

Article

The Gasification and Pyrolysis of Biomass Using a Plasma System

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Abstract: This research paper analyzes the use of plasma technology to process biomass in the form of dried, mixed animal manure (dung containing 30% moisture). The irrational use of manure as well as huge quantities of it can negatively impact the environment. In comparison to biomass fermentation, the plasma processing of manure can greatly enhance the production of fuel gas, primarily synthesis gas ($\text{CO} + \text{H}_2$). The organic part of dung, including the moisture, is represented by carbon, hydrogen, and oxygen with a total concentration of 95.21%, while the mineral part is only 4.79%. A numerical analysis of dung plasma gasification and pyrolysis was conducted using the thermodynamic code TERRA. For 300–3000 K and 0.1 MPa pressure, the dung gasification and pyrolysis were calculated with 100% dung + 25% air and 100% dung + 25% nitrogen, respectively. Calculations were performed to determine the specific energy consumption of the process, the composition of the products of gasification, and the extent of the carbon gasification. At 1500 K, the dung gasification and pyrolysis consumed 1.28 and 1.33 kWh/kg of specific energy, respectively. A direct-current plasma torch with a power rating of 70 kW and a plasma reactor with a dung processing capacity of 50 kg/h were used for the dung processing experiments. The plasma reactor consumed 1.5 and 1.4 kWh/kg when pyrolyzing and gasifying the dung. A maximum temperature of 1887 K was reached in the reactor. The plasma pyrolysis of dung and the plasma–air gasification of dung produced gases with specific heats of combustion of 10,500 and 10,340 kJ/kg, respectively. Calculations and experiments on dung plasma processing showed satisfactory agreement. In this research, exergy analysis was used to quantify the efficiency of the plasma gasification of biomass. One of the research tasks was to develop a methodology and establish standards for the further standardization of monitoring the toxic emissions of dioxins, furans, and Benzo[a]pyrene.

Keywords: biomass; plasma reactor; processing; synthesis gas; thermodynamics; experiment; exergy; optimization



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1. Introduction

In its development, humanity has reached a point when the awareness of the limited nature of natural resources and the need to take measures to preserve the environment coincide with the growing problem of recycling household and industrial waste and maximizing the use of secondary raw materials and energy resources. Of the renewable energy sources, the most important for the annual increase in their capacity are municipal solid, agricultural, and forestry waste. The world now generates more than 2 billion tons of municipal solid waste annually, which is expected to increase by 70% to 3.4 billion metric tons by 2050 [1]. In Kazakhstan, about 5 million tons of household waste are produced annually, of which 5% is processed. It already accumulates more than 100 million tons of household waste nowadays [2,3]. In accordance with the concept, by 2030, the waste recycling proportion should increase to 40%, and by 2050, it should increase to 50%. In

addition to municipal solid waste, a significant part of organic waste is represented by biomass formed in the agro-industrial complex after processing and preparing products for sale. Livestock enterprises and poultry farms produce considerable amounts of biomass (BM), mainly through manure and bird droppings. Every year, 1.5–2 billion tons of manure is produced in the world [4]. It negatively affects the environment due to the huge amounts and irrational use. Currently, the development of technology for processing waste from the agro-industrial complex is a pressing, unresolved environmental and technological problem for crop production, livestock farming, and poultry farming. The traditional use of BM has been composting [5]. Composting is a biological process that occurs under aerobic conditions (the presence of oxygen) with adequate moisture and temperatures that involves the hygienic transformation of organic wastes into a homogeneous and plant-available material. For the preparation of ideal compost and within a short period of time, there is a need to keep all the factors affecting compost preparation in the ideal range. Compost plays a crucial role in improving the soil structure, as it allows more air into the soil, facilitates drainage, and reduces erosion. During droughts, compost helps to keep soil from drying out. However, composting is quite limited in its application because of a number of disadvantages. In industrial composting, space requirements are the biggest issue. Compost fields can extend for hundreds of meters and require perimeter drainage ditches, equipped sludge ponds, and aquifers that prevent manure runoff from seeping into groundwater. Remember the unpleasant odor as well. Composting is a long process. Animal excrement may contain pathogens that cause dangerous diseases. In order to destroy them, they must be heated, which is not always achievable with composting. Autothermal methods for converting BM into combustible gas by gasification and pyrolysis are known [6].

