Efficiency of biomass and solid waste energy processing based on the cogeneration plant with plasma heat source

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Abstract. The urgency of the use of low-grade organic fuels and wastes, in particular municipal solid (MSW), is due to recent developments in energy saving and energy efficiency. This directly relates to the direction of renewable energy, responsible for involving all wastes, such as MSW, in fuel energy balance to provide heat and electricity to decentralized power supply areas. This paper presents the process of high-temperature thermal decomposition of MSW in the steam-air medium of plasma under excessive pressure to generate electrical energy. The high enthalpy and great reactivity of the plasma gasifying agent makes it possible to carry out the process of thermal decomposition in the autothermal mode. The high-temperature mode and the use of plasma blast provides a high degree of conversion of waste into combustible components (CO, CH₄, H₂), the resulting gas mixture. The technological process significantly reduces the formation of potentially hazardous substances that affect the kinetics of the process. After generating electrical energy, the exhaust gases are subjected to complex purification from the products of combustion and cogeneration of residual thermal energy. In particular, purification from toxic nitrogen oxides (NO_x) occurs, the formation of dioxins, furans and other dangerous derivatives of chloride compounds is prevented. Thermal energy, discharged at various sites of the plant, is almost completely used for the needs of the cogeneration plant and its units, which allows to achieve a total efficiency of at least 86%. The ability of the cogeneration plant to work on various types of solid waste gives a wide range of applications and operational capabilities.

1 Introduction

In recent years, almost in all countries, the close attention has been paid to the problem of the reuse of the resulting production and consumption wastes, including municipal solid waste (MSW). MSWs are man-made resources being hazardous to the environment, and when ignited, dioxins, furans and other toxic substances are formed. At the same time, the composition of MSW is not the same and varies depending on climatic conditions [1-4].

One of the ways to recycle MSW is to use them as sources of secondary raw materials, allowing to achieve an increase in production efficiency by saving materials and ensuring the expansion of the raw material base. The state policy in the field of the environmental development of the Russian Federation for the period up to 2030 provides for the development of a number of areas such as the involvement of waste in re-economic turnover through the fullest possible use of starting raw materials; use of the resulting waste through recycling, regeneration, recovery, reuse; introduction and use of low-waste and resource-saving technologies and equipment.

One of the benchmarks in the Energy Strategy of the Russian Federation for the period up to 2035 is sustainable energy development, which includes environmental safety and innovative development. The document also noted the unreasonably low share of the use of local fuels (including MSW) in regional energy balances [5-8]. The set of proposed measures to overcome the current practice includes: encouraging the reduction of the formation of new and utilization of accumulated waste; stimulation of scientific research and support for the development of promising technological solutions aimed at reducing the negative impact on the environment and environmental risks; new technologies for gasification of various raw materials, including biomass, MSW, etc [9-13].

The choice of gasification technologies with a plasma heat source is justified by the peculiarities of the process. The method of chemical heat treatment of waste, due to the intensification of the process of plasma-chemical transformations and a high concentration of energy per volume unit [14-17]. Gasification with a plasma heat source can be used to solve a wide range of tasks, including the processing 98% of all types of waste. Plasma gasification is based on a high-temperature process (up to 1100 °C), which allows to get the

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maximum yield of energy gas, and a further temperature increase (from 1200 °C and above) makes it possible to obtain synthesis gas with a minimum content of tar and harmful impurities. It follows that with increasing temperature, an increase in the percentage of combustible components in the gas, and, accordingly, the calorific value is observed [18-23].

As a result, the main task set in the development of innovative technical solutions for the creation of cogeneration plants is to obtain a high-calorific combustible energy gas with an almost complete absence of tars and toxic components in the resulting mixture.

2 Methodology and research tools

When disposing of MSW, a special interest is caused by the process of thermal processing using the plasma generator as a source of thermal energy and to conduct the process at an overpressure in the reactor. It's known from the literature that plasma has a temperature of at least 3000 °C, which makes it possible to destructure almost all solid waste, and an excessive pressure reduces the yield of tar, improves productivity and favorably affects the formation of methane (CH₄) in the gas mixture [24-26].

Most gas generators in the cogeneration units are designed to work with natural gas (methane), and require significant modifications in the case of using a different gas mixture. At the the same time, an increase in the composition of the gas mixture of methane will remove the need for modernization of the unit, which will also have a positive effect on the efficiency of the power plant.

To study this issue and confirm the assumptions put forward, an experimental setup for the high-temperature thermal decomposition of MSW and plant biomass in plasma under pressure was developed (Figure 1). The facility is designed to study the production of high calorific combustible gas and its effect on the efficiency

of electric energy generation.

The experimental installation was made of heat-resistant stainless steel that allows to work under pressure up to 2 MPa and temperatures up to 1500°C and consists of the following main elements: reactor 1, scrubber 2, gas distribution unit 3, plasma generator 8, electric generator 9.

Experimental installation works as follows: the reactor 1 is loaded with the material under study and tightly closed. After checking the connections, the process of forcing the pressure in the reactor 1 and the pipeline system of the installation is carried out. The pressure medium is argon supplied from cylinders through the collector system 4. The pressure created depends on the experimental conditions, but does not exceed 2 MPa. The pressure pumping system is connected to the main gas pipeline through the gas distribution unit 3, which is needed to control the pressure in reactor 1, through sensor 5. When the required pressure in the system is reached, the argon supply is stopped, and the pressure in the system is held and regulated by valve 6 and throttle device 7.

