carbon dioxide emissions. When plasma is used, it is theoretically possible to obtain 0.25 kg of hydrogen and 0.75 kg of carbon from 1 kg of methane. The energy consumption for the process is about 10 MJ.

A setup capable of producing up to 2 kg of hydrogen per hour has been created at the *Institute for Electrophysics and Electrical Power of Russian Academy of Sciences* for the study of the process of plasma pyrolysis of gaseous and liquid hydrocarbons [5]. The schematic of the laboratory setup is shown in Fig. 1.

The main element of the setup is a variable current electric arc plasma torch with a power of up to 90 kW and a thermal efficiency of up to 95% [6]. A mixture of methane and argon was used as the plasma-forming gas. The setup also includes a plasma chemical reactor, a heat exchanger, a carbon separation unit from the gas flow, a gas composition analysis system, a gas purification system, and an exhaust fan.

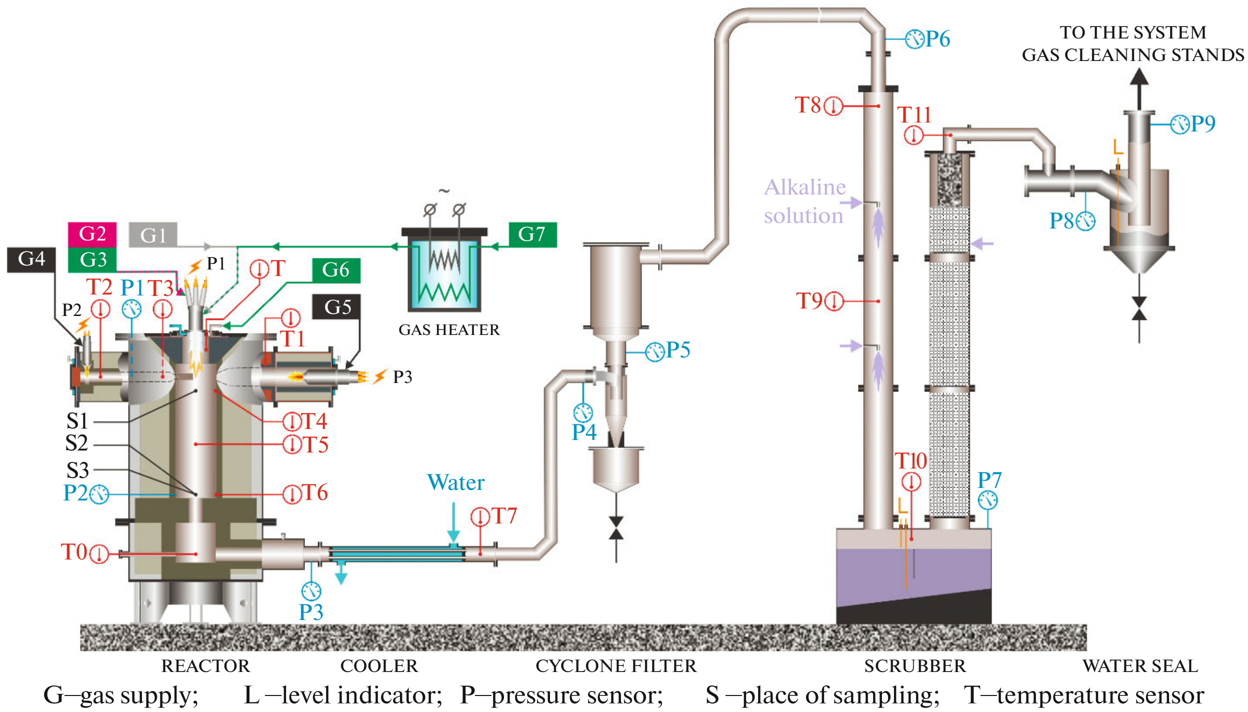

Fig. 1. Diagram of the laboratory setup for plasma pyrolysis.

A mixture of methane (G7) and argon (G2) is fed into the plasma torch. Heating from the electric arcs causes the pyrolysis of methane, resulting in the formation of hydrogen and carbon. The heated plasma flow, consisting of hydrogen, solid carbon, argon, and unreacted methane, then enters the plasma-chemical reactor, where the methane decomposition process is completed. The flow is then cooled in the heat exchanger and directed to the carbon separation unit and gas purification system.

The methane conversion reached 86%, and the energy consumption for producing 1 kg of hydrogen was 20 kW h. The obtained experimental data fully confirms the functionality and efficiency of the technology.