A growing interest in biomass gasification has been seen in Europe over the past few years. For example, in Italy, over the past 10 years, more than 50 small-scale installations for the gasification of biomass to produce combustible gas have been built, which has reduced the economic and environmental burden. The main disadvantages of BM gasification include the insufficient stability of the modes, which leads to interruptions in the operation of gas generator stations and causes their low availability; the high cost of gasification technologies, which have increased due to the need to clean the gas from resin and solid particles, which is required for most types of gas-consuming equipment; and the high nitrogen content, which reduces the heat of the combustion and complicates the use of gas in highly efficient technological converters, and for the synthesis of chemicals. Thus, the main method of BM utilization in the world is the bacterial fermentation of biomass [7]. This method opens up possibilities for creating the environmentally friendly energy of the future. A well-known product of this method is biogas. It is a renewable energy source and is a mixture of methane, carbon dioxide, and hydrogen gases formed during the anaerobic breakdown of BM [8–10]. Bacterial fermentation is a multi-stage process requiring the breakdown of long and complex molecular chains. BM cannot be converted into biogas efficiently since wood cellulose and lignocellulose, found particularly in manure, are difficult for bacteria to digest. Plants producing biogas are not very productive (not more than 100 cubic meters of gas per ton of biomass), and biogas processing takes up to 12 days. To accelerate the process of converting BM into biogas, chemical, physical, and mechanical methods or a combination of these can be used [11]. Most technologies, however, are either ineffective or expensive, or they use aggressive chemical reagents that are harmful to the environment. Plasma facilitates and accelerates the conversion of BM into combustible gases [11,12]. Long and complex molecular chains of BM are broken using plasma energy. As a result of BM plasma–chemical processing, fuel gas, primarily synthesis gas ($\text{CO} + \text{H}_2$), can be obtained more efficiently and the plant productivity can be increased 150 to 200 times. The plasma reactor's high temperature and multiple reductions in the waste processing time enable this [12–18]. BM plasma–chemical processing can yield synthesis gas that can be used as a working fluid for high-efficiency electric generators of the new generation, including solid oxide fuel cells [19]. A promising environmentally friendly technology

for BM processing is the plasma one [14,16,20,21]. Unlike other technologies, plasma processing involves high temperatures in the reactor, which almost completely convert the carbon contained in the waste into carbon monoxide and allow for the neutralization of any harmful substances present. The combustible gas obtained by the plasma processing of BM is characterized by a high calorific value (10–14 MJ/m³). A plasma torch, which is the main component of the plasma reactor, heats plasma-forming gas by an electric arc at a temperature of about 10,000 K. The plasma flame heats the waste to 1550–2000 K and beyond, converting the organic waste into gas and the inorganic waste into neutral slag. The resulting products are inert and non-toxic. Applications of plasma technologies for the processing of biomass have positive potential for dissemination in agro-industrial countries because they can reduce carbon footprints and generate heat and electricity. Table 1 presents an analysis of the potential impacts of novel plasma technology on the environment [22].

Table 1. Potential impacts of plasma technology on the environment.

Positive Impacts	Negative Impacts
Waste disposal	
The efficient processing of hazardous and difficult-to-process waste, toxic chemicals, and medical and biological waste. The processing of waste into synthesis gas and neutral substances. There are virtually no by-product emissions due to the high processing temperatures.	Synthesis gas obtained from waste requires further use to produce power.
Energy production and cost	
Using synthesis gas to generate electricity, reducing dependence on fossil fuels and carbon emissions.	Plasma technology has relatively high energy costs.
Investments	
Using plasma technology for waste processing is relatively less expensive and has the shortest payback period.	Plasma technology is novel and high-tech, which limits its viability.

As can be seen from the table, plasma BM processing technology is an innovative technology and an effective tool for processing BM into useful products (synthesis gas and neutral slag) obtained with minimal environmental damage.

2. Materials and Methods

2.1. Materials

As BM, a blend of cattle, horse, sheep, goat, and pig dried manure was used (dung containing 30% moisture). The characteristic composition of BM (dung) is as follows in wt. %: H₂O—30; C—29.07; H—4.06; O—32.08; S—0.26; N—1.22; P₂O₅—0.61; K₂O—1.47; CaO—0.86; and MgO—0.37. Most of the organic matter in BM consists of cellulose ((C₆H₁₀O₅)_n) and some organic sulfur (S). BM comprises 95.21% organic matter, including moisture, and is made up of carbon, hydrogen, and oxygen, while mineral matter makes up 4.79%. BM has a heat of combustion of 16 MJ/kg. For the plasma gasification and pyrolysis of BM, the following mixtures were used by weight: 100% BM + 25% air and 100% BM + 25% nitrogen, respectively.