After creating the required pressure, the plasma generator is started to heat the reactor 1 to the required temperature, which is controlled and regulated by the thermostat. The resulting gases are discharged through the throttle 7, and some of the gases are sent for gas analysis. The duration of the experiments varied in the range from 2 to 3 hours.

3 Results and discussion

Data were obtained at the experimental plant on the formation of methane during thermal processing of MSW and plant biomass (sawdust) under various pressures using a plasma heat source.

The resulting graphical dependencies (Figure 2) confirm the assumptions. It is seen that with increasing pressure, the methane content in the gas mixture

Fig. 1. Experimental setup.

increases. The nature of the dependencies is also compared with literature sources. It is noted that with increasing pressure, the resin content in the gas is much lower. This is due to the increased duration of the stay of gases in the reaction zone and the acceleration of heat and mass transfer processes in consequence of the creation of excess pressure.

Fig. 2. The dependence of the volume content of methane in the gas mixture on the temperature at different pressures.

Further, a full component analysis of the resulting mixture of gases from different raw materials was carried out under the same process conditions with the highest pressure. Comparison of calculated and experimental data was carried out. Analysis of gas samples was carried out on the chromatograph "Crystal-5000", on a column with activated carbon. At the same time, oxygen and nitrogen on the chromatogram showed only a peak. The area of all peaks was determined by the content of the components in the gas mixture (absolute calibration was used). In consequence of the low content in the mixture of combustible gases of ballast components (less than 1%), they were considered as nitrogen.

Comparative analysis shows a slight discrepancy between the data, but the general nature of the formation of gas mixture components is similar for all [27-32]. It can also be noted that at an average process temperature of 1200°C, the calculation shows a greater amount of combustible components in the gas mixture. This fact allows to conclude that there is still an opportunity to increase the calorific value of the generated gas, and therefore its energy potential.

As noted earlier, the plasma generator serves as a source of heat to ensure the stabilization of the process of thermochemical processing of waste [33-34]. In this case, the plasma generator consumes electrical energy. To identify the energy costs for processing, modeling was performed and the dependence of the gasifier capacity on the power of the plasma generator was obtained. The simulated dependence is linear and shows that the performance of the gasifier is proportional to the power of the plasma generator. For clarity, the simulation was carried out for raw materials with different humidity. To estimate energy costs, the data obtained were reduced to 1 kg of processed raw materials. Electricity consumption averaged 0.81

kW•h/kg (at 55%), 0.7 kW•h/kg (at 47%) and 0.39 kW•h/kg (at 22%).

It should be noted that the simulation was carried out for stationary operation of the gas generator. During start-up and warm-up, the power consumption is naturally higher [35-37].

A comparative analysis was made of experimental data on the performance of a standard gasifier and a gasifier with a plasma heat source [38-40]. Under the condition of operation in the autothermal mode and the same temperature, the performance of the gasifier with a plasma heat source is about 1.8 times higher. Experimentally, a gasifier with a plasma heat source achieved a mode in which 14 MJ of energy was obtained from 1 kg of MSW at an energy cost of 2.5 MJ / kg. A theoretical assessment of the use of a cogeneration unit based on a gasifier with a plasma heat source showed that the specific power output could be 6.5 MJ / kg, and the efficiency of converting the primary energy of MSW to electrical energy will be at least 45%.

In the process of research, the resulting gases with the best indicators on calorific content and methane content, after cooling and purification from fine particles, were fed to a standard 2 kW electric gas generator (GROUP SH3000SE model). A stand with metering devices and the possibility of creating home conditions for the operation of electrical appliances with load control were used as a source of load and measurements.

To assess the effectiveness of the generator on the resulting mixture of gases at the beginning of the work was analyzed on natural gas (methane). The data obtained were taken as reference. As a result, when working on natural gas, the electric generator gave out more than the stated power of about 2.1 kWh, after which the automatic protection system worked. When working on the resulting mixture of gases with a low methane content, the electric generator did not work stably, gave out power in the range from 1.1 to 1.4 kWh and turned off periodically. This confirmed the thesis about the need to upgrade the device. However, when working on a mixture of gases with a methane content (about 18%), the electric generator worked relatively stably and gave out power in the range from 1.4 to 1.6 kWh. With an increase in the gas content of methane, even up to 18%, it has increased the stability of the generator and increased the efficiency of power generation up to 72% relative to the standard. When using a gas mixture without methane, the efficiency was 57%, which is a critically low figure for a power plant.

The results obtained indicate the need to increase the methane content in the gas mixture, which results in the production of combustible gases containing methane by thermochemical processing of raw materials under pressure using a plasma heat source. However, the use of high pressure has a number of drawbacks - the intensity of metal and the cost of equipment increase. Also requirements for operational safety are increased. Solving these problems is an additional incentive for further research in the field of thermal processing of raw materials at elevated pressure.

4 Conclusions

The use of plasmatrones for the processing of MSW and plant waste allows for the processing of the organic component to produce high-calorific combustible gas. At the same time, the implementation of the process under excessive pressure allows accelerating heat and mass transfer processes, increasing productivity and reducing equipment dimensions. In addition, it becomes possible to use gas cleaning methods that are not economically viable at atmospheric pressure. This prevents the formation of especially harmful substances that have a negative impact on the environment. The good convergence of the calculated and experimental data on the processing of solid waste and plant raw materials allows you to use the results to predict the composition of the combustible gas and the specific energy consumption of the studied technology. The gas obtained in gasifiers with a plasma heat source contains up to 90% of combustible components and is a high-quality raw material for the needs of small energy. This indicator allows to reach the total efficiency of the cogeneration unit at least 86%. The ability of the cogeneration plant to work on various types of solid waste provides a wide range of applications and operational capabilities.

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