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GASIFICATION OF BIOMASS IN PLASMA GASIFIER

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ABSTRACT: This paper presents the results of thermodynamic analysis and experiments on plasma gasification of biomass by the example of wood waste. Thermodynamic computation revealed that synthesis gas utilizable in heat-and-power engineering, metallurgy and chemical industry can be produces from wood waste. Air gasification of wood waste allows producing synthesis gas with yield of 71.6% (CO - 41.9%, H_2 - 29.7%). Experiments on wood waste plasma gasification were conducted in a setup composed of plasma gasifier of 50 kg/h nominal productivity and DC plasmatron of 70 kW nominal power. As a result of wood waste plasma gasification synthesis gas of 67.1% concentration was produced. Measured temperature in the bottom of the plasma gasifier was 1,560 K. Discrepancy between experimental and calculated data by the yield of synthesis gas was not more than 7%. Harmful impurities were revealed in neither gas nor condensed products of wood waste plasma gasification.

Keywords: plasma, reactor, biomass, gasification, synthesis gas

1. INTRODUCTION

In its development, humanity has reached a point where awareness of the limitation of natural resources and the need to take measures to preserve the environment have merged with the growing problem of recycling waste and maximizing the use of secondary raw materials and energy resources. From renewable energy sources, the most important by annual increase in volumes is solid waste including biomass. Total waste in the world is enormous. Some of it is recycled but a lot is simply dumped, causing problems for people and the environment. For example, the total amount of wastes produced only in EU, amounted to 2.3 billion tons annually (Katsaros and Nguyen, 2018). Biomass contributes as the world's fourth largest energy source today up to 14% of the world's primary energy demand. Biomass is a versatile source of energy in that it can be readily stored and transformed into electricity and heat. It has also the potential that it is used as a raw material for production of fuel and chemical feedstock. Production units range from small scale up to multi-megawatt sizes. Development of biomass use contributes to both energy and other non-energy policies (Veringa, 2005). In this paper we concider wood waste (WW) being a species of biomass and constituting the greater part of it. The world annually produces about 1 billion tons of WW. The main part of the WW (80%) is wood and

products of its processing (sawdust, bark, wood chips). The capacity of power stations operating on WW is 35 million kW. Energy produced from WW in developed countries is 4% of all primary energy consumption and in developing countries it is 26% (Prins Mark, 2005). The most common WW processing technology is gasification (Veringa, 2005; Lan et al., 2018; Mourão et al., 2015). From 1 kg WW it is possible to obtain about 2.5 m^3 of energy gas, the main combustible components of which are carbon monoxide (CO) and hydrogen (H_2). Recently, 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 synthesis gas ($CO+H_2$) by reducing the concentration of ballasting gases (CO_2 and N_2). However, in the post-Soviet areas, waste, including WW, is practically not used and the problem of their utilization is very relevant.

In this paper we discuss the results of thermodynamic analysis of high-calorific fuel gas production by gasification of WW in air plasma. Also experimental installation is presented and the results of experiments on gasification of WW in air plasma compare with the computation.

2. THERMODYNAMIC CALCULATIONS

In this article WW is represented by mixture of sawdust and wood chips. The WW is compoused by 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 - 0.01, SiO_2 – 0.01, SO_3 – 0.01, P_2O_5 – 0.02, 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 is only 0.23% (CHEM, 2016; Graedel, 2003).

Software package Terra (Gorokhovski et al., 2005) was used to perform thermodynamic calculations of WW plasma air gasification. Calculations were carried out in the temperature interval 298 – 3,000 K and a pressure of 0.1 MPa. The initial technological mixture with mass ratio WW to air equal 1 was used for air gasification. The aim was to determine the integral parameters of the gasification process: equilibrium composition of the gas phase of the gasification products, the degree of carbon gasification and specific power consumption for the process.

