Plasma processing of agricultural waste: thermodynamic analysis and experiment

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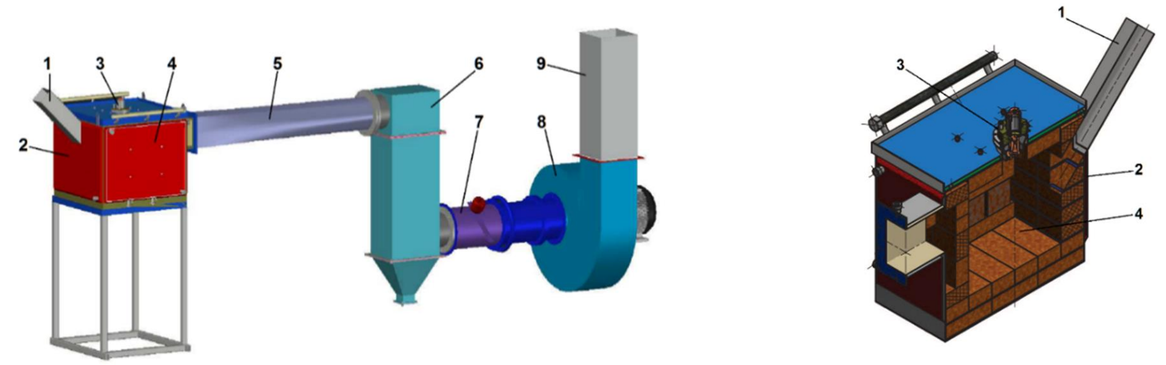
For both environmental and economic reasons, there is a continuing wide interest in the processing and disposal of industrial and domestic waste, including biomass and agricultural waste (AW), and the development of recycling technologies (Davidson, 2011; Messerle et al., 2018; Messerle et al., 2020; Miller, 2010). AW is formed in the agro-industrial complex after processing and preparing products for sale. A significant part of AW is provided by poultry farms and livestock enterprises, mainly in the form of bird droppings and manure. Their huge amount and irrational use negatively affects the environment. One of the well-known products of AW processing is biogas, which is formed due to the process of biomass fermentation under the influence of bacteria. The process of obtaining biogas is very long (up to 12 days), and plants for producing biogas from AW are characterized by low productivity (up to 100 m^3 per ton of waste). An alternative method of recycling AW is its high-temperature plasma gasification and pyrolysis. Plasma processing of AW makes it possible to intensify the process of obtaining fuel gas, which consists mainly of synthesis gas ($CO + H_2$), and increase the plant productivity by 150–200 times. This is achieved due to the high temperature in the plasma reactor and a multiple reduction in the waste processing time.

This paper presents the results of thermodynamic analysis and experimental studies of the plasma processing of AW, which confirmed the prospects for the implementation of plasma gasification of AW with the production of high-calorie fuel gas. Dried mixed manure from cattle, horses, sheep, goats and pigs (dung with a moisture content of 30%) was used as AW. Characteristic composition of AW (dung), wt.%: H_2O – 30, C – 29.07, H – 4.06, O – 32.08, S – 0.26, N – 1.22, P_2O_5 – 0.61, K_2O – 1.47, CaO – 0.86, MgO – 0.37. The organic matter of AW is mainly cellulose ($(C_6H_{10}O_5)n$) with a small amount of organic sulfur. The organic part of AW, including moisture, is represented by carbon, hydrogen, and oxygen with a total concentration of 95.21%, while the mineral part is only 4.79%.

To carry out the thermodynamic analysis of plasma gasification and pyrolysis of AW, the universal program for calculating multicomponent heterogeneous systems TERRA was used (Gorokhovski et al., 2005; Messerle et al., 2018). It has its own database of thermodynamic properties of 3000 individual substances in the temperature range of 300–6,000 K. It was created for high-temperature processes computations and based on the principle of maximizing entropy for isolated thermodynamic systems in equilibrium. Calculations of AW plasma processing were performed for the temperature range of 300–3,000 K at a pressure of 0.1 MPa for the following thermodynamic systems, mass fractions: 1 AW + 0.25 air (plasma gasification) and 1 AW + 0.25 nitrogen (plasma pyrolysis). The purpose of the calculations was to determine the composition of the gas phase of the gasification products, the degree of carbon gasification, and the specific energy consumption for the process. The calculations showed that the degree of gasification increases with increasing temperature in both processes, but somewhat faster during gasification than during pyrolysis. However, at T = 950 K, the degree of gasification reaches 100% for both processes. The compositions of the gas phase of the products of AW plasma gasification and pyrolysis are qualitatively similar. At an optimum temperature of 1,500 K, which provides both complete gasification of AW carbon and the maximum yield of combustible components (99.4 vol.% during AW gasification and 99.5 vol.% during pyrolysis), and decomposition of toxic compounds of furan, dioxin, and benz(a)pyrene, the following composition of combustible gas was obtained, vol.%: CO – 29.6, H_2 – 35.6, CO_2 – 5.7, N_2 – 10.6, H_2O – 17.9 (gasification) и CO – 30.2, H_2 – 38.3, CO_2 – 4.1, N_2 – 13.3, H_2O – 13.6 (pyrolysis). Specific energy consumption at a temperature of 1,500 K is 1.28 and 1.33 kWh/kg, respectively, for gasification and pyrolysis of AW.

