Plasma Gasification of Organic Waste for Production of Motor Fuel

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Abstract—The paper presents the results of computational and experimental studies of plasma gasification of industrial organic waste with the aim of obtaining a combustible (high-calorific) synthesis gas (H₂ + CO) for power generating devices. Experimental results on the fuel composition, obtained in the process of organic waste gasification, are presented. The change in the composition of the fuel gas depending on the time of gasification of organic waste has been studied. Alteration of the calorific value of synthesis gas in the process of gasification of organic waste is shown.

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1. INTRODUCTION

The problem of utilizing organic waste, including medical and biomedical materials, is global all over the world. Recently, the problem of medical waste disposal has been complicated by the situation associated with the COVID-19 pandemic. There was a significant increase in the production of disposable medical masks, and the consumption of medical clothing in hospitals increased. According to the Russian legislation, all medical waste must be disposed of in an environmentally friendly manner.

Thermal technologies for incineration of medical waste and materials do not ensure complete decomposition of complex chemical elements into simple compounds, since the temperature level in such technologies does not exceed 800–900°C. The best technology in terms of safety, productivity, and efficiency is the electroplasma technology, but its application is limited because of its novelty and high operating costs. When these difficulties are overcome, a plasma plant for processing industrial waste can be proposed for utilization, gasification, or annihilation of waste.

To solve the problems of using plasma technology for processing, neutralizing, and destroying hazardous organic waste, it is necessary to conduct a set of tests of an efficient and environmentally safe electroplasma installation. Experimental research is required to find the best technological parameters for waste disposal: composition of waste gases, dependence of waste gases on the temperature in the reaction chamber of plasma electric furnace, specific energy consumption during the technological process, calorific value of the fuel gas, and slag neutrality.

2. RESEARCH

The main element in an electroplasma installation set and the technological chain for waste processing is the plasma electric furnace (Fig. 1); the temperature in furnace reaction zone (3) is as high as 1300–1500°C. Such temperatures can be achieved with electric arc plasmotron (6) with a power of 20–50 kW.

In the process of waste processing, the resulting slag is melted in melting chamber (4). In the plasma electric furnace, slag (8) is drained as the chamber is filled with melt.

The technology is based on the high-temperature (1300 ÷ 1500°C) plasma effect and complete decomposition of high-molecular organic compounds and gasification of utilized products with arc

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plasma to simple chemical compounds to produce a useful product (synthesis gas), which is a mixture of hydrogen and carbon monoxide, as well as inert slag.

A schematic diagram of the experimental plasma–thermal electric furnace with a capacity of up to 20 kg/h is shown in Fig. 1. The plasma electric furnace is lined inside with fireclay bricks and is designed for refinement of the technology of high-temperature (plasma) gasification of renewable carbon-containing waste of various origins (sawdust, rags, polyethylene, biomedical waste, etc.).

Waste is delivered in boxes with overall dimensions of 200 × 200 × 250 mm. It is fed into the working space of the electric furnace through loading device (2), which is equipped with a lock chamber. It prevents escape of flue gases from the working chamber into the atmosphere at overpressure and suction of atmospheric air into the working chamber during its discharge. Waste moves along the inclined hearth in gasification zone (3) with the help of hydraulic pusher (1), connected to the oil station and control unit.

The lining and gasification zone are preliminarily heated by gas burner (5) with a power of 42 kW and plasmatron (6) with a power of 50 kW. Later on, only the plasmatron maintains a temperature of 1300°C during gasification.

The mean mass temperature of the air plasma flowing out of the plasmatron is 4000 K. The synthesis gas (fuel gas) obtained in the gasification zone is fed to the centrifugal bubbling apparatus (CBA) to quench the plasma–chemical reactions and to cleaned from dust. The ash residue formed after the waste gasification, containing underburned particles and carbon residue, enters combustion zone (4) (Fig. 1), where carbon burns out under the action of plasma jet and melts into inert slag.