Figure 1 shows the variation in concentration of gaseous components depending on the temperature of the WW air gasification. With increasing temperature the yield of the synthesis gas increases to a maximum at T = 1,600 K. Maximal concentration of combustible components of synthesis gas reaches 71.6% (CO - 41.9%, H_2 - 29.7%). It should be note that already at 1,200K the total concentration of synthesis gas is 71.3%, which differs little 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 reduced slightly due to the appearance in the gas phase of atomic hydrogen (H), which concentration reaches 7.8% (T = 3,000 K). Concentration of ballasting nitrogen (N_2) remains almost constant in the temperature range 1,200 – 3,000 K, being 27.8 – 26.7% respectively. The concentration of methane (CH_4) decreases sharply and at the temperature 1,200 K converges to zero.

The degree of carbon gasification XC (Fig. 2) is determined from the carbon content of the solid residue. Specifically, X_C is calculated according to the following expressions: $X_C = \frac{C_{ini} - C_{fin}}{C_{ini}} \cdot 100\%$, 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 appears from Fig. 2 carbon gasification degree amounts 100 % at a temperature 1,200 K. It is seen that the carbon is completely transformed into the gaseous phase forming CO at a temperature higher than 1,200 K. This provides a hundred percent carbon gasification.

Specific power consumption (Fig. 3) was defined as a difference between the total enthalpy of the final (current temperature of the process) and initial (T=298 K) state of the system reduced to 1 kg of working substance (mixture of WW and plasma forming air). Specific power consumption for the process of the WW gasification increases with temperature along the full its range. For the temperature

T = 1,600 K, at which the yield of synthesis gas reaches its maximum (Fig. 1), the specific power consumption for air gasification of the WW constitute 1.25 kW h/kg. Such moderate energy consumption for air gasification of WW associated with compensation of endothermic effect due to the heat of the oxidation reaction of carbon in air.

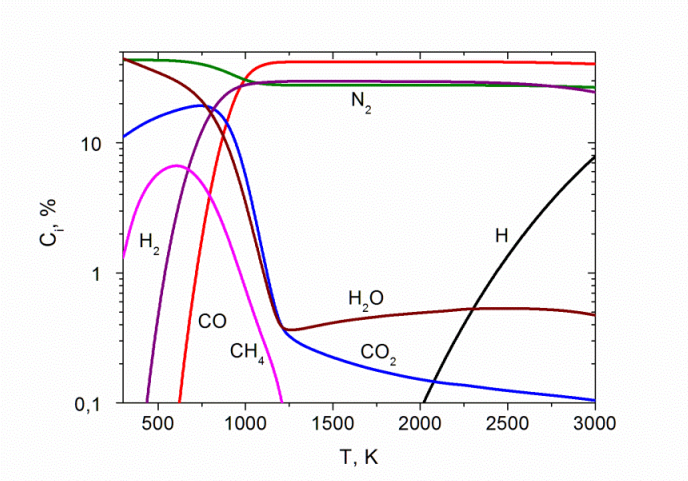

Figure 1. Variation in concentration of gaseous components depending on the temperature of WW air gasification.

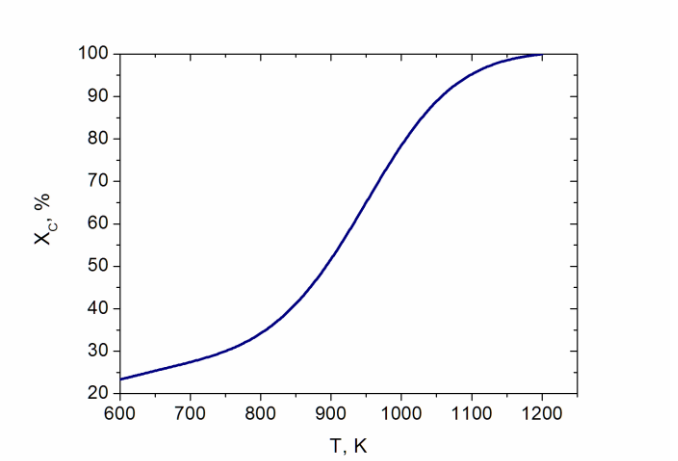

Figure 2. Carbon gasification degree dependence on temperature of WW gasification.

