detritus | Multidisciplinary Journal for Waste Resources & Residues

CISA

GASIFICATION OF BIOMASS IN A PLASMA GASIFIER

Vladimir Messerle [1], Alexandr Ustimenko [2,*], Oleg Lavrichshev [2], Nadezhda Slavinskaya [3], and Zholat Sitdikov [2]

[1] *Combustion Problems Institute, Ministry of Education and Science of Kazakhstan, Almaty, Kutateladze Institute of Thermophysics of SB RAS, Novosibirsk, Kazakhstan*
[2] *Plasmatechnics R&D LLP, Institute of Experimental and Theoretical Physics of al-Farabi Kazakh National University, Almaty, Kazakhstan*
[3] *Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Garching, Germany*

Article Info:
Received:
4 December 2019
Revised:
12 March 2020
Accepted:
17 March 2020
Available online:
24 July 2020

Keywords:
Plasma
Reactor
Biomass
Gasification
Synthesis gas

ABSTRACT

This paper presents the thermodynamic analysis and experimental results on the plasma gasification of biomass using the example of wood waste. Thermodynamic computations revealed that synthesis gas can be produced from wood waste for utilization in the heat-and-power engineering, metallurgy and chemical industries. The air gasification of wood waste produces a synthesis gas yield of 71.6% (CO-41.9% and H_2-29.7%). Experiments on the plasma gasification of wood waste were conducted in an experimental setup composed of a plasma gasifier with 50 kg/h nominal productivity and a DC plasmatron with 70 kW nominal power. Based on gas analysis, the exit gas of the plasma setup exhibited the following composition, vol.%: CO-42.0, H_2-25.1, and N_2-32.9. The measured temperature in the bottom of the plasma gasifier was 1,560 K. The discrepancy between the experimental and calculated yield of synthesis gas was not more than 7%. Harmful impurities were not observed in the gases or the condensed products generated from the plasma gasification of wood waste.

1. INTRODUCTION

Humans have reached a point in their development at which an awareness of the limitations of natural resources and a need to preserve the environment have merged with the growing problem of recycling waste and maximizing the use of secondary raw materials and energy resources. Solid waste, such as biomass, from renewable energy sources has been shown to exhibit the most important increase in annual production volume. A substantial amount of waste is present worldwide, some of which is recycled, although large amounts of waste are simply dumped, causing problems for people and the environment. For example, the total amount of waste produced in the EU alone has amounted to 2.3 billion tons annually (Katsaros and Nguyen, 2018). Biomass is currently the world's fourth largest energy source, accounting for up to 14% of the world's primary energy demand and biomass power units range from small-scale to multi-megawatt sizes. Biomass is a versatile source of energy in that it can be readily stored and transformed into electricity and heat and also has the potential to be used as a raw material for chemical industry. The development of biomass use contributes to both energy and other non-energy policies (Veringa, 2005). In this paper, we consider wood waste (WW) as a species of biomass constituting the greater part of it.The world produces approximately 1 billion tons of WW annually. The main components of WW (80%) are wood and products from its processing (sawdust, bark, and wood chips). Power stations operating with WW have capacities of 35 million kW, producing 4% of the total primary energy consumption in developed countries; and 26% of the total primary energy consumption in developing countries (Prins Mark, 2005). During traditional WW incineration, the main combustion product is carbon dioxide, which increases the greenhouse effect. The use of WW in the energy sector is the final stage of logging production,and aimed at improving the effectiveness of environmental measures. The most common WW processing technology is gasification (Veringa, 2005; Lan et al., 2018; Mourão et al., 2015). During WW gasification, the main product is synthesis gas, not carbon dioxide, which is primarily generated when WWs are burned. From 1 kg of WW, it is possible to obtain approximately 2.5 m^3 of power gas, and the main combustible components of the gas are carbon monoxide (CO) and hydrogen (H_2). According to the heat input method, WW gasification processes are divided into autothermal and allothermal processes. During the autothermal process, thermal energy that is needed to achieve the required temperature comes from the combustion of a portion of the WW; during the allothermal process,