2.2. Thermodynamic Modeling Method

Thermodynamic calculations were used to determine the integral indicators of BM plasma processing, including the equilibrium gas phase composition, carbon gasification level, and specific energy usage. In order to study the thermodynamics of waste plasma processing, TERRA was used, a program designed for the calculation of multicomponent heterogeneous systems [19]. The TERRA program uses the maximum entropy principle for isolated thermodynamic systems in equilibrium, unlike traditional chemical thermody-

namic methods that utilize Gibbs energy, equilibrium constants, and Guldberg and Libra's mass action law to calculate the equilibrium parameters. Combined with the laws of the conservation of mass, energy, and electric charge, the fundamental laws of thermodynamics provide the methodological basis for thermodynamic calculations. For closed thermodynamic systems, this allows for the construction of a mathematical model for the formation of gaseous, condensed, electrically neutral, and ionized substances in equilibrium. The system under study was generally heterogeneous, consisting of several phases divided by visible boundary lines, and all individual gaseous substances were included in one gaseous phase. A gas phase must be present in every system considered, while condensed substances may not be present. According to the second law of thermodynamics, the equilibrium of such systems is characterized by a maximum entropy relative to the thermodynamic degrees of freedom, such as the temperature (T), pressure (P), and concentration (C_i) of the equilibrium mixture. Once the thermodynamic equilibrium is achieved, the phase and chemical composition of the systems are uniquely related to the remaining state variables (the pressure, temperature, density, and internal energy). The TERRA database contains information about more than 3000 substances with thermochemical properties between 300 and 6000 K.

2.3. Experimental Setup and Procedure

The plasma–chemical process of BM was investigated for determining the integral indicators of the process (the mass average temperature, mass ratio of the oxidizer to the BM, specific energy consumption, carbon gasification level, and gaseous product yield and composition). The methodology for determining the integral indicators of the waste recycling process is based on the reduction in the material and heat balances of the plasma installation. Using instruments to measure the electric parameters, flow rates and compositions of the reagents and waste processing products, and average mass temperatures and heat losses, all components of the experimental plasma installation were measured.

Experimental studies of BM plasma–chemical gasification and pyrolysis were carried out on an installation, the main elements of which were a direct-current plasma torch with a nominal power of 70 kW and a plasma–chemical reactor with a BM capacity of about 50 kg/h [14,23]. Figure 1 shows reactor 2 with plasma torch 3. In addition to them, the experimental installation consisted of a power supply system, systems for supplying plasma-forming gas and cooling water to the plasma torch and reactor, a plasma torch control system, and a purification system for exhaust gases (Figure 2). Gaseous products from BM plasma processing 7 were sampled in the experimental installation for later analysis. After the gasification process was completed, the condensed products were taken for analysis from the bottom of the reactor.

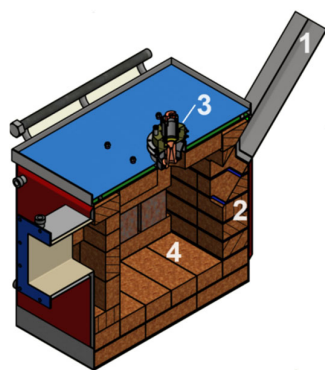


Figure 1. Diagram of a plasma reactor for waste gasification (cross section): 1—branch pipe for loading briquetted waste into the reactor; 2—plasma reactor; 3—direct-current electric arc plasma torch; 4—waste gasification zone.

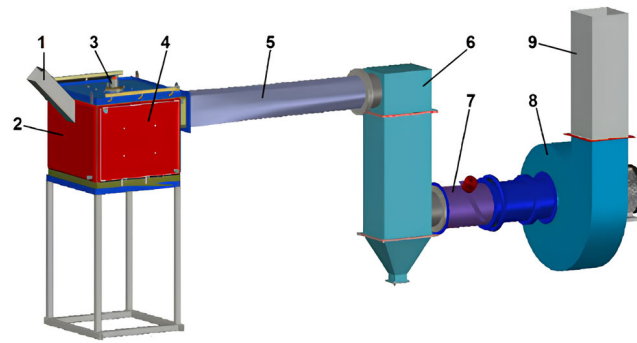


Figure 2. Diagram of the experimental installation for plasma gasification of waste: 1—briquetted waste loading pipe; 2—plasma reactor; 3—direct-current arc plasma torch; 4—waste gasification zone; 5—waste gas cooling section; 6—bag filter for purifying waste gases; 7—section for sampling and measuring gas temperature; 8—exhaust fan; 9—ventilation pipe.

Plasma reactor 2 was designed for BM plasma processing. The reactor was designed in the form of a cube lined with refractory bricks 0.065 m thick, and the size of the inner side of the cube is 0.45 m. The reaction volume of the reactor is 0.091 m³. The reactor wall is equipped with a pipe for loading briquetted BM 1 into the reactor. Observation windows and thermocouples were installed in the reactor walls to permit pyrometric temperature measurements. The plasma installation is capable of processing about 50 kg/h of BM.