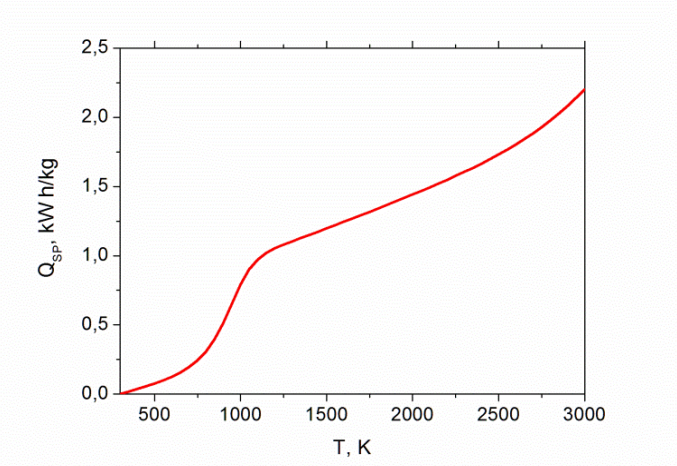

Figure 3. Specific power consumption for the process of WW plasma gasification dependence on temperature.

Found parameters and identified regularities of the process of WW plasma gasification were used to develop an experimental installation.

3. EXPERIMENTAL

Experimental studies of the WW gasification were performed on the installation (Fig. 4), main elements of which are a plasma chemical reactor (Fig. 5) with productivity by WW up to 50 kg/h and long live DC plasmatron (plasma generator) of 70 kW nominal power (Golish et al., 2009). To increase service life of the plasmatron a method of the plasma pyrolysis of hydrocarbon gases with the subsequent deposition of the condensed products of the pyrolysis on water-cooled copper electrodes of the plasmatron was developed. According to the method, a propane-butane mixture is fed into the zone of arc discharge between the cathode and anode. As a result, the vapor of carbon is formed in the cavity of the cathode and on the inner surface of the anode. Electron microscopy and Raman spectroscopy instrumental studies of the electrode coating showed that it consisted of the composite nanostructured carbon material including largely single-walled and multi-walled carbon nanotubes and other carbon forms with a certain amount of copper atoms intercalated in the carbon matrix. Experimental study of the long life plasmatron showed that at the plasmatron power of 72.6 kW (I=220 A, U=330 V), plasma forming air flow rates of 250 l/min and propane-butane flow rate of 1.8 l/min, temperature at the plasmatron nozzle exit section was 5,500 K (Fig. 5). At 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 regenerable nanocarbon coating of copper electrodes (Il'in, et al., 2010).