* Corresponding author:
Alexandr Ustimenko
email: ust@physics.kz

Detritus / Volume 12 - 2020 / pages 62-72
https://doi.org/10.31025/2611-4135/2020.13989

heat is supplied from outside; for example, heat can be supplied from a plasma generator. In the process of autothermal gasification, tar is formed and accumulated in the gas purification filters and is difficult to remove, which causes energy losses (Porteous, 2005; Materazzi, 2013). The heat supply method determines the composition of the synthesis gas and the energy consumption for its production. During the air gasification of WW, the specific yield of synthesis gas obtained in the autothermal process is 15.4-52.4% higher (with a decrease in its quality) than the yield of synthesis gas obtained in the allothermal process. In plasma gasification, the proportion of noncombustible components in the producer gas decreases to 23.2-61.0%, and the energy consumption for heating the gasification products to the necessary temperature decreases by 17.4-46.5% (Brattsev et al., 2011). Thus, the advantages of employing plasma methods for WW processing are the complete decomposition of wastes; the decrease in the volume of the exhaust gas produced; the smaller carryover of dispersed particles; the high performance achieved with small-scale equipment; the creation of a desired gaseous atmosphere; the ability to adjust the operation of the process by changing the flow rate of air and power of plasmatrons; and the increase in the production and quality of synthesis gas without changing the consumption of the oxidizing agent. The main disadvantage of WW plasma gasification is the required energy consumption for the generation of plasma. Recently, the plasma gasification of wastes has become widespread (An'shakov et al., 2007; Byun Youngchul et al., 2012; Heberlein and Murphy, 2008; Matveev et al., 2016; Surov et al., 2017; Zhang et al., 2012; Zhovtyansky et al., 2013). Plasma gasification achieves the maximum yield of the synthesis gas ($CO+H_2$) by reducing the concentration of the ballasting gases (CO_2 and N_2). However, in post-Soviet regions, the use of wastes, including WW, essentially does not occur; thus, the problem of its utilization is very relevant.

In this paper, we discuss the results of the thermodynamic analysis of fuel gas, which is free of harmful impurities, produced by the gasification of WW in air plasma. Additionally, the experimental installation system is presented, and the experimental results of the gasification of WW in air plasma are compared with the computation results. The foundation of plasma gasification of WW was established during the creation of the plasma technology for the gasification of solid fuel (Matveev et al., 2008; Messerle and Ustimenko, 2007).

2. MATERIALS AND METHODS

2.1 Materials

In this article, WW was composed of a mixture of sawdust and wood chips. WW constitutes a significant share of the waste generated by the woodworking industry. According to (CHEM, 2016; Graedel, 2003) WW is composed of the following chemical components, wt.%: C - 49.88, O - 43.81, H - 5.98, N - 0.10, K_2O - 0.01, CaO - 0.12, MgO - 0.02, MnO - 0.01, Fe_2O_3 - 0.01, Al_2O_3 - 0.01, SiO_2 - 0.01, SO_3 - 0.01, P_2O_5 - 0.02, and Na_2O - 0.01. The organic part of WW is carbon, oxygen, hydrogen and nitrogen with a total concentration of 99.77%, whereas the mineral part of WW only accounts for 0.23%. The higher heating value (HHV) of the WW was calculated by an equation based on the ultimate analysis (Demirbaş and Demirbaş, 2004): $Q=1{,}000\cdot(33.5\cdot C + 142.3\cdot H - 15.4\cdot O - 24.5\cdot N)$ [kJ/kg]. The HHV was 18,450 kJ/kg.

2.2 Computations

The Terra (Gorokhovski et al., 2005) software package was used to perform thermodynamic calculations of WW plasma air gasification. This software was intended for numerical calculations of high-temperature processes and possesses its own extensive database of thermodynamic properties of 3,000 individual substances over a temperature range of 300 to 6,000 K. The database includes the thermodynamic properties of the organic and mineral components of WW and contains the thermochemical properties of radicals, ionized components and electronic gas, which are accounted for in thermodynamic calculations. In contrast to traditional thermochemical methods of equilibrium computations, which use the equations of chemical reactions, Gibbs energy, equilibrium constants, and the Guldberg and Waage law of mass action, the Terra software is based on the principle of maximum entropy for isolated thermodynamic systems in equilibrium and does not use the equations of chemical reactions, operating with many chemicals within the database.

2.3 Experimental installation system

Experimental studies of WW gasification were performed in the experimental installation system (Figure 1), which consists of a plasma chemical reactor (Figure 2) with WW productivity up to 50 kg/h and a long life DC plasmatron (plasma generator) with 70 kW nominal power (Golish et al., 2009). Figure 2 shows an image of the reactor with a lifted lid and plasma flame. To increase the service life of the plasmatron, a method was developed for the plasma pyrolysis of hydrocarbon gases with the subsequent deposition of the condensed products generated from pyrolysis on water-cooled copper electrodes of the plasmatron. According to the method, a propane-butane mixture is fed into the zone of arc discharge between the cathode and anode (in thermodynamic analysis, due to the very low flow rate, the propane-butane mixture was not taken into account). As a result, carbon vapour is formed in the cavity of the cathode and on the inner surface of the anode. Electron microscopy and Raman spectroscopy studies of the electrode coating showed that it consisted of a composite nanostructured carbon material including largely single-walled and multi-walled carbon nanotubes in addition to other carbon forms with a certain amount of copper atoms intercalated in the carbon matrix. An experimental study of the long life plasmatron showed that at a plasmatron power of 72.6 kW (I=220 A, U=330 V), a plasma forming air flow rate of 250 l/min and a propane-butane flow rate of 1.8 l/min, the temperature at the plasmatron nozzle exit section was 5,500 K (Figure 2). Based on the resource tests of the plasmatron for 1,000 hours, the erosion of the copper electrodes was not fixed, as the true electrode functions were performed by the regenera-