The temperatures in the reactor and at its outlet were measured using an Ircon Ultrimax Plus UX10P digital pyrometer, used to measure temperatures from 870 to 3300 K. The error in the temperature measurement depends on the temperature range in which the measurement is made. Thus, when measuring temperatures up to 1770 K, the error is up to $\pm 0.5\%$ of the measured value, in the range of 1770–2300 K— $\pm 1\%$, and when measuring above 2300 K, the error increases to $\pm 2\%$ of the measured temperature value. The temperature resolution is not lower than 1 degree. The Khromatek-Gazochrom-2000 gas chromatograph analyzes the gaseous products of BM processing. This chromatograph analyzes 6 components (H_2 , N_2 , CO_2 , CO , CH_4 , O_2) with a relative error of up to 5%. To determine the content of residual carbon in the slag and the degree of the carbon conversion of the waste, after the completion of the experiment and cooling of the reactor, samples of condensed products are taken from the reactor's slag formation zone. In order to determine the amount of carbon left in the slag samples, the absorption–gravimetric method is used.

Measurement of the exhaust gas flow was performed using a measuring orifice plate that uses the pressure drop method to measure the gas flow. The ratio between the diameter of the orifice and the diameter of the pipeline was 0.2. The relative error in measuring the exhaust gas flow rate was 0.5%.

3. Results and Discussion

3.1. Thermodynamic Modeling

The results of the calculations of the composition of the gas and condensed phases, the degree of carbon gasification, and the specific energy consumption of the BM plasma processing are presented in Figures 3–8. Figure 3 shows the degree of gasification of the BM during the air gasification (curve 1) and pyrolysis (curve 2) depending on the temperature. The figure shows that the degree of gasification increased with the increasing temperature in both cases, but during gasification, it was slightly faster than during pyrolysis. However, at a temperature of 950 K, the degree of gasification reached 100% for both processes.

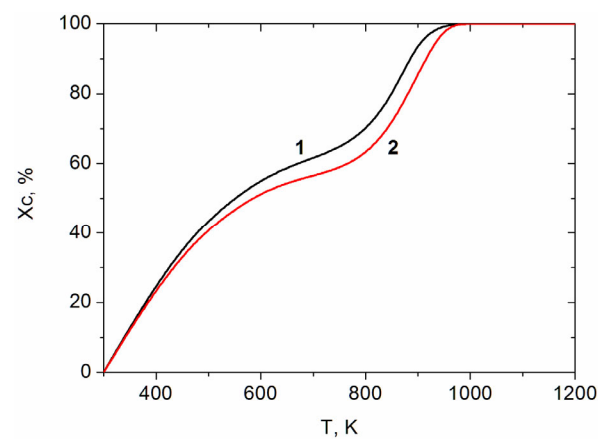


Figure 3. Dependence of the degree of gasification of BM carbon on the temperature of air gasification (1) and pyrolysis (2).

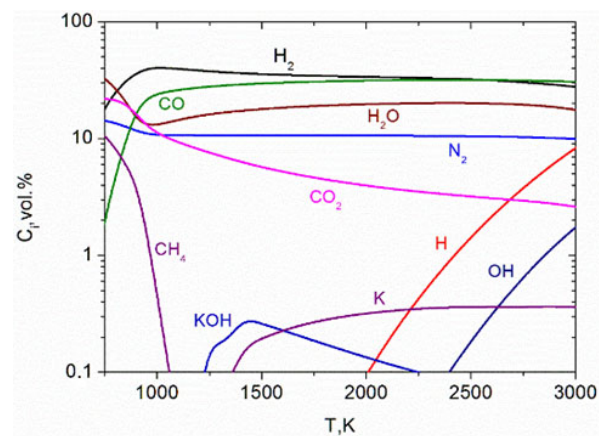


Figure 4. Composition of the gas phase during BM plasma-air gasification as a function of temperature.

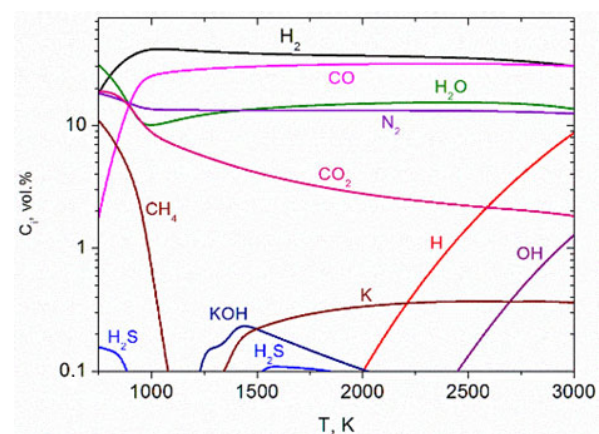


Figure 5. Composition of the gas phase during BM plasma pyrolysis as a function of temperature.