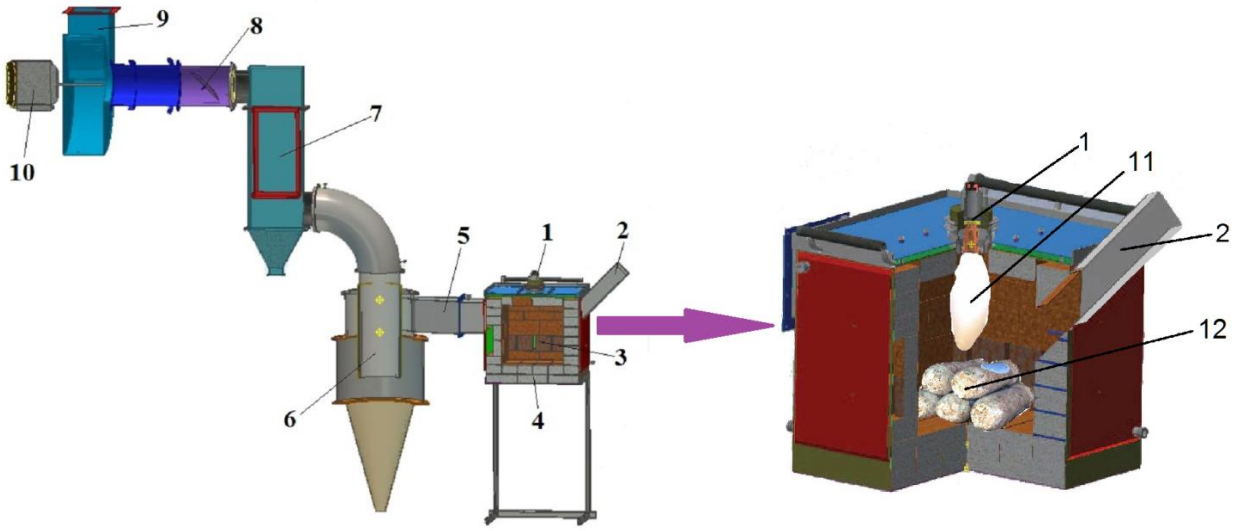

Figure 4. Layout of the experimental unit for plasma gasification of WW and scheme of the plasma reactor: 1 – arc plasmatron; 2 – pipe for supplying of briquetted WW; 3 – WW gasification zone; 4 – reactor; 5 – chamber for combustible gas removal from the reactor; 6 – cyclone combustion chamber; 7 – gas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

The composition of the experimental setup (Fig. 4), except the reactor 4 and plasmatron 1, includes the plasmatron power management system and systems of gas and water supply into the reactor and plasmatron and exhaust gas cleaning 7. Installation is equipped with sampling system of gas and condensed products of WW gasification process for their analysis (Messerle et al., 2018). Plasma reactor was designed for plasma gasification of WW. The reactor is a cube. It is lined by refractory

bricks thickness of 0.065 m. A size of the inner side of the cube is 0.45 m. The reaction volume of the reactor is 0.091 м^3. Pipe for supplying of briquetted WW 2 can be used to measure the temperature inside the reactor using infrared pyrometer. Pyrometer Ircon Ultrimax Plus UX10P is used for temperatures from 600 to 3,000ºC (873-3,273 K). Metering error depends on temperature range and it is ±0.5% of measured value for temperature range up to 1,500ºC (1,773 K), ±1% for the range 1,500-2,000ºC (1,773-2,273 K) and it increases to ±2% for the temperature over 2,000ºC (2,273 K). Temperature resolution is not worse than 1ºC. The device is equipped with COM port for connection to computer, and the temperature can be controlled by RS-232C protocol during experiment and performs results in on-line regime. Sampling interval of the device is 0.5 s.

The process of WW plasma gasification is as follows. After starting the plasmatron 1 and heating inner liner surface of the bottom of the reactor 4 prior to temperature 1,215 K (about 15 minutes), WW briquettes are served into the gasification zone 3 through the pipe 2 (Fig. 4). 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 up to 1,600 K. The gaseous products are taken out of the reactor into the cyclone combustion chamber 6, and the condensed products are accumulate in the bottom of the reactor. The combination of the zone of heat release from plasma flame with one of WW gasification 3 and slagging contributes to the intensification of WW processing. The cooled gaseous products enter the gas purification unit 7, after which via gas sampling system is supplied to the analyzer. Ventilation system 9 including and pressure control valve 8 provides a low pressure in the reactor up to 10 mm of water column.

Figure 5. Photo of the plasma torch in action with lifted lid of the reactor.

Figure 5 gives a perspective view of the reactor with lifted lid and plasma flame. As a result of the WW plasma gasification synthesis gas was produced. Figure 6 shows the flame of gas exiting the pipe 2 at a short time disabling of exhaust system. It can be seen that the resulting fuel gas is intensively ignited in air. Measured temperature of this flame was about 1,600 K. During the experiment, the fuel gas is withdrawn using exhaust system. Measured temperature in the bottom of the reactor was 1,560 K. Under the influence of air plasma flame, the weight average temperature in the reactor reached 1,600 K, an organic part of WW was gasified and inorganic part (ash) was accumulated in the slag formation zone (Fig. 7) of the reactor and in the bag filter 7 (Fig. 4). The obtained synthesis gas was incinerated in cyclone combustion chamber 6. Combustion products were continuously withdrawn from the installation through the cooling and purification systems. The ash was removed from the reactor after shutdown of the plasmatron and cooling the reactor. The plasmatron was turned off 25 minutes after the download of the first WW briquette. 30 briquettes of total mass 9.9 kg were gasified during this period. WW briquettes consumption was 23.8 kg/h. Air flow rate through plasmatron was 23.6 kg/h.