ble nanocarbon coatings of the copper electrodes (Il'in, et al., 2010).

The composition of the experimental setup (Figure 1), except reactor 4 and plasmatron 1, includes the plasmatron power supply, gas and water supplies into the reactor and plasmatron and exhaust gas cleaning 7. The experimental installation system is equipped with a sampling system for the analysis of the gas and condensed products generated from WW gasification (Messerle et al., 2018). A plasma reactor was designed for plasma gasification of WW. The reactor is a cube lined by refractory bricks with thicknesses of 0.065 m. The size of the inner side of the cube is 0.45 m, which gives the reaction volume of the reactor of 0.091 m^3. The pipe for supplying WW briquettes 2 can be used to measure the temperature inside the reactor using an infrared pyrometer. A Pyrometer Ircon Ultrimax Plus UX10P is used to measure temperatures from 600 to 3,000°C (873-3,273 K). The measurement error depends on the temperature range, and it is ±0.5% of the measured value for the temperature range up to 1,500°C (1,773 K), ±1% for the temperature range from 1,500-2,000°C (1,773-2,273 K), and it increases to ±2% for the temperature range over 2,000°C (2,273 K). The temperature resolution is not lower than 1°C. The device is equipped with a Serial port to enable connection to the computer, and the temperature can be controlled by the RS-232C protocol during the experiment, which generates results in an on-line regime. The sampling interval of the device is 0.5 seconds.

The process of WW plasma gasification is as follows. Plasmatron 1 is started, and the inner liner surface of the bottom of reactor 4 is heated to a temperature of 1,215 K (approximately 15 minutes); then, the WW briquettes are introduced into gasification zone 3 through pipe 2 (Figure 1). The weight of each briquette is 0.33 kg. It takes two minutes to supply 5 briquettes. The WW is gasified in the air plasma flame, providing an average mass temperature in the reactor volume of up to 1,600 K. The gaseous products are removed from the reactor and transferred into cyclone combustion chamber 6, and the condensed products accumulate in the bottom of the reactor. The combination of the heat release zone from the plasma flame with WW gasifier 3 and slagging contributes to the intensification of WW processing. The cooled gaseous products enter gas purification unit 7, after which with the help of sampling system gas is supplied to the analyser. Ventilation system 9, including the pressure control valve 8, provides a low pressure in the reactor up to 10 mm of the water column.

3. RESULTS AND DISCUSSION

3.1 Thermodynamic calculations

The Terra (Gorokhovski et al., 2005) software package was used to perform the thermodynamic calculations of WW plasma air gasification. The calculations were carried out in the temperature range of 298-3,000 K and at a pressure of 0.1 MPa. The aim of these calculations was to determine the integral parameters of the gasification process, such as the equilibrium composition of the gas phase of the gasification products, the degree of carbon gasification and the specific power consumption of the process. The initial technological mixture with a mass ratio of WW to air of 1 was used for air gasification. This mass ratio is based on a series of calculations of plasma-air gasification of WW with varying excess air coefficients. The mass ratio selection criteria were the achievement of 100% carbon gasification, the maximum concentration of combustible components ($CO + H_2 + CH_4$) in the waste gasification products and the suppression of nitrogen oxide formation. We should also note that the stoichiometric ratio is the exact ratio between air and WW at which com-