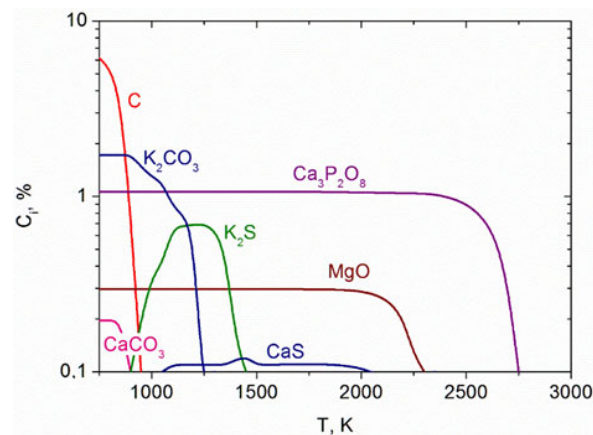


Figure 6. Composition of the condensed phase during BM plasma-air gasification as a function of temperature.

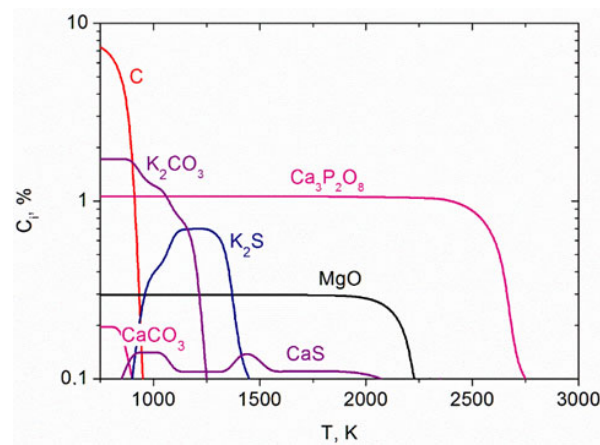


Figure 7. Composition of the condensed phase during BM plasma pyrolysis as a function of temperature.

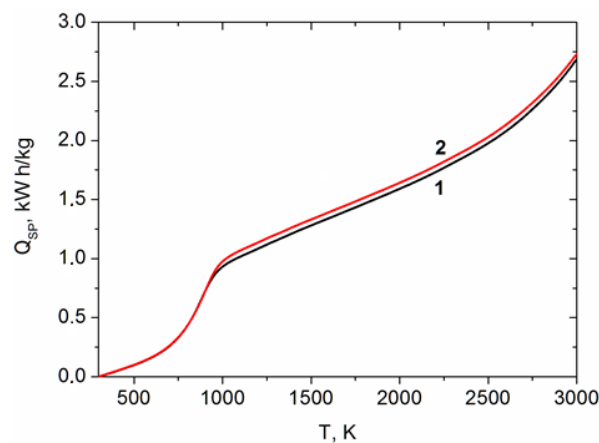


Figure 8. Specific energy consumption during BM plasma gasification (1) and plasma pyrolysis (2) as a function of temperature.

The BM plasma gasification and pyrolysis produced gas phase products with comparable compositions (Figures 4 and 5). As a result of the BM processing at 1500 K, with the complete decomposition of furans, dioxins, and benzo(a)pyrene, the following composition of combustible gas was obtained in vol.%: CO—29.6; H₂—35.6; CO₂—5.7; N₂—10.6; H₂O—17.9 (plasma-air gasification—Figure 4); and CO—30.2; H₂—38.3; CO₂—4.1; N₂—13.3;

H₂O—13.6 (plasma pyrolysis—Figure 5). From Figures 4 and 5, it is clear that at a temperature of 1500 K, the maximum yield of combustible components is ensured, reaching 65.2 vol.% during gasification and 68.5 vol.% during BM pyrolysis. In this case, the plasma–air gasification and pyrolysis of BM did not yield by-products (KOH, K) greater than 0.6 and 0.5 vol.%, respectively.

Figures 6 and 7 show the changes in the composition of the condensed phase depending on the temperature of the gasification and pyrolysis processes, respectively. A comparison of these figures reveals that the condensed component concentration curves are similar qualitatively and quantitatively. In both cases, at 950 K, carbon enters the gas phase as CO. At 1500 K, tricalcium phosphate (Ca₃P₂O₈), magnesium oxide (MgO), and calcium sulfide remain condensed. They are safe for the environment.

Based on a kilogram of working fluid, Figure 8 illustrates the temperature dependence of specific energy consumption for BM gasification (curve 1) and pyrolysis (curve 2). There is a qualitative similarity between the curves. BM gasification and pyrolysis consumed 1.28 and 1.33 kWh/kg of specific energy at 1500 K, respectively. The lower mass ratio of the oxidizers/BM during pyrolysis results in an increased energy consumption in pyrolysis due to the lower heat release during the oxidation reactions of carbon and hydrogen.