After the CBA, the fuel gas is fed into the afterburner, where it burns down to CO₂. Before being released into the atmosphere, the gas passes into the mixer for subsequent cooling by mixing with the required amount of atmospheric air.

The source of energy for gasification of the organic part and melting of the ash residue is the plasmatron, as well as the chemical energy of carbon oxidation reactions. Oxygen enters the working chamber of the electric furnace through the plasmatron with the plasma-forming gas (air). Slag is periodically discharged through tap hole (8) into rolling carriage (9).

At the electric furnace outlet, the temperature of the exhaust (flue) gas is measured with a chromel-alumelium thermocouple ChA with a temperature range of 500–1300°C (in a short-term mode, up to 1500°C).

Concentration of the H₂, CO, CO₂, N₂, O₂, and CH₄ gases at the electric furnace outlet was measured by the multicomponent gas analyzer TEST-1, included in the equipment complex.
2. ANALYTICAL STUDIES

Analysis of the elemental composition of organic matter, including biomedical waste, namely, medical masks and disposable syringes, showed that medical masks are made from polymers with wide molecular weight distribution, such as polypropylene, and disposable medical syringes are made from polyvinyl chloride (PVC), which is a polymeric material. Table 1 shows the elemental composition of waste.

Gasification of carbon-containing (organic) materials can be simplistically described with basic chemical reactions (Table 2).

Each reaction occurs in its own temperature range. A steady-state mode of electric furnace operation exhibits stationary temperature distributions of moving waste and gas flow along the furnace height in its working space. This determines the distribution of the energy effects of chemical reactions along the furnace height.

This reaction takes place in the presence of reagents in the reaction space at a temperature above the equilibrium one. Under sequential heating, the waste decomposes with the release of various gaseous substances, which will take part in the oxidation reactions (Table 2). The simulation results are shown in Fig. 2.

Thus, knowing the temperature distribution along the furnace height, we can obtain specific values of masses of gases participating in the reactions for any elementary volume of the working space of the plasma electric furnace for a given productivity of electroplasma plant for waste processing.

The influence of the flow rate of the plasma-forming gas and the temperature in the reaction chamber of the electroplasma furnace on the appearance of methane in the gas was studied numerically. Air was used as a plasma-forming gas in the experiments. Thermodynamic compositions of the resulting

| Composition, % mass | C | H₂ | N₂ | O₂ | H₂O | Ash |
|---------------------|---|----|----|----|-----|-----|
| Polyethylene granules | 85.7 | 14.3 |    |    |     |     |

Table 2. Reactions of SMW thermal processing

| No | Reactions | Thermal effect |
|----|-----------|----------------|
|    |           | kJ/kM         | kJ/kg | kJ/m³ |
| 1  | C+O₂=CO₂  | 395 000       | 32 890 | —     |
| 2  | 2C+O₂=2CO | 110 000       | 9 600  | —     |
| 3  | C+CO₂=2CO | −175 500      | −14 610 | —     |
| 4  | C+H₂O=CO+H₂| −130 500      | −10 860 | —     |
| 5  | C+2H₂O=CO₂+2H₂ | −132 000 | −10 990 | —     |
| 6  | C+2H₂=CH₄  | −74 900       | −6 240  | —     |
| 7  | 2CO+O₂=2CO₂| 285 600       | —     | 12 750 |
| 8  | 2H₂+O₂=2H₂O (liquid) | 286 800 | —     | 12 780 |
| 9  | 2H₂+O₂=2H₂O (vapor) | 241 800 | —     | 10 760 |
| 10 | CH₄+2O₂=CO₂+2H₂O (vapor) | 801 920 | —     | 35 800 |
| 11 | CO+H₂O=CO₂+H₂ | 40 400      | —     | 1 800  |
| 12 | C₂H₄+3O₂=2CO₂+2H₂O | 1 322 500   | —     | 59 040 |
| 13 | 2H₂S+3O₂=2H₂O+2SO₂ | 518 110    | —     | 23 130 |
Fig. 2. Composition of gases escaping from waste at different temperatures.