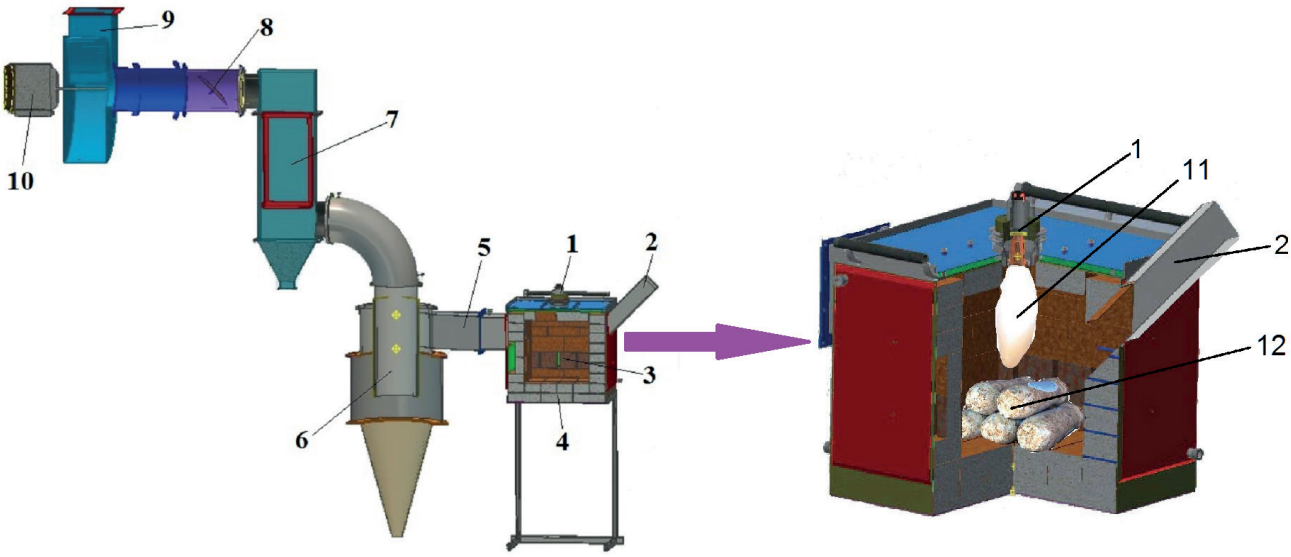

FIGURE 1: Layout of the experimental unit for plasma gasification of WW and scheme of the plasma reactor: 1 – arc plasmatron; 2 – pipe for supplying the WW briquettes; 3 – WW gasification zone; 4 – reactor; 5 – chamber for combustible gas removal from the reactor; 6 – cyclone combustion chamber; 7 – gas purification unit with a bag filter; 8 – control valve; 9 – ventilator of the exhaust system; 10 – engine of the exhaust system; 11 – plasma flame; 12 – WW briquettes.

plete combustion occurs, and the products only contain carbon dioxide and steam. The stoichiometric ratio for WW combustion is 6.

Figure 3 shows the variation in the concentration of gaseous components depending on the temperature of the WW air gasification. With increasing temperature, the synthesis gas yield increases to a maximum at T = 1,600 K. This result occurs due to an increase in CO and H_2 concentrations and a corresponding decrease in CH_4 and CO_2 concentrations because of their thermal dissociation. The maximum concentration of combustible components in the synthesis gas reached 71.6% (CO - 41.9% and H_2 - 29.7%). It should be noted that at 1,200 K, the total synthesis gas concentration is 71.3%, which differs little in value from its maximum value. The concentration of oxidants (CO_2+H_2O) at these temperatures does not exceed 0.7%. With increasing temperature, the concentration of synthesis gas is slightly reduced due to the appearance of atomic hydrogen (H) in the gas phase, which reaches a concentration of 7.8% (T = 3,000 K). The concentration of ballasting nitrogen (N_2) remains almost constant in the temperature range of 1,200-3,000 K and is 27.8-26.7%. The concentration of methane (CH_4) decreases sharply, and its concentration converges to zero at a temperature of 1,200 K.

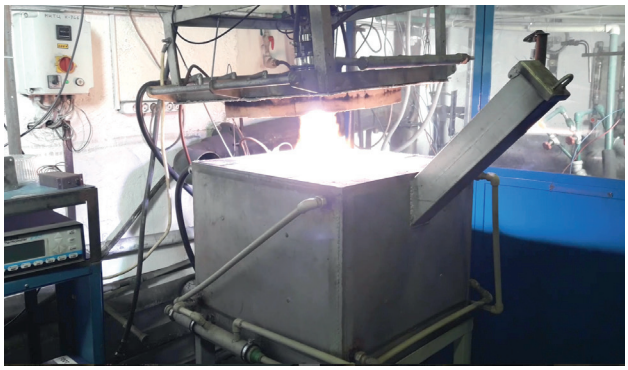

FIGURE 2: Photo of the plasmatron in operation with the reactor lid lifted.