The calculations show that with the plasma pyrolysis of BM with slightly higher energy consumption, the yield of combustible gas is higher than with plasma gasification. With the plasma pyrolysis of BM and gasification, synthesis gas was formed with yields of 68.5 and 65.2 vol.%, respectively. At the same time, harmful components were not detected.

3.2. Results of the Experiment and Comparison with Calculated Values

The plasma reactor is used to heat lumps or packaged materials with a high-temperature plasma jet, pyrolyze or gasify the organic materials, and melt the mineral components of the processed waste. In order to plasma-gasify the BM, the reactor's inner surface was heated to 1415 K, after which BM briquettes weighing 0.28 kg were fed into it via a pipe. The plasma–chemical reactor is capable of processing 180 BM briquettes in an hour. In the reactor volume, at least 1600 K is provided by an air (or nitrogen during pyrolysis) plasma jet. This temperature causes the organic waste to gasify and the inorganic waste to melt. With the aid of cleaning and cooling systems, the flammable gas was continuously removed from the installation. Following the shutdown and cooling of the reactor, the molten mineral part of the BM was removed for analysis.

When conducting experiments on the plasma–air gasification of BM, the plasma torch power was 71 kW ($I = 215$ A, $U = 330$ V) and the plasma-forming air flow rate was 250 L/min at a pressure of 0.101 MPa and a temperature of 293 K. During the experiments on the pyrolysis of BM in nitrogen plasma (250 L/min), the power of the plasma torch was 75.2 kW ($I = 235$ A, $U = 320$ V). The gasification and pyrolysis of BM in the plasma–chemical reactor consumed 1.42 and 1.5 kWh/kg, respectively, according to the experimental results.

As the vacuum in the reactor decreased, a flame burned at the outlet of the pipe used for loading briquettes (Figure 9). A stable, bright torch was formed as a result of the ignited flammable gas. Water-cooled probes with thermocouples measured the 1600 K flame temperature. During the processing of the BM, the reactor lining reached a maximum temperature of 1887 K.

Following the loading of the first BM briquette, the plasma torch was turned off 27 min later. During this period, 80 briquettes weighing 22.4 kg were gasified, which corresponded to a BM productivity of 50 kg/h for the reactor. The gasification and pyrolysis of the BM consumed 12.5 kg/h of air and nitrogen, respectively, which represented 100% BM and 25% gas.

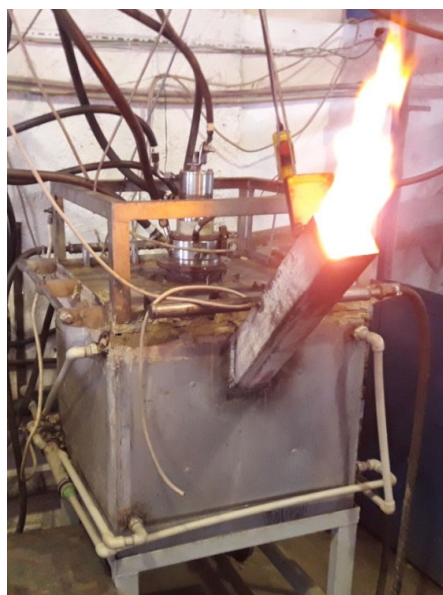


Figure 9. Flames of flammable gas emanating from the pipe supplying BM briquettes.

The plasma–air gasification and pyrolysis of the BM were studied experimentally for determining the plasma–chemical reactor’s operating parameters. Exhaust gases were analyzed, samples of condensed products were collected from the slag formation zone, and the carbon content was evaluated in the slag. At the reactor’s outlet, the gas composition was as follows in vol.%: CO—25.9; H₂—32.9; CO₂—3.5; N₂—37.3 (pyrolysis in nitrogen plasma); and CO—32.6; H₂—24.1; CO₂—5.7; N₂—35.8 (plasma–air gasification). As a result of the pyrolysis and plasma–air gasification of the BM, combustible gases were generated with specific heats of combustion of 10,500 and 10,340 kJ/kg, respectively. As a result of the pyrolysis and plasma–air gasification of the BM, 58.8 and 56.7 vol.% of synthesis gas was produced. In the plasma–chemical reactor during the plasma–air gasification of 22.4 kg of BM, 1.35 kg of ash and slag residues were collected, as well as 1.3 kg during the plasma pyrolysis. There was about 6% of the original mass of BM left as ash and slag residue. Both times, a volumetric flowmeter measured 79.3 Nm³/h (59.5 kg/h) of exhaust gas flow.

