Microwave assisted biomass gasification of sawdust and wood pellet

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Abstract: Development of alternative approaches in the field of pyrolysis and gasification of biomass is possible step in streamlining the process of recovery of organic wastes. The use of microwave radiation offers essential benefits, like homogenous heating of the whole structure, in comparison to conventional heating methods. Using the microwave reactor, where the prevention against oxidation process is improved, leads to the increased production of combustible gases like methane and hydrogen. Two microwave reactors HR-Lab and HR 200 were used in this experimental work to produce syngas by microwave thermal processing of sawdust and wood pellets and the study of waste recovery. Subsequent investigation of syngas composition and tar quantity was performed. The optimization of the gasification process of biomass in the form of wood pellets showed that the syngas obtained in the microwave reactor HR-Lab at gasification temperature 800 °C improved the syngas quality, had a high heating value of 16.237 MJ/kg and can be used as a fuel for gas engines. The results of calculation with assumed values show that the large microwave reactor HR-200 would be able to produce 0.55 m^3N/h dry gas per each kilogram gasified biomass and in total 109.86 m^3N/h. The total amount of produced humid gas at the temperature 750 °C is at 584.90 m^3/h. This gas contains 28.8 % of evaporated water and about 12.2 g/m^3 of tar and dust.
Keywords: Microwave pyrolysis; Syngas; Energy Efficiency; Thermal processing.

Introduction

Due to the legislation of EU and its incorporation into the legislation of individual EU countries a big emphasis is put on the deployment of renewable energy (Némethová et al., 2014). In Slovakia, e.g., the greatest potential has energy from biomass, followed by solar, geothermal, hydro and wind energy. For future energy production is more than 80 % of this potential technically exploitable (Janíček et al., 2009, Janíček et al., 2012). Waste generation has a serious impact on the environment, causing pollution and greenhouse gases emission, as well as significant losses of materials – a particular problem for the EU which is highly dependent on imported raw materials (European Union, 2010).

In order to replace fossil fuels it is increasing interest in renewable energy sources, especially in the bioenergy area. Biomass has been for a long time considered as a one of the most promising renewable energy sources on Earth (Kubica, Pípa, 2008). One of its advantages is the possibility of conversion into a gaseous respectively liquid fuel form (Isahak et al., 2012), hydrogen and electricity (Damartzis et al., 2011, Kirkels et al., 2011, Lin et al., 2009).

Despite the undeniable advantages of the process of obtaining the energy from biomass, there are various obstacles to more widespread use and commercialization of biogas and biorefining industry. On the one hand, there are non-technical restrictions by example related to the limited use of land, or different assessment of the effects on the environment. On the other hand, there are obstacles, respectively technical limitations related to imperfection of the conversion of the primary organic material (Demirbas, 2009).

Pyrolysis and gasification are effective methods used within the conversion process of the biomass into the final product (synthesis gas or syngas). Both processes take place in the reactor, the composition of the synthesis gas is strongly dependent on an appropriate set of operating conditions (temperature, pressure, temperature profile, composite composition of the biomass, etc.). In both cases, pyrolysis and gasification, there is the need for an external heat source (Budarin et al., 2011). Pyrolysis is the first step in gasification and combustion and occurs in absence or nearly absence of oxygen. Pyrolysis is maybe the oldest process of conversion of biomass to a higher-grade fuel known as charcoal, which is a fuel with nearly double the energy density of the initial material and burns at higher temperature. Gasification is also a thermal-chemical degradation of substance, similar to pyrolysis, however it involves the partial oxidation, therefore it can be considered as a process between pyrolysis and combustion. In the gasification the amount of oxygen is not sufficient to allow the fuel to be completely oxidized. The process temperatures employed are usually higher than 650 °C (Janíček et al., 2009, Janíček et al., 2012).

In term of arrangement, fixed and fluidized beds are the most common solution of reactor design (Dong et al., 2010, Van der Meijden et al., 2009). The use of microwave radiation as an alternative source of heat within thermochemical gasification and pyrolysis has already been tried (Bu et al., 2012, Du et al., 2011), but detailed studies and analyzes of these processes have not yet been published. The most essential benefits of microwave heating compared to conventional heating methods can be considered homogeneous heating of the whole structure, which results from the physical mechanisms of the interaction of the radiation on a molecular level (Sobhy, A., Chaouki, J., 2010). Quick start of heating and high dynamics of the process is another advantage of this approach. Finally, the experience with the application of microwaves in chemical and food industry proves that it is a nature, tested and economically acceptable technology.