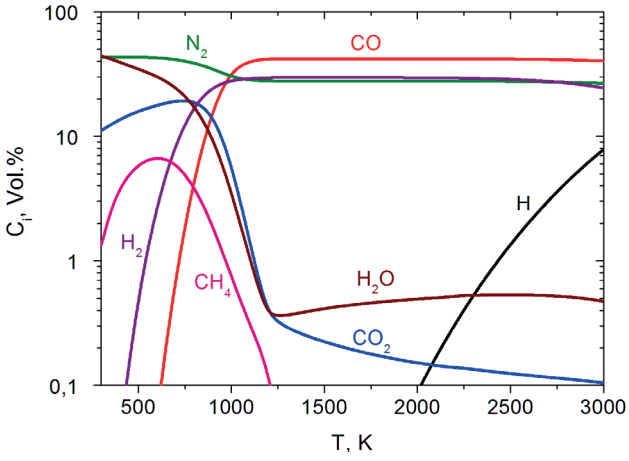

FIGURE 3: The variation in the concentration of gaseous components depending on the WW air gasification temperature.

The degree of carbon gasification X_C (Figure 4) is determined from the carbon content of the solid residue. Specifically, X_C is calculated according to the following expression: , where C_{ini} is the initial amount of carbon in the WW, and C_{fin} is the final amount of carbon in the solid residue. As shown in Figure 4, the degree of carbon gasification amounts to 100% at a temperature of 1,200 K. Carbon is completely transformed into the gaseous phase, forming CO at a temperature higher than 1,200 K. This process provides a hundred percent carbon gasification.

The specific power consumption Q_{SP} (Figure 5) was defined as a difference between the total enthalpy of the final I_{FIN} (current temperature of the process) and initial I_{INI} (T=298 K) state of the working substance (mixture of WW and gasifying agent) reduced to 1 kg of WW. Q_{SP} is calculated according to the following expression: , where m_{WS} is the mass of the working substance, and m_{WW} is the mass of WW. The specific power consumption for the process of WW gasification increases with temperature throughout its range. For the temperature T = 1,600 K, at which the yield of synthesis gas reaches its maximum (Figure 3), the specific power consumption for air gasification of the WW constitutes 2.49 kW h/kg. Such moderate energy consumption for air gasification of WW is associated with compensation in the endothermic effect due to the heat of the oxidation reaction of carbon in air.

The carbon gasification efficiency characterizes the WW gasification process efficiency and is an important indicator of the energy efficiency of the gasification process (Matveev et al. 2008). The criterion of the energy efficiency of the solid fuel gasification process is defined as the relative thermal power of the produced combustible gas. The physical heat of the produced combustible gas was not considered when the relative thermal power was determined. The efficiency of the WW gasification process can be calculated by the following formula: , where m_G is the mass of combustible gas produced, Q_G is the heat of combustion of the combustible gas, [kJ/kg], and Q_{WW} is the heat of combustion of WW [kJ/kg]. The WW gasification efficiency (Figure 6) increases sharply with

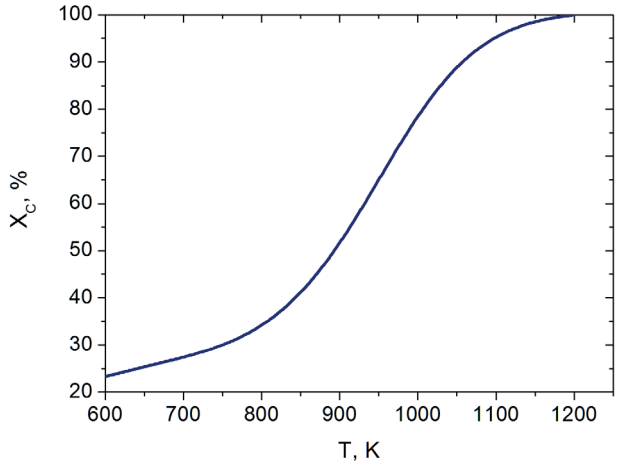

FIGURE 4: The degree of carbon gasification depending on the WW gasification temperature.

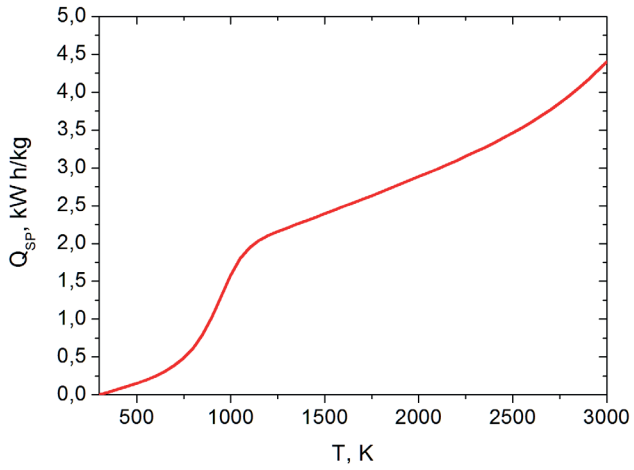

FIGURE 5: Specific power consumption for the WW plasma gasification process depending on temperature.