With a synthesis gas yield at about 60%, the combustion heat is approximately 10,000 kJ/kg, which allows highly efficient generators such as piston generators and fuel cells to be used to produce electricity from synthesis gas. Hydrogen sulfide traces need to be removed from the synthesis gas.

The BM gasification by plasma–air gasification and pyrolysis in nitrogen plasma was compared with the thermodynamic calculations. At 1500 K, where the BM carbon is completely gasified and toxic compounds such as furans, dioxins, and benzo(a)pyrene decompose completely, the thermodynamic calculations yielded the following compositions of gas in vol.%: CO—30.2; H₂—38.3; CO₂—4.1; N₂—13.3; H₂O—13.6 (plasma pyrolysis); and CO—29.6; H₂—35.6; CO₂—5.7; N₂—10.6; and H₂O—17.9 (air–plasma gasification). As a result of the pyrolysis and gasification, the synthesis gas yields reached 68.5 and 65.2 volume percents, respectively. Accordingly, there is no more than a 16% discrepancy between the experiment and calculations for the yield of the aim product (synthesis gas). The difference might have been caused by an uncontrolled dilution of exhaust gases through the suction of ambient air into the vacuum-operated setup and the uneven mixing of BM and plasma.

As a result of the pyrolysis and gasification of the BM, the carbon content levels in the samples of ash and slag waste were determined by absorption–gravimetric methods to be 2.1 and 2.99%, respectively. Accordingly, 91.3 and 87% of BM carbon was gasified during the pyrolysis and gasification, respectively. A maximum 13% discrepancy exists between the experimental and calculated (100%) values of the carbon gasification. The experimental

results indicate that the pyrolysis and gasification of the BM in the plasma–chemical reactor consumed 1.5 and 1.42 kWh/kg working fluid, respectively. Specific energy consumptions at 1500 K were calculated at 1.33 kWh/kg and 1.28 kWh/kg, respectively. For the plasma pyrolysis and gasification, there was less than an 11% discrepancy between the experiments and calculations. In the experiments and calculations, the products produced by BM plasma pyrolysis and plasm–air gasification were found to be free of harmful contaminants, which confirmed that the BM plasma processing technology is environmentally friendly. There was good agreement between the calculated and experimental data for the main integral indicators of the BM plasma processing, with a discrepancy of not more than 16.6% between the two. As a result, the TERRA program can be used to calculate the plasma processing of BM as a valid tool.

3.3. Exergy Analysis of Plasma Technologies

The plasma technology efficiency for the gasification and pyrolysis of BM applications with the help of a thermodynamic analysis and experimental studies of the processes is considered above. A comparative assessment of the plasma technology efficiency using exergetic calculations is considered below. The large-scale application of exergy to thermodynamic efficiency studies began in 2000 [24–26]. In the modern world, the term “exergy”, introduced in 1953 by Zoran Rant (from the Greek *ex*—external, *ergos*—work) to denote the technical work potential has found wide application in fields such as energy, chemistry, physics, mechanical engineering, geology, economics, engineering, and biology, as well as in information and data measurement systems, agriculture, and farming [27]. The application of the exergy method to describe the above-mentioned plasma technology is presented in [24,28,29]. For efficiency analyses, E-analyses are used: energetic, environmental, economic, and exergetic analyses and their combinations. The E-analyses of the efficiency of the plasma gasification (utilization) of carbon-containing materials include food waste [30,31], medical waste utilization [32–44], solid household waste [45–53], plastic and its derivatives, including Bakelite [20,21,54–57], buried waste [58,59], used tires [60,61], waste fuel and lubricants [62], and urban (municipal) and sewage sludge [63–65]. Several studies have analyzed the efficiency of plasma technology for processing biomass [11,66–70], poultry manure [71], methane [72,73], biomass—wood [74–76], biogas [77], and coal [78]. An extensive analysis of the exergy efficiency of a magnetohydrodynamic and gas turbine-combined cycle power plant was carried out in [79]. From the review of the aforementioned works, it follows that there is a relatively small number of publications dedicated to the exergy efficiency of the plasma gasification of biomass. In this regard, this article examines the efficiency of the plasma gasification of biomass using an exergy analysis.