Fig. 3. Content of CH₄ products in synthesis gas. [O₂]—minimum amount of oxygen required for complete gasification.

Synthesis gas were calculated with the temperature varied from 300 to 3000°C for different amounts of supplied oxygen in the plasma-forming gas. In the process of calculations, the methodology given in [1–3] was used. The results of these experiments are shown in Fig. 3.

According to the diagram in Fig. 3, the CH₄ content declines with increase in the temperature and oxygen content in the reaction chamber of the electroplasma furnace.

3. EXPERIMENTAL ELECTRIC ARC PLASMATRON

The electric arc plasmatron is a fundamental element of the new efficient technology for processing organic waste and part of equipment of the electroplasma installation for implementation of this technology.
A heated air temperature of 3500–4000 K ensures a mean mass temperature of 1100–1300°C in the reaction zone of the plasma electric furnace, which is necessary for gasification of solid organic waste to produce a high-calorific fuel gas. In the studies performed, a plasmatron with copper tubular electrodes of stepped geometry was used [4].

The power source of the plasmatron is presented by two modernized thyristor rectifiers of the APR-404 type, connected in series. We have an open-circuit voltage of 640 V and a rated current of 400 A. For regulation of the strength of the arc discharge current, a ballast resistance in the form of a water rheostat with an adjustable resistance of 0.6–8 Ohm is used. Gas and water supply systems of the experimental installation ensure the long-term operation of the plasmatron.

The current-voltage (CV) characteristic of the arc is the most important electrophysical and energy characteristic of arc plasmatron. It determines the region of stable arc burning at change in the defining parameters: current strength, flow rate and type of plasma-forming gas, medium pressure, and geometric dimensions of the plasmatron discharge chamber. The power supply parameters, which ensure reliable operation of plasmatron in a long-term mode, are determined by the type of the CV characteristic and the level of attainable voltage and arc current values.

The CV characteristic of the arc in the studied plasmatron for various air flow rates is shown in Fig. 4. If we draw a curve of equal power of the plasmatron of 50 kW, it can be seen that it is possible to slightly decrease or increase the power in order to maintain the required temperature in the zone of gasification of the plasma electric furnace waste.

The ascending branch of the CV characteristic allows the arc discharge to burn stably in the power range from 20 to 50 kW in a given range of plasma-forming gas flow rates.

![Fig. 4. Current-voltage characteristics of the arc. Working gas: air.](image)

![Fig. 5. Thermal efficiency of electric arc plasmatron: ▲—experimental data; lines—calculations.](image)
In addition to stability of arc burning in a vortex gas flow and technical measures to ensure the duration of the electrode operation, the efficiency of the plasma device is determined by the coefficient of conversion of electrical energy into heat. In electric arc plasmatrons, electrodes perceive heat from arc radiation, convective heat transfer between the arc discharge, plasma-forming gas and electrode walls, conductive heat transfer and, finally, the cathode and anode arc spots. The heat from the outside of the electrodes is removed by the cooling water. The efficiency of plasmatron is determined by the value of measured heat fluxes.

The heat flux to the output electrode-cathode is

\[ Q^k = c_p \cdot G^k (T_{out} - T_{in}) \cdot 4.18 \ [\text{kJ}] \]

and that to the inner electrode-anode is

\[ Q^A = c_p \cdot G^A (T_{out} - T_{in}) \cdot 4.18 \ [\text{kJ}] \]

The power spent on the plasmatron is \( P = U \cdot I \), kW. Then the thermal efficiency of the plasmatron is

\[ \eta_T = 1 - \frac{Q^k + Q^A}{U \cdot I} \]

The plasmatron efficiencies calculated by formulas (1)–(3) and experimental data are shown in Fig. 5. The presented diagram illustrates good convergence of the calculated and experimental results for the electric arc plasmatron intended for waste gasification/disposal.

