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WILLOW BIOMASS AS A FEEDSTOCK FOR GASIFICATION

Summary

A study concerns the balance of mass and energy in the process of gasification of willow chips (acquired in 5-year rotation), as well as in the process of combustion of the gasification product with flue gas heat recovery. Thermochemical conversion of willow biomass resulted in the production of raw gas with the calorific value of 4937 kJ/kg. The product of gasification comprised a mixture of gaseous compounds, tars and water vapour. The gaseous compounds determined in the study included: hydrogen (8.30%), carbon monoxide (27.51%), methane (1.51%), carbon dioxide (3.79%), nitrogen (55.87%) and small amounts of hydrocarbons C1-C3. The ultimate production output of willow fuel was equal to 91.5 kg of chips per hour and the power output achieved 315 kW. Raw gas produced from willow biomass, mixed with air, was burnt at a temperature exceeding 1000^{o}C and the flue gas heat was recovered in a water boiler and distributed in the central heating system. The collected thermal energy accounted for over 79% of the chemical energy of the biomass at the start of the process.

***Key words**: willow, biomass, gasification, gasifier, raw gas, mass and energy balance*

1. Introduction and aim of the study

Using food products as energy sources (non-food) is regarded as unsustainable. For this reason, work into developing technologies of producing second generation biofuels (liquid, gaseous) from non-food raw materials, including perennial energy plants, has been under way in EU countries [1-4]. Gasification is one of well-developed processes of thermochemical biomass conversion. The method can be used to produce syngas, but also - after further conversion - renewable fuels, such as second generation biodiesel (biomass to liquid - BTL), hydrogen, methanol, chemicals and electrical power [5-7]. Moreover, biomass enables production of syngas with various values of C:H ratio, calorific value, temperature, depending on the biomass type. With a known type of biomass, it is possible to make a preliminary determination of the syngas composition, which will be produced and select the biomass to meet one's needs [8]. Currently, nearly 99% of the starting material for gas generators is based on fossil fuels, where coal accounts for 63%, oil for 15%, natural gas for 13% and petcoke - for approx. 9% [9]. Biomass and waste account for not much more than 1% of the feedstock and – due to the requirements set by Directive 2009/28/EC [1] and Polish regulations [10] – the proportion of biomass in RES, including that acquired in agricultural areas, will be growing steadily. The annual potential of biomass consumption for energy purposes is estimated by various authors to lie within the range from 350 EJ [11] to as much as 2900 EJ/year [12], which may account for 600% of the primary energy production in the world (510.3 EJ) in 2010 [13]. On the other hand, according to Hoogwijk et al [14], the potential of biomass produced on agricultural land within 50 years may be as high as 988 EJ/year.

It was assumed in this study that it is possible to produce raw gas, as an alternative to natural gas, in a prototypic 0.5 MW gasifier, from willow biomass acquired in 5-year rotation by the Eko-Salix method on marginal soil, which cannot be used for the cultivation of edible crops [15]. It was assumed that this type of thermochemical conversion of lignocellulose willow biomass could be used in dispersed systems in rural areas where natural gas is not available. During the combustion of raw gas, heat or process steam would be produced (e.g. to be used in local food production plants, abattoirs, etc.). A demonstration system for biomass conversion to raw gas, which is to be constructed at UWM in Olsztyn – after the gas purification – could be integrated with a supply system of a solid oxide fuel cell, which would co-generate electrical power and heat.

The aim of the study included preparing a balance of mass and energy in the process of gasification of willow chips, the process of combustion of the gasification product in a burner with flue gas heat recovery, as well as determination of the raw gas composition.

2. Study methodology

The process of gasification of willow biomass from plants produced in the Eko-Salix system was examined in a pilot plant at the University of Warmia and Mazury in Olsztyn. The system consisted of the following parts: a counter-current gasifier with the power capacity of 500 kW (Fig. 1) with continuous fuel feed, water sealing and mechanical ash removal; a fuel scraper feeder with a buffer tank and a separating lock; an ash removal cone with afterburning air nozzles; a water sealing tank; an afterburning air fan; a gasifying air fan; a water boiler; a gas pipeline; a process gas burner; an oil pilot burner and a burner air fan.

Fig. 1. The counter-current gasifier used in the experiment

The plant was fitted out with a control computer system, which was also used for securing, visualising and archiving data, allowing to control the process fully. The control system was used to regulate the fanned air output to the reactor and burner and to control the feeders and ash remover. The monitoring system shows the current and historic values of the following data: fan settings; temperature and pressure in the system; boiler power output; settings and current of feeders and mixer. Moreover, a multi-point thermocouple probe was installed before the experiment to measure the temperature inside the reactor, at its various depths, a zirconia oxygen analyser in the flue duct behind the boiler and measurement points were established to measure the air expenditure to the reactor and to the burner.