Figure 6. Photo of the combustible gas control flame from the pipe for supplying of briquetted WW.

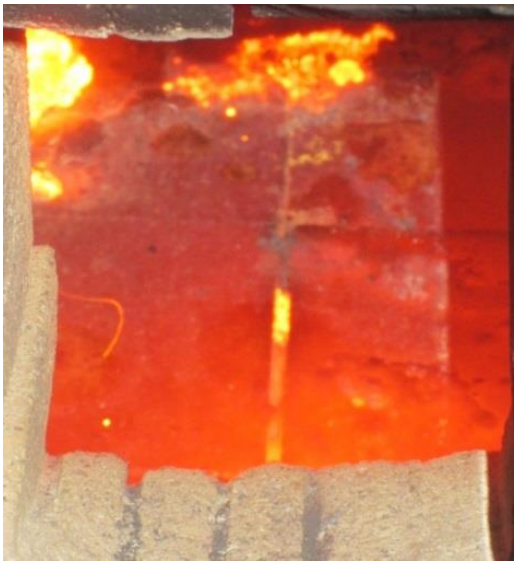

Figure 7. Photo of hot ash on the bottom of the reactor after plasmatron turn off.

By the results of experimental study of the WW plasma gasification plasma reactor operating conditions were determined, the exhaust gas analysis was performed, the samples of the condensed products were collected from slag formation zone of the reactor, and the residual carbon content in the slag was determined. Gas analysis performed on a gas chromatograph SRI 8610C, showed the following composition of the gas at the exit of gas purification unit, vol.%: CO – 42.0, H_2 – 25.1, N_2 – 32.9. Specific heat of combustion of the synthesis gas produced by air gasification amounts to 9,450 kJ/kg. The total concentration of the synthesis gas was 67.1%, which agreed well with the thermodynamic calculations. The yield of synthesis gas according to the calculation at 1,600 K was 71.6% (CO – 41.9%, H_2 – 29.7%). Thus, the discrepancy between experiment and calculation by the yield of the target product (synthesis gas) did not exceed 6%. Concentration of thermodynamically predicted N_2 was 27.8%. This difference could be because of unguided dissolution of experimentally produced synthesis gas by ambient air.

After gasification 9.9 kg of WW 0.013 kg of ash was collected from the bottom of the reactor (Fig. 8).

This quantity of ash is about 0.12% from initial quantity WW. Residual fly ash (0.1% of ash) was flowed away with exhaust gas. Measured with help of volumetrical orifice flow rate of exhaust gas was 48.3 kg/h. The discrepancy between experimental and calculated flow rate is 2%.

In the experiments, as well as in calculations, no harmful impurities were found in the products of the WW plasma gasification. Carbon content of the slag in the sample was 1.13 wt.%, which corresponded to the degree of the WW carbon gasification 96.6%. It was found using absorption-gravimetric method. The discrepancy between the experimental and calculated values of carbon gasification degree did not exceed 3.5%.

Specific power consumption for the WW gasification in the plasma reactor according to the results of experiments amounted to 1.53 kWh/kg of working substance. Efficiency of plasma source was ignored when determining specific power consumptions. In the calculation specific power consumption for air-plasma gasification of the WW was 1.25 kWh/kg (Fig. 3). The discrepancy between the calculated and experimental values of specific power consumption for the process is 18%. It is due to the fact that 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 the cooling water.

4. CONCLUSIONS

Thermodynamic calculations showed that the maximum yield of the synthesis gas at plasma gasification of wood waste in air medium is achieved at a temperature of 1,600 K.

At the air plasma gasification of the WW synthesis gas with a concentration of 67.1% was obtained. Specific heat of combustion of the synthesis gas produced by air gasification amounted to 9,450 kJ/kg.

In the experiments, as well as in thermodynamic calculations, no harmful impurities were found in both gas and condensed products of the WW plasma gasification.

Comparison of experimental results and calculations on plasma gasification of WW showed good agreement.

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