4. EXPERIMENTAL STUDIES

Before the tested material (industrial waste) is fed into the chamber of plasma electric furnace, it must be prepared (packed in boxes).

Before the main waste disposal process, for the technological process to be correct, the electroplasma furnace was initially warmed up to the required temperature in the working chamber. After the temperature in the gasification zone increased to 1100–1300°C, the supply of packages with the waste to the furnace began.

The waste feeder is a vertical shaft with two gates. The gate drives are controlled by hydraulic drives connected to the automatic process control system (APCS). This system enables control of the loading system in automatic and manual modes. The hydraulic drive system provides reciprocating motion of the pusher and transfer of the waste over the inclined hearth of the furnace. It enables change in the speed of the forward and back travel of the pusher, ensuring that the waste is in the reaction chamber of the electric furnace for a certain period of time.

The time of waste stay in the furnace is determined depending on the original composition of waste and productivity. For example, packages with waste of 1 kg pass through the gasification zone in 3 minutes, i.e., 20 packages per hour are supplied for gasification, providing an electric furnace capacity of 20 kg/h. This time of waste stay in the reaction chamber allows complete decomposition of the complex chemical constituents of the waste to simple compounds in the form of gas.

The working chamber of the plasma electric furnace and the lining are heated by an electric arc plasmatron with a power of 50 kW. The temperature in the chamber is controlled by a thermocouple, and a signal is sent to the APCS through a normalizing converter. When the operating temperature in the furnace chamber reaches 1200°C, a control signal is sent from the controller to the power source for subsequent reduction of the plasmatron power to further maintain the temperature and re-melt the inorganic waste residue.

The fuel gas (synthesis gas) released in the gasification zone is taken from the furnace chamber. It is fed into the centrifugal bubbling apparatus (CBA), where it is mixed with the water flow, forming a liquid-bubble mixture for quenching chemical reactions and cleaning from dust. The liquid is aqueous alkaline solution. The degree of flue gas cleaning from solid particles is 96–98%; the cleaning from
chlorine and sulfur is about 80%. Before the CBA, gas is sampled by the gas analyzer, which controls the composition of the resulting synthesis gas.

A thermocouple built in the chimney before the CBA monitors the temperature of the taken fuel gas. After the CBA, the synthesis gas is fed to the afterburner, where it is burned to CO$_2$. The volumetric flow rate of humidified flue gases at the CBA outlet (at the inlet to the afterburner) is 100–110 nm$^3$/h. The gas burner maintains a temperature of 1200°C in the afterburner chamber.

From the afterburner, the flue gases are discharged into the cooler ($t \leq 200$°C) for subsequent cleaning in filters and emission into the atmosphere. To cool the flue gases, the required amount of atmospheric air is supplied to the mixer, which is controlled by the automatic control system. The control signal is generated depending on the required temperature of the flue gases discharged into the atmosphere.

The ash residue formed during the waste processing is melted into inert slag under the influence of plasma jet with a temperature of 4000 K. As the bath of liquid melt is filled, the slag is periodically discharged through the tap hole into the rolling carriage.

Along the technological chain of the electroplasma installation - from synthesis gas production to flue gas emission into the atmosphere - the gas temperature is measured by thermocouples (T), and the composition of the exhaust gases (G) is determined by the TEST-1 gas analyzer (Fig. 6).

To ensure a specified productivity of the electric furnace in terms of waste, it is necessary to know the weight of the packages and the rate (frequency) of their feed into the electric furnace.

Based on the mathematical modeling of the process of high-temperature gasification of organic waste, an optimal temperature in the reaction zone of the electric furnace (gasification zone) of 1300–1500°C was chosen.