The scope of research included experiments which were necessary to prepare the mass and energy balance of the willow chips gasification process in a 500 kW unit, which included: analysis of the composition of the raw gas; temperature measurement in the reactor; measurement of the air flow rate to the reactor and to the burner and a gasifier balance study.

The gas composition was determined with Siemens Ultramat 23 and Siemens Calomat 6 analysers as well as with a VARIAN CP 4000 gas chromatograph. Gas samples were taken from the gas duct and the flue gas duct with a PSS-5 portable system of gas conditioning, manufactured by M&C type PSS-5. Air flow rates were measured with a Prandtl probe manufactured by TESTO and with a Testo 512 pressure difference gauge. Temperatures inside the reactor were measured with a special multi-point thermocouple probe and a CHY 506A digital gauge. The tars were analysed in accordance with the procedures described in the standard PKN-CEN/TS15439:2007 (U) (CEN/TS 15439: 2006 (E).

Natural dried willow chips obtained from 5-year plants cultivated in the Eko-Salix system were used as feedstock for gasification. The fuel is characterised in Table 1.

The mass and energy balance for the willow chips gasification process was prepared for the steady state, with the following criteria: constant fuel level in the reactor, set temperature and gas composition at the gas generator outlet, which remain unchanged for over an hour.

The balance diagram of the gasification and combustion process in the installation is shown in Figure 2.

Table 1. Characteristics of willow chips cultivated in the Eko-Salix system, used for gasification

Feature	Value
Bulk density (kg/m3)	187.11
Moisture content (%)	19.02
Ash content (% of d.m.)	1.45
Higher heating value (MJ/kg of d.m.)	19.47
Lower heating value (MJ/kg)	15.30
Particulate matter (% of s.m.)	19.61
Volatile matter (% of d.m.)	78.33
C (% d.m.)	49.23
H (% d.m.)	5.34
S (% of d.m.)	0.020
N (% of d.m.)	0.47
Cl (% of d.m.)	0.024

3. Results

The mass balance of the gasification and combustion of willow biomass is shown in Table 2. Willow chips and air were fed into the gasification reactor at the rate of 91.5 and 122.6 kg/h, respectively. The air-to-fuel ratio in the biomass gasification process was equal to 1.34, the air excess ratio in the gasification process was equal to 0.28 (Table 4) and in the combustion of raw gas - 1.96. The product of gasification was obtained at the rate of 212.6 kg/h; it consisted of gas – a mixture of hydrogen, carbon monoxide, carbon dioxide, methane and C1-C3 hydrocarbons, water vapour and tars. Inorganic matter in the form of ash was produced at the rate of 1.5 kg/h (Table 2). The gasification product was diluted with air at the rate of 27.0 kg/h. The diluted gas was burnt in the burner with a large amount of air (648.1 kg/h), which generated a temperature of over 1000^{o}C. Hot flue gas at the rate of 987.7 kg/h was cooled down with circulating water (18.5 kg/h) and, subsequently, it passed to the chimney.

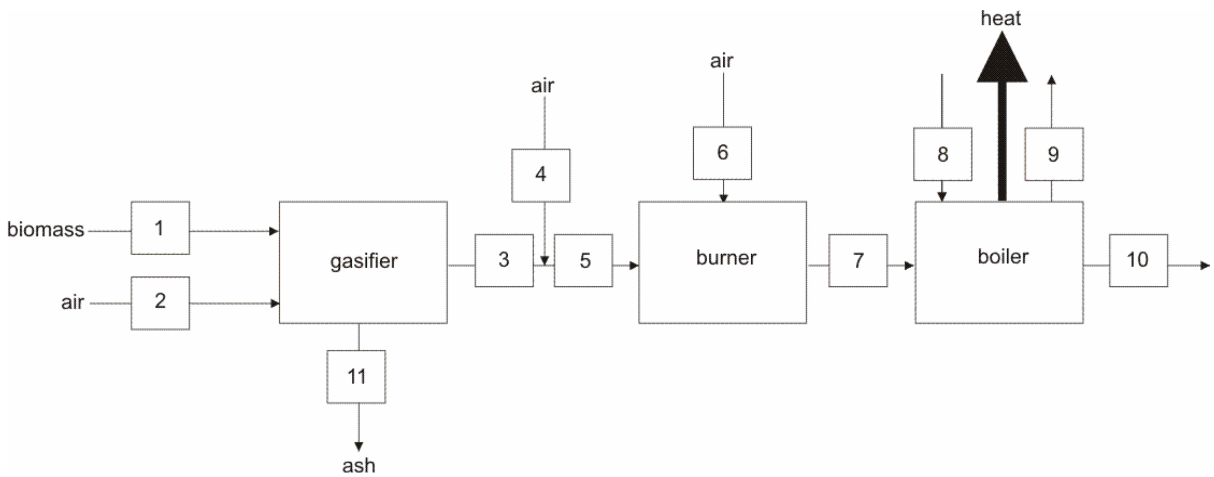

Fig. 2. The balance diagram of the gasification and combustion process; Biomass - flux 1 - is fed to the gas generator with air - flux 2. Product of gasification - flux 3. Inorganic matter from fuel remains in the bottom part of the reactor as ash - flux 11, from where it is regularly removed. The gasification product is diluted with air - flux 4, which enters the gas flow route through leaks as a result of decreased pressure in the reactor. Diluted gas - flux 5, is burnt with air fed into the burner - flux 6. Hot flue gas - flux 7, is cooled down in the boiler chamber and subsequently it passes to the chimney - flux 10. Heat from the flue gas is recovered by circulating water - fluxes 8 and 9.