AW gasification experiments were conducted on the installation (Fig. 1 a), comprised of a DC plasma torch with rated power of 100 kW and a plasma reactor with rated capacity of 50 kg/h (Messerle et al., 2020). Along with the reactor and plasma torch, the experimental setup includes systems for supplying plasma gas and cooling water to the plasma torch and reactor, a power supply for the plasma torch, and a purification system for the exhaust gases. The experimental setup is equipped with a system for sampling gaseous waste gasification products for their subsequent analysis. The condensed products of the gasification process accumulated at the bottom of the reactor and were taken for analysis after it was turned off. The AW was gasified in an air (or nitrogen during pyrolysis) plasma jet, which provided a mass-average temperature in the reactor volume of at least 1600 K. The organic part of the AW was gasified, and the inorganic part of the waste was melted. The resulting synthesis gas was continuously removed from the plant through purification and cooling systems. The molten mineral part of the waste was removed from the reactor after it was shut down and cooled down. In the course of experiments on AC plasma treatment, the power of the plasma torch was 104.1 and 97.1 kW, respectively, for pyrolysis and gasification. Specific energy consumption for the processing of AW in a plasma-chemical reactor was 1.5 and 1.4 kW h/kg during pyrolysis and gasification, respectively. The maximum temperature of the lining of the lower part of the reactor during the processing of AW reached 1887 K. The plasma torch was turned off 27 minutes after loading the first briquette AW. During this time, 75 briquettes with a total weight of 22.5 kg were gasified, which corresponded to the reactor's AW capacity of 50 kg/h. The flow rate of the plasma-forming gas (air or nitrogen) was 19.4 kg/h. At the outlet of the reactor, a gas of the following composition was obtained, vol.%: CO – 25.9, H_2 – 32.9, CO_2 – 3.5, N_2 – 37.3 (pyrolysis in nitrogen plasma); CO – 32.6, H_2 – 24.1, CO_2 – 5.7, N_2 – 35.8 (air plasma gasification). The output of synthesis gas reaches 58.5 vol.% during pyrolysis and 56.7 vol.% during gasification. This agrees well with the thermodynamic calculation data. According to the thermodynamic calculation at a temperature of 1,500 K, which ensures complete gasification of AW carbon and decomposition of toxic compounds of furan, dioxin, and benzo(a)pyrene, a yield of synthesis gas during pyrolysis was 68.5 vol.% and during gasification 65.2 vol.%. Thus, the discrepancy between experiment and calculation in terms of the yield of the target product (synthesis gas) does not exceed 16%. The discrepancy in the total concentration of ballast impurities (CO_2, N_2, H_2O) did not exceed 24 vol.%. The specific heat of combustion of the combustible gas formed during pyrolysis and plasma-air gasification of AW is 10,500 and 10,340 kJ/kg respectively. After gasification of 22.5 kg of AW, 1.35 kg of ash was collected from the bottom of the plasma-chemical reactor during plasma-air gasification and 1.3 kg of ash during plasma pyrolysis. This amount of ash is about 6% of the original mass of AW. The measured flue gas flow was 40.6 kg/h in both cases. The carbon content in the slag sample was also determined by the absorption gravimetric method, which amounted to 2.1 and 2.99%, respectively, during pyrolysis and gasification of the AW. This corresponds to the degree of carbon gasification AW 91.3 and 87% during pyrolysis and gasification, respectively. The maximum discrepancy between the experimental and calculated (100%) values of the degree of carbon gasification does not exceed 13%. The discrepancy between experiment and calculation in terms of specific energy consumption for plasma pyrolysis and gasification processes does not exceed 11%. No harmful impurities were found in the products of plasma pyrolysis and air gasification of AW both in calculations and in experiments.



a b

Figure 1. Scheme of the experimental installation (a) and a plasma reactor for plasma gasification of waste (cross section) (b): 1 – pipe for loading briquetted waste, 2 – plasma reactor, 3 – electric arc plasma torch, 4 – waste gasification zone, 5 – exhaust gas cooling unit, 6 – gas cleaning unit, 7 – section with gas sampling and temperature measurement system, 8 – exhaust fan, 9 – ventilation pipe.

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