The technological process of hydrogen production based on the developed plasma equipment is proposed to be constructed as follows.

Hydrocarbon raw materials (natural gas or gas condensate) are fed into the plasma torch together with a carrier gas (argon or nitrogen). As a result of the interaction of the gas flow with the electric arcs, the pyrolysis process begins in the plasma torch itself. The pyrolysis process is then completed in the volume of the plasma chemical reactor, on which the plasma torch is installed. Then, the gas flow enters the unit for separating solid carbon, and then the gas flow separation unit. Hydrogen is supplied to the consumer, while the carrier gas and undecomposed hydrocarbons are returned to the technological process. In this case, only the plasma torch and plasma chemical reactor are new technological process units, while the units for separating solid carbon from the gas flow and gas flow separation have long been produced by industry.

The electrical energy required to produce 1 kilogram of hydrogen and 3 kilograms of carbon black in industrial production using this technology is no more than 18 kW h. The technological process itself has no carbon dioxide emissions. However, 70% of the electricity is obtained from fossil fuels. Taking this aspect into account, about 7 kg of carbon dioxide will be emitted per 1 kg of hydrogen produced. Table 1 shows the electricity consumption and carbon dioxide emissions for plasma pyrolysis, electrolysis, and steam methane reforming technologies.

Compared to electrolysis, plasma pyrolysis consumes three times less electrical energy per kilogram of hydrogen produced, and compared to steam catalytic reforming, carbon dioxide emissions are at least one-third lower.

The proposed technology of plasma pyrolysis of hydrocarbons in the current production of electricity allows for a significant reduction in carbon dioxide emissions. This technology is suitable for low and medium-tonnage hydrogen production in places where it is directly consumed, such as chemical and food production, filling stations, pharmaceutical companies, etc.

Table 1. Comparison of hydrogen production methods

Parameter	Plasma pyrolysis (this work)	Electrolysis	Steam methane reforming
Energy consumption, kW h per 1 kg of H_2	18	55–60	≈1
CO_2 emissions, kg per 1 kg of H_2	7	22–24	≈11

PLASMA REFORMING

Steam reforming technology allows for large-scale production, but has significant drawbacks such as incomplete methane conversion, high carbon footprint, and the need to heat water vapor to high temperatures [7]. *Institute for Electrophysics and Electrical Power of Russian Academy of Sciences* has developed and tested a process for synthesizing gas using plasma reforming. The technology is based on a high-voltage alternating current plasma torch created at the Institute [8]. It allows for the production of synthesis gas with the required hydrogen to carbon monoxide ratios within a wide range (1–3) using a single piece of equipment and is suitable for small and medium volumes.

Despite its relative energy intensity, the technology can be environmentally and economically attractive when using "green" electricity, as it allows for the industrial processing of carbon dioxide.

Two experiments were conducted on a laboratory plasma chemical installation (Fig. 1). The goal of the first experiment was to study the processes of steam and carbon dioxide plasma conversion of methane. The plasma-forming mixture consisted of water vapor (G1 = 3 g/s), methane (G3, G7, a total of 3.5 g/s), and carbon dioxide (G2 = 3 g/s) fed into the plasma torch. The power of the plasma torch was 120 kW. The composition of the synthesis gas obtained during the experiment is shown in Fig. 2. The methane conversion was 99.5%.

The goal of the second experiment was to study the processes of carbon dioxide plasma conversion of methane. A mixture of methane (G3, G7) and carbon dioxide (G2) was fed into the plasma torch during the experiment. The total flow rate of methane was 2.4 g/s, the carbon dioxide flow rate was 6.9 g/s, and the power of the plasma torch was 120 kW. The composition of the synthesis gas obtained during the experiment is shown in Fig. 3. The conversion rate was 99.8%.

As can be seen from the experimental results, the plasma process allows for the production of syngas with a wide range of H_2 to CO ratios (1–3) and the ability to flexibly vary this ratio during the technolog-