3.4. Exergy Analysis of Plasma System Application for Biomass Processing

The exergy calculation is based on the specific heat consumption in the combined Carnot cycle, also known as exergy analysis, where “ex” stands for exergy [80]. The calculation of the thermal efficiency of ideal cycles through their average thermodynamic temperatures for the combined Carnot cycle was carried out using Formulas (1)–(6):

The efficiency for the initial combined cycle is as follows:

$$\eta_c = 1 - T_0/T_1 = (N + exQ)/Q_h \quad (1)$$

The efficiency for the “upper” cycle is as follows:

$$\eta_h = 1 - T_2/T_1 = N/Q_h \quad (2)$$

$$q_p = 1/\eta_c = Q_h/(N + exQ) \quad (3)$$

$$q_w = (1 - \eta_h)/\eta_c/(1 - \eta_h) = exQ/(N + exQ)/(1 - N/Q_h) = \eta_t \bar{q}_H \quad (4)$$

$$\eta_t = 1 - 2T_0/(T + T_0) \quad (5)$$

$$exQ = \eta_t Q \quad (6)$$

where η_t is the thermal efficiency of the “lower” cycle; η_h is the thermal efficiency of the “upper” cycle; η_c is the thermal efficiency of the “combined” cycle; exQ is the exergy of the heat; T_0 is the temperature of the environment at $P_0 = 0.101$ MPa; T is the biomass combustion (gasification) temperature; T_1 is the average thermodynamic temperatures of the first cycle; T_2 is the average thermodynamic temperatures of the second cycle; Q is the BM thermal power (lower thermal potential); Q_h is the higher thermal potential; N is the electric power; q_w^- is the proportional heat consumption of the higher cycle for obtaining work; q_H^- is the proportional heat consumption of the higher cycle for obtaining heat [80].

The use of exergy analysis allows us to evaluate the quality of the energy and calculate the efficiency of individual units. For comparative analysis, we calculated the efficiency indicators of traditional biomass combustion and its plasma gasification. Table 2 presents the results of the comparative calculations of the exergy of these processes.

Table 2. Comparative calculations of exergy.

	Biomass Combustion in a Conventional Furnace	Biomass Combustion in an Experimental Furnace	Gasification of Biomass in a Plasma Reactor
Q —BM thermal power, kW		222	
T —BM combustion (gasification) temperature, K	1023 *	1100	1600
T_0 —temperature of environment ($P_0 = 1$ atm), K		295	
η_t —thermal efficiency of the “lower” cycle according to Formula (5)	0.552	0.577	0.689
exQ —exergy of heat according to Formula (6), kW	122.5	128.1	153.0

* The data were taken from the work of researchers from the Department of Mechanical Engineering, the University of Maryland, as the most optimal and efficient in terms of energy consumption and the environment [81].

The recommended decomposition temperatures for toxic compounds are as follows: furans: 1053–1273 K [82–84]; dioxins: 973–1473 K [85–89]; and benzo(a)pyrene: 673–1073 K [90,91] (with continuous temperature exposure requirements of 2 s). Therefore, at a combustion time of 2 s at a temperature of 1050 K, 70% of the toxic compounds decompose, while at 1173 K, 90% decompose. Biomass is gasified at 90% efficiency at temperatures higher than 1300 K. Standardizing the minimum allowable temperature limits for biomass thermal processing equipment is expected to reduce the emissions of harmful substances (dioxins, furans, and benzo(a)pyrene) and the carbon footprint. Having analyzed the exergy ratios of the biomass combustion heat, we can conclude that the exergy efficiency of plasma biomass gasification is 25% higher than that of traditional methods. Specifically, the exergy of the heat in plasma gasification is 153 kW, compared to 128.1 kW in an experimental furnace and 122.5 kW in a traditional furnace [92,93].

4. Conclusions

Thermodynamic calculations and experimental studies of the plasma gasification and pyrolysis of agricultural waste were performed, which showed the promise of using a plasma–chemical reactor for processing waste to produce flammable gas and inert mineral material.

Thermodynamic calculations allow for determining the integral indicators of BM plasma processing: the equilibrium composition of the gas phase of the processing products, the degree of carbon gasification, and the specific energy consumption for the process. A temperature of 1500 K appears to be the best temperature for gasifying BM carbon as well as for decomposing toxic furans, dioxins, and benzo(a)pyrene. At a temperature of 1500 K,

the maximum yield of combustible components is ensure, reaching 65.2 vol.%, during gasification and 68.5 vol.% during BM pyrolysis.

The concentrations of synthesis gas obtained from the plasma–air gasification and plasma pyrolysis of BM were, respectively, 56.7 and 58.8%. By the plasma–air gasification and plasma pyrolysis of BM, flammable gases with calorific values of 10,340 and 10,500 kJ/kg were produced.

In a comparison of the BM plasma processing process indicators, the calculated data and experimental data showed satisfactory agreement, with a discrepancy of not more than 16%.

BM products processed with plasma were found to be free of harmful impurities both in the calculations and experiments, confirming the environmental benefits of plasma technology.

Using the exergy ratios of the biomass combustion heat, we can conclude that plasma biomass gasification is 25% more efficient. This shows that the plasma gasification of biomass is more effective than traditional incineration.

By gasifying and pyrolyzing biomass in a plasma reactor, biomass disposal problems can be solved with minimal environmental impact.

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