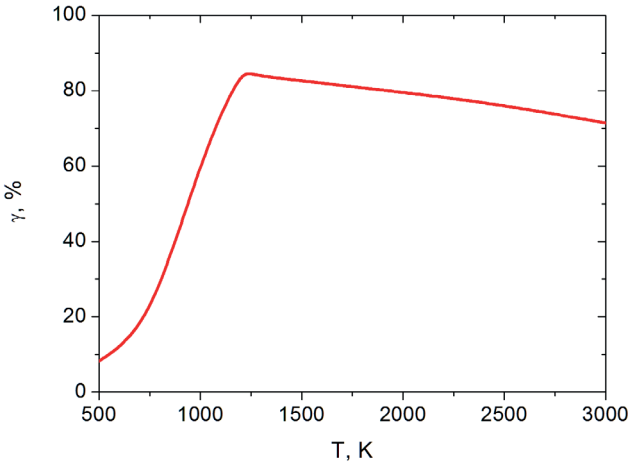

FIGURE 6: The dependence of the WW gasification efficiency on temperature.

temperature to a maximum of 85.6% at a temperature of 1,200 K. With a further increase in temperature, the WW gasification efficiency gradually decreases, which is explained by an increase in the specific power consumption of WW gasification at the previously achieved 100% of carbon gasification. For the temperature T = 1,600 K, the WW gasification efficiency for the air gasification of WW is rather high at 82%.

The parameters that were determined and the regularities of the WW plasma gasification process that were identified were used to develop an experimental installation system.

3.2 Experiment

As a result of the WW plasma gasification, synthesis gas was produced. Figure 7 shows the flame of the gas exiting pipe 2 at a short time disabling of the exhaust system. The resulting fuel gas is intensively ignited in air. The measured temperature of this flame was approximately 1,600 K. During the experiment, the fuel gas was withdrawn using the exhaust system. The measured temperature in the bottom of the reactor was 1,560 K. Under the influence of the air plasma jet, the weight average temperature in the reactor reached 1,600 K, an organic portion of the WW was gasified, and an inorganic portion (ash) of the WW was accumulated in the slag formation zone of the reactor and in bag filter 7 (Figure 1). The obtained synthesis gas was incinerated in cyclone combustion chamber 6. The combustion products were continuously removed from the installation through the cooling and purification systems. The ash was removed from the reactor after the plasmatron was shut down and the reactor was cooled. The plasmatron was turned off 25 minutes after the download of the first WW briquette. Thirty briquettes with a total mass of 9.9 kg were gasified during this period. The consumption of the WW briquettes was 23.8 kg/h. The air flow rate through the plasmatron was 23.6 kg/h. The parameters of the synthesis gas (composition and temperature of gasification products) were maintained during the periodic loading of the waste into the reactor by the uniform supply of briquettes every 50 seconds by sampling the gas after establishing a stationary regime of gasification for 20 seconds. We should also note that since the measured temperatures were comparatively low in the experiment and varied within 1,560-1,600 K, the role of radicals, ionized components, and electronic gas could not be significant. This phenomenon is confirmed by the calculated concentrations of these components at these temperatures (for example, at T=1,600 K, vol.%: electronic gas - $0.5 \cdot 10^{-15}$, H^- - $0.2 \cdot 10^{-19}$, OH - $0.1 \cdot 10^{-5}$, and CH - $0.4 \cdot 10^{-13}$).

The experimental study results for the plasma reactor operating conditions during WW plasma gasification were determined; in addition, an exhaust gas analysis was performed, the samples of the condensed products were collected from the slag formation zone of the reactor, and the residual carbon content in the slag was measured. Gas analyses were performed on a gas chromatograph SRI 8610C, which showed the following gas composition at the exit of the gas purification unit, vol.%: CO - 42.0, H_2 - 25.1, and N_2 - 32.9. The specific heat of the combustion of the synthesis gas produced by air gasification amounted to 9,400 kJ/kg. The total concentration of the synthesis gas was 67.1%, which agreed well with the thermodynamic calculations. The calculated yield of the synthesis gas at 1,600 K was 71.6% (CO - 41.9% and H_2 - 29.7%). Thus, the discrepancy between the experimental and calculated target product yields (synthesis gas) did not exceed 6%. The thermodynamically predicted concentration of N_2 was 27.8%. This difference could be because of the unguided dissolution of the experimentally produced synthesis gas by ambient air.