Table 2. Mass balance of the gasification and combustion of willow biomass

Type of data	kg/h
Biomass (fuel) fed to reactor	91.5
Air fed to reactor	122.6
Product of gasification (gas)	212.6
Gas-diluting air	27.0
Diluted gas	239.6
Air to burner	648.1
Hot flue gas	987.7
Cold water	18.5
Hot water	18.5
Ash (slag)	1.5

The energy balance of the gasification and combustion of willow biomass is shown in Table 3. The chemical energy of the fuel was equal to 389.4 kW, and the energy recovered was 315.0 kW, which means that the process efficiency was equal to 79.1%. Energy loss in the process of gasification and combustion was equal to 17.4% and 3.5%, respectively. The chemical energy of gas amounted to 226.0 kW and that of tars and dust - 91.3 and 0.6 kW, respectively.

Table 3. Energy balance of the gasification and combustion of willow biomass

Type of data	kW	%
Chemical energy of fuel	389.4	100
Chemical energy of gas	226.0	56.9
Chemical energy of tar	91.3	22.3
Chemical energy of particulates	0.6	0.14
Chemical energy of gas and contaminants	10.5	2.6
Recovered energy	315.0	79.1
Energy loss in the gasification process	69.4	17.4
Energy loss in the combustion process	14.0	3.5

The main energy carriers in the dry gas, produced in the process of gasification of willow biomass, were carbon monoxide (27.51%) and hydrogen (8.30%) (Table 4). The H/CO ratio was equal to 0.30. Small amounts of the following compounds were also found: methane, ethene, ethane, propane: 1.51, 0.06, 0.07, 0.03%, respectively. Moreover, the gas contained nitrogen (55.78%), carbon dioxide (3.79%) and oxygen (2.7%). The calorific value of dry gas (not diluted with air) was equal to 4937 kJ/kg. This gas composition does not differ much from that established in other studies (Table 5).

The fraction of tar, dust and water vapour accounted for: 0.16, 0.001 and 0.35 kg/kg of fuel, respectively. Evaluation of the gas purity is shown as the tar and dust contents in the gas generator outlet flux. The tar and particulate contents were 74.4 and 0.5 g/kg of gas, respectively.

Table 4. Composition of gas produced by gasification of willow biomass

Molar composition of dry gas	% (v/v)
H_2	8.30
CO	27.51
CH_4	1.51
CO_2	3.79
C_2H_4	0.06
C_2H_6	0.07
C_3H_8	0.03
N_2	55.87
O_2	2.70
H/CO	0.30
LHV of dry syngas** (kJ/kg)	4937
Excess air	0.28
Air/fuel	1.34

** gas undiluted with air

4. Conclusions

No irregularities were observed in the course of the process of thermochemical conversion of willow biomass in the gasifier. The willow wood was completely gasified. The process resulted in production of raw gas with the calorific value of 4937 kJ/kg. The product of gasification was comprised of a mixture of gaseous compounds, tars and water vapour. The content of the following gaseous compounds was determined: hydrogen, carbon monoxide, methane, carbon dioxide, ethene, ethane, propane. The ultimate output of the willow fuel was equal to 91.5 kg of chips per hour and the power output achieved was 315 kW.

Raw gas produced from willow biomass, mixed with air, was burnt at a temperature exceeding 1000^{o}C and the flue gas heat was recovered in a water boiler and distributed in a central heating system. The collected thermal energy accounted for over 79% of the chemical energy of biomass at the start of the process.

Raw gas produced from willow biomass in dispersed systems can be an alternative to natural gas and, when purified, it can be used in a fuel cell (SOFC) to co-generate electricity and heat.

The fuel dosing system requires properly-ground biomass. An effective biomass chipper should be used in the chip preparation process or the chips should be sieved.

Table 5. Composition of synthesis gas in other studies

Source	Type of biomass	N_2	CO	H_2	CH_4	CO_2	LHV MJ/m^3 dry gas
[16]	Wood pellets 6 mm	50.4	25.7	11.9	2.6	9.9	5.4
	Bagasse pellets 6 mm	52.6	23.3	9.9	2.8	11.4	5.0
[17]	Wood pellets 12 mm	41.0	31.4	13.0	3.6	12.6	8.2
[18]	Wood pellets 6 mm	54.68-56.67	27.47-25.53	7.13-7.96	1,88-1.44	6.22-7.06	4.99-4.67

5. References

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