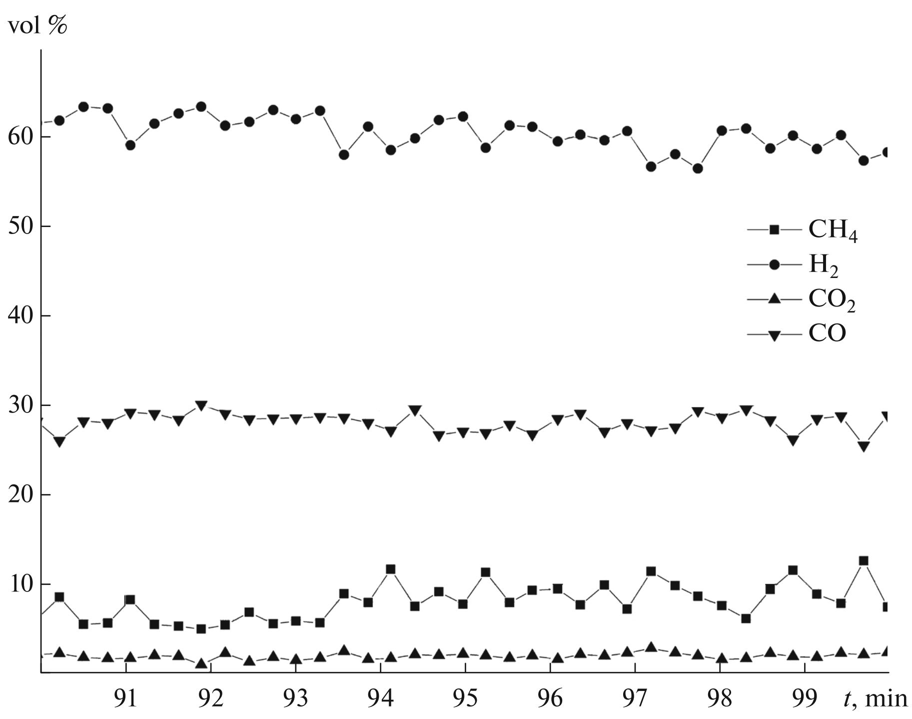

Fig. 2. Results of experiments on steam-carbon dioxide plasma conversion of methane.

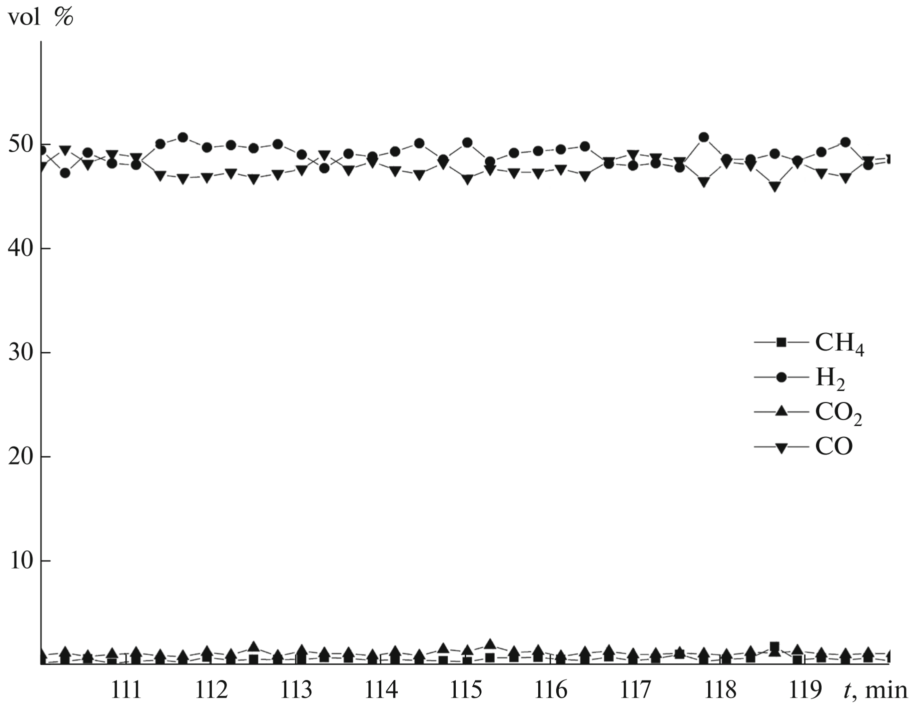

Fig. 3. Results of experiments on carbon dioxide plasma conversion of methane.

ical process by changing the composition of the raw material fed into the technological installation. This technology can be in demand for the creation of small and medium-tonnage productions.

CONCLUSIONS

Two plasma arc methods for producing hydrogen from natural gas have been proposed. It has been established that the degree of conversion of methane during plasma pyrolysis is 86%. During plasma reforming of natural gas in the presence of carbon dioxide and a mixture of carbon dioxide and steam, it exceeded 99%. These results are achieved due to the high temperature in the reaction zone, as well as the qualitative mixing of the reactants. The proposed methods can be used for hydrogen production in small and medium-tonnage volumes.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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