After gasification of 9.9 kg of WW 0.013 kg of ash were collected from the bottom of the reactor. This quantity of ash is approximately 0.12% from the initial quantity of WW. Residual fly ash (0.1% ash) was transferred away with the exhaust gas. The volumetric orifice flow rate of the exhaust gas was 48.3 kg/h. The discrepancy between the experimental and calculated flow rates is 2%.

In the experiments and in the calculations, neither tar nor harmful impurities were found in the products of the WW plasma gasification. The carbon content of the slag in

FIGURE 7: Photo of the combustible gas control flame from the pipe for supplying the WW briquettes.

the sample was 1.13 wt.%, which corresponded to 96.6% WW carbon gasification. The carbon content was determined using the absorption-gravimetric method. The discrepancy between the experimental and calculated values of carbon gasification did not exceed 3.5%.

According to the results of experiments, the specific power consumption of the WW gasification in the plasma reactor reached 3.05 kWh/kg of the working substance. The calculated specific power consumption of the air-plasma gasification of the WW was 2.49 kWh/kg (Figure 5). The discrepancy between the calculated and experimental values of the specific power consumption for the process was 18%. This discrepancy is because in thermodynamic calculations, the lowest possible energy consumption in an isolated thermodynamic system is determined without taking into account the exchange of heat and work with the environment. In practice, the plasma reactor itself and the plasmatron are characterized by considerable heat losses to the environment with cooling water.

4. CONCLUSIONS

Thermodynamic calculations showed that the maximum synthesis gas yield from the plasma gasification of wood waste in an air medium is achieved at a temperature of 1,600 K. A total concentration of 67.1% was obtained for the WW synthesis gas with the air plasma gasification of WW. The specific heat of combustion of the synthesis gas produced by air gasification reached 9,400 kJ/kg. In the experiments and in the thermodynamic calculations, there were no harmful impurities found in either the gas or the condensed products of WW plasma gasification. A comparison of the experimental and calculated results of the plasma gasification of WW showed good agreement.

In contrast to traditional gasification methods, 100% WW gasification is achieved in the plasma-air gasification of WW, the WW gasification efficiency reaches a significant value of 85.6% at a relatively low process temperature (1,200 K), and gasification products do not contain harmful substances.

ACKNOWLEDGEMENTS

The development of the plasmatron for the plasma gasifier was completed under a state contract with IT SB RAS (AAAA-A17-117030910025-7), and the study of biomass gasification in the plasma gasifier was supported by the Ministry of Education and Science of the Republic of Kazakhstan in the form of program-targeted financing (BR05236507 and BR05236498).

REFERENCES

An'shakov, A.S., Faleev, V.A., Danilenko, A.A, Urbakh, E.K., Urbakh, A.E., 2007. Investigation of plasma gasification of carbonaceous technogeneous wastes. Thermophysics and Aeromechanics. 14(4), 607–616. https://doi.org/10.1134/S0869864307040105

Brattsev, A.N., Kuznetsov, V.A., Popov, V.E., Ufimtsev, A.A., 2011. Arc gasification of biomass: Example of wood residue. High Temperature. 49, 244–248. http://doi.org/10.1134/S0018151X11010020

Byun Youngchul, Cho Moohyun, Hwang Soon-Mo, Chung Jaewoo, 2012. Thermal Plasma Gasification of Municipal Solid Waste (MSW), Gasification for Practical Applications, Dr. Yongseung Yun (Ed.). ISBN:978-953-51-0818-4. 183–209. http://dx.doi.org/10.5772/48537

CHEMical properties of wood. Chemical composition of wood. 2016. Available from http://www.drevesinas.ru/woodstructura/chemical/1.html [Accessed on 07 November 2019]. (In Russian)

Demirbaş, A., Demirbaş, A.H., 2004. Estimating the Calorific Values of Lignocellulosic Fuels. Energy Exploration & Exploitation. 22(2), 135–143.·https://doi.org/10.1260%2F0144598041475198

Gorokhovski, M., Karpenko, E.I., Lockwood, F.C., Messerle, V.E., Trusov, B.G., Ustimenko, A.B., 2005. Plasma Technologies for Solid Fuels: Experiment and Theory. Journal of the Energy Institute. 78(4), 157–171. https://doi.org/10.1179/174602205X68261

Golish, V.I., Karpenko, E.I., Luk'yashchenko, V.G., Messerle, V.E., Ustimenko, A.B., Ushanov, V.Zh., 2009. Long-Service-Life Plasma Arc Torch. High Energ Chem+. 43(4), 318–323. https://doi.org/10.1134/S0018143909040134

Graedel, T.E., Allenby, B.R., 2003. Industrial Ecology. Prentice Hall. ISBN 0130467138, 9780130467133: 363 p.