Wood pellets are the most common type of pellet fuel and are generally made from compacted sawdust and related industrial wastes from the milling of lumber, manufacture of wood products and furniture (Arshanitsa et al., 2016). In this paper, microwave-assisted gasification in two microwave reactors HR-Lab and HR 200 of sawdust and wood pellets was carried out under optimal conditions designed based on previous studies (Janíček et al., 2016). The main task of this study was the comparative study of microwave-assisted gasification of sawdust and wood pellets using two different reactors (HR-Lab and HR 200) and subsequent investigation of syngas composition and tar quantity.

Experimental

The series of experiments with gasification of different waste samples were carried out at the company Aton–S.A. in Stradomia Wierzchnia (Poland). The microwave reactors used in these experiments were designed and built by Aton S.A. These series of tests were conducted on behalf of the company ASSA Ewenex Energy. Gasification of the waste was carried out in the laboratory microwave reactor HR-Lab whereas the microwave-assisted oxidation of syngas took place in reactor MOS. The tests with biomass were performed also in the larger microwave reactor HR 200, which may be considered as up scaling and yields results comparable with the pilot tests. The microwave reactors HR-Lab and HR 200 differ only in size, whereas the operating and construction principles are the same. Reactor HR 200 has a throughput of 200 kg/h therefore this trial could be considered as a kind of up scaling into industrial scale. Samples for the analysis of gases was sucked by means of the conditioner PSS-5, in which the gases were cooled, drained and cleaned from dust particles. The prepared gases were analysed using gas chromatograph Perkin-Elmer Autosystem XL - Arnel type M2008 with different detectors for determination of methane, hydrogen and aliphatic hydrocarbons. The determination range of analysed components was from 0.01 to 100 %. The system has collaborated with TOTALCHROM integration program. The analyses were performed based on the standard PN-EN ISO 6975: 2005 compliant with the standards ASTM D1946 and GPA 2286. The volume of the feeder loop was 1 cm^3. The temperatures of thermostat and detector TCD was 110 °C and 200 °C, resp. Sulphur compounds (hydrogen sulphide, mercaptans) were determined by chromatograph Perkin-Elmer with detector EPD. The standard error in determining of the substances was 1.5 % of measured value. Measuring of the dust concentration in syngas was made by the reference method according to the Ordinance of Polish Environment Ministry [OJ No. 206: 2008, pos. 12911] using a set of gravimetric dust meter EMIOTEST 2598. The measuring set consisted of a special aspiration velocity sensor with outer filtration and dust separator, the computer control unit E2598 and the suction unit AZ-15. As the filtration materials used flat filters with a diameter of 100 mm made of fibreglass.

Results and discussion

The aim of the experiment was to determine the parameters of the process in the optimal conditions (Janíček et al., 2016) for the formation of combustible gases in particular methane in the process gas in order to use it as a fuel for gas engines. Samples for the analysis of gas components were cooled, drained and cleaned from dust particles before measurements. The most important syngas components are listed in Table 1.

Table 1. Syngas composition from MW gasification of biomass

Gas component	Content in [% mol.]			
	HR-lab		HR-200	
	Pellets $T = 800\,°C$	Pellets $T = 650\,°C$	SawDust $T = 650\,°C$	Pellets $T = 650\,°C$
Ethane + Ethene	2.935	0.946	1.527	1.258

Propane + Propene	0.608	0.506	0.401	0.183
N-Butane	0.225	0.116	0.101	0.002
2,2 Dimethylobutane	0.097	0.022	0.022	0.032
N-Hexane	0.011	0.019	0.008	0.002
Carbon dioxide	14.528	16.193	19.799	14.990
Oxygen	0.000	0.000	0.000	0.000
Nitrogen	8.968	41.871	45.615	46.143
Methane	15.003	8.369	6.583	7.319
Carbon monoxide	37.787	22.161	17.569	20.057
Hydrogen	19.204	9.418	8.037	9.471

According to the reproduced composition of the syngas in the gasification of wooden pellets at 800 °C in the HR - Lab was obtained about 15 % - methane, 38 % - carbon monoxide, 19 % - hydrogen and 3 % - ethane + ethene, which indicate a good suitability for gas engines.

The calorific values of all investigated biomass samples were calculated according to the norm PN-EN ISO-6976: 2008. In view of the energy calculations, the best results were obtained with the gasification in the small reactor HR-Lab using the biomass in form of wood pellets. The treatment temperature of 800 °C seems to improve the syngas quality. The measurement results of the syngas composition were carried out in the dry and dust free gas. In the real conditions after HR-Lab the syngas contains steam, dust, tar and other substances, which significantly affect the quality and gas engine operation. However, the gas prior to entering the gas engine should be conditioned, which included de-dusting, de-oiling and drying, so these results are relevant for the further considerations.