5. EXPERIMENT RESULTS AND ANALYSIS

Numerical studies of organic waste gasification/utilization have shown that the generated synthesis gas has a calorific value of 11.7 MJ/m$^3$. Calculations with increase in the oxygen content were also carried out. The results obtained showed that an increase in oxygen leads to a decrease in the hydrogen content in the resulting synthesis gas and an increase in the content of CO and CO$_2$. From analysis of the calculated data, the excess oxygen content reduces the electricity consumption by the electric arc plasma from 1.52 kWh/kg to 0.4 kWh/kg.

This is due to the fact that in the course of waste disposal with excess oxygen content, combustion occurs, the calorific value of the synthesis gas remaining almost unchanged and amounting to 11.1 kJ/m$^3$. Further increase in the oxygen flow rate will lead the gasification process to the autothermia mode. The plasmatron will only be needed to stabilize the process and compensate for the heat losses.

With the addition of about 20% of water (imitation of wet waste), synthesis gas with the ratio $\text{H}_2:\text{CO} = 2:1$ with a calorific value of 11.58 MJ/m$^3$ was obtained.

The experimental studies carried out have confirmed the earlier calculated results. Figure 7 shows the change in the calorific value of waste in a certain period of time.
The diagram shows the change in the caloric value of the synthesis gas resulting from one portion of waste over time. The weight of the waste portion was determined in dependence on the productivity of the electroplasma installation. At the beginning of the waste supply to the furnace reaction chamber, the caloric value of the produced gas grows. Then this value reaches its peak, where the maximum release of the energy of the chemical reactions and the complete decomposition of the complex chemical compounds into the simplest ones occur.

Then a decrease follows due to complete decomposition of all elements. The peak is caused by the fact that in experimental studies the waste was fed in portions with regular intervals into the gasification chamber of the plasma electric furnace. To guarantee constancy of the synthesis gas caloric value, it is necessary to ensure continuous supply of the waste.

Figure 8 shows the data of the TEST-1 gas analyzer obtained during gasification of organic waste. The time interval in Fig. 8 repeats the time indicated in Fig. 7. The following conclusions can be drawn from comparison of these two diagrams: at the maximum caloric value of the resulting syngas, 26% of CO, 22% of CH_4, and 13% of H_2 dominate in its elemental composition.

To ensure uniform distribution of the caloric value and elemental chemical composition of the produced gas, it is necessary to carry out uniform loading of the waste into the working space of the
Electroplasma furnace. Thus, the peaks are brought to one level and the process of waste gasification/utilization takes place in the form of optimal technological process.

The diagram of variation of the elemental composition of the produced gas over time is shown in Fig. 9. During the experiment, based on the gas analyzer readings, the mass of the portion of the loaded waste and the time interval for feeding into the reaction zone of the electroplasma furnace were calculated. Analyzing the results obtained, we can make a conclusion about the optimal organization of waste loading and the time of waste portion stay in the reaction zone at a gasification temperature of at least 1200°C.

CONCLUSIONS

Preliminary thermodynamic calculation of plasma gasification of organic wastes, which were used in experimental studies at a laboratory electroplasma installation, showed the possibility of obtaining a high-calorie synthesis gas.

Experimental plasma electric furnaces, electric arc plasmatrons with a power of 50 kW, and a laboratory electroplasma installation for processing organic waste with a capacity of up to 20 kg/h have been tested.

The specific energy consumption for the production of synthesis gas ranges from 0.48 kW·h/kg to 2.2 kW·h/kg, depending on the initial composition of waste.

The calorific value of the synthesis gas obtained is 8 to 13 MJ/kg, which allows its application for combustion in power generating units.

Comparison of the calculated and experimental data for the process of high-temperature gasification of organic waste show good convergence.

From analysis of the experimental data, it can be concluded that the installation developed can be used for gasification of organic waste with production of fuel gas. In addition, its use for disposal of biomedical materials has been tested.

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