Heberlein, J., Murphy, A.B., 2008. Topical review: Thermal plasma waste treatment. J Phys D Appl Phys. 41(5), 053001 (20 p). https://doi.org/10.1088/0022-3727/41/5/053001

Il'in, A.M., Messerle, V.E., Ustimenko, A.B., 2010. The Formation of Carbon Nanotubes on Copper Electrodes under the Arc Discharge Conditions. High Energ Chem+. 44(4), 326–331. https://doi.org/10.1134/S0018143910040120

Katsaros, G., Nguyen, T.-V., 2018. Masoud Rokni Tri-generation System based on Municipal Waste Gasification, Fuel Cell and an Absorption Chiller. Journal of Sustainable Development of Energy, Water and Environment Systems. 6(1), 13-32. http://dx.doi.org/10.13044/j.sdewes.d5.0172

Lan, W., Chen, G., Zhu, X., Wang, X., Liu, Ch., Xua, B., 2018. Biomass gasification-gas turbine combustion for power generation system model based on ASPEN PLUS. Science of the Total Environment. 628–629:1278–1286. https://doi.org/10.1016/j.scitotenv.2018.02.159

Materazzi, M., Lettieri, P., Taylor, R.,Chapman, C., 2013. Thermodynamic modelling and evaluation of a two-stage thermal process for waste gasification. Fuel. 108, 356–369. https://doi.org/10.1016/j.fuel.2013.02.037

Matveev, I.B., Messerle, V.E., Ustimenko, A.B., 2008. Plasma Gasification of Coal in Different Oxidants. IEEE T Plasma Sci. 36(6), 2947–2954. https://doi.org/10.1109/TPS.2008.2007643

Matveev, I.B., Serbin, S.I., Washchilenko, N.V., 2016. Plasma-Assisted Treatment of Sewage Sludge. IEEE T Plasma Sci. 44(12), 2960–2964. https://doi.org/10.1109/TPS.2016.2604849

Messerle, V.E., Mosse, A.L., Ustimenko, A.B., 2018. Processing of biomedical waste in plasma gasifier. Waste Manag. 79, 791–799. https://doi.org/10.1016/j.wasman.2018.08.048

Messerle, V.E.; Ustimenko, A.B., 2007. Solid Fuel Plasma Gasification. In: Syred N. and Khalatov A. (eds.) Advanced Combustion and Aerothermal Technologies. NATO Science for Peace and Security Series C: Environmental Security. Springer, Dordrecht, 141–156. https://doi.org/10.1007/978-1-4020-6515-6_12

Mourão, R., Marquesi, A.R., Gorbunov, A.V., Filho, G.P., Halinouski, A.A., Otani, C., 2015. Thermochemical Assessment of Gasification Process Efficiency of Biofuels Industry Waste with Different Plasma Oxidants. IEEE T Plasma Sci. 43(10), 3760–3767. https://doi.org/10.1109/TPS.2015.2416129

Porteous, A., 2005, Why energy from waste incineration is an essential component of environmentally responsible waste management. Waste Management. 25, 451–459. https://doi.org/10.1016/j.wasman.2005.02.008

Prins Mark, J., 2005, Thermodynamic analysis of biomass gasification and torrefaction. – Eindhoven : Technische Universiteit Eindhoven. Proefschrift. ISBN 90-386-2886-2.

Surov, A.V., Popov, S.D., Popov, V.E., Subbotin, D.I., Serba, E.O., Spodobin, V.A., Nakonechny, G.V., Pavlov, A.V., 2017. Multi-gas AC plasma torches for gasification of organic substances. Fuel. 203, 1007–1014. https://doi.org/10.1016/j.fuel.2017.02.104

Veringa, H.J., 2005. Advanced techniques for generation of energy from biomass and waste. ECN Biomass. 24 p. Available from https://pdfs.semanticscholar.org/a3a7/5f62c333b8ddac59fc00e59fac2f3ccd0311.pdf [Accessed on 07 November 2019].

Zhang, Q., Dor, L., Fenigshtein, D., Yang, W., Blasiak, W., 2012. Gasification of Municipal Solid Waste in the Plasma Gasification Melting Process. Appl Energ. 90, 106–112. https://doi.org/10.1016/j.apenergy.2011.01.041

Zhovtyansky, V.A., Petrov, S.V., Lelyukh, Yu.I., Nevzglyad, I.O., Goncharuk, Yu.A., 2013. Efficiency of Renewable Organic Raw Materials Conversion Using Plasma Technology. IEEE T Plasma Sci. 41(12), 3233–3239. https://doi.org/10.1109/TPS.2013.2275936