Measurements of dust and tar concentration in syngas

During heating of the biomass formed from cellulose and lignin at temperatures up to about 400 °C primary tar occurs. Tars are mostly aldehydes, alcohols, complex phenols and furans. By further heating decompose these compounds to phenolic ether (about 500 °C), heterocyclic ether (700 °C) and finally to polycyclic aromatic hydrocarbons (PAH, about 900 °C) (Giemza, 2016, Kramer and Mühlbauer, 2002). At temperatures above 1100 °C, the tars disintegrate with sufficient residence time to small molecules with fewer than six carbon atoms (Evans and Milne, 1997, Wiese, 2007). Generally tar content decreases when heating temperature increases (Wiese, 2007).

The measuring of the dust concentration in syngas was carried out in the real conditions after the reactor HR-Lab using a set of gravimetric dust meter EMIOTEST 2598. The results are listed in Tab. 2.

Table 2. Results of dust and tar concentration measurements following the HR-Lab treatment

Sample	Steam content in humid gas	Tar and dust (soot)	Residue on ignition at 200 °C (dust)
	%	g/m^3	g/m^3
Wood pellets at 650 °C		17.2	5.12
Wood pellets at 650 °C		11.8	4.07
Mean values	**28.2**	**14.5**	**4.59**
Sawdust at 650 °C	36.2	11.1	6.17
Wood pellets at 800 °C		7.6	2.51
Wood pellets at 800 °C		16.7	5.47
Mean values	**28.7**	**12.2**	**3.99**

Due to the high content of tar and dust in the gas resulting from the gasification of the biomass it was unable to clearly distinguish the contents of the individual components in the gas sample. The results in Table 2

include the amount of tar and dust and residue on ignition in the temperature of 200 °C. Analysing the results of measurements it can be clearly confirmed that the higher gasification temperature reduces the amount of tar in syngas. In order to adapt the gas to the engine requirements a suitable technology is necessary to eliminate these compounds.

Volume of syngas produced on small reactor HR-Lab

The calculation of the gas volume formed by gasification of biomass was carried out based on the trial with wood pallets in the reactor HR - LAB at the process temperature of 800 °C using the results of the weight loss (Tab. 3) and the measurements of syngas composition.

Table 3. Material mass parameter of gasification at 800 °C in HR-Lab

Parameter	Amount
Throughput	8 kg/h
Weight loss = 75 %	6 kg/h
Remaining residues	2 kg/h
Tar and dust content	12.2 g/m^3

The density of the combustible gas mix at standard temperature and pressure conditions (STP) is a summation of the densities of its single components. Tab. 4 shows the results of these calculations.

Table 4. Density of syngas from biomass gasification at SRC

Gas composition	Content in dry gas %	Content in humid gas %	Density of components at STP kg/m^3	Resulting gas density at STP kg/m^3
H_2O	-	28.7	0.864	0.248
Methane+Ethane	17.938	12.8	0.717	0.092
CO	37.787	26.9	1.250	0.337
CO_2	14.528	10.4	1.977	0.205
Nitrogen	8.68	6.4	1.250	0.080
Hydrogen	19.204	13.7	0.090	0.012
Density of gas mix at STP (273,15K, 101.325 kPa) - ρ_1				0.973

The syngas density at SRC corresponds to the syngas density at real conditions at the temperature of 750 °C and pressure of 100 kPa.

Using combined gas flow equations, the volumetric flow rates per kilogram of biomass (q_1, q_{1d} and q_2) were calculated from the total amount of processed material per hour and each flow rates for different conditions. The results are listed in Tab. 5.

Table 5. Volumetric flow rates of syngas at different conditions

condition of gas	Volumetric flow of gas	Unit
Q_1 - Humid gas at STP (273 K, 101.325 kPa)	6.16	m^3_N/h
Q_{1d} - Dry gas at STP (273 K, 101.325 kPa)	4.39	m^3_N/h
Q_2 - Humid gas at real conditions (750°C, 100 kPa)	23.44	m^3/h
Volumetric flow of gas per 1 kg load		
q_1 - Humid gas at STP (273 K, 101.325 kPa)	0.77	m^3_N/h
q_{1d} - Dry gas at STP (273 K, 101.325 kPa)	0.55	m^3_N/h
q_2 - Humid gas at real conditions (750°C, 100 kPa)	2.92	m^3/kg

On the basis of calculations it can be concluded, that from1 kg biomass in form of wood pellets at the weight-loss of 75 % round 0.55 m^3_N/kg syngas is generated. This syngas had a high calorific value of 16.2 MJ/m^3 and is considered to be a good quality fuel that is suitable for use in gas engines. Before use as a fuel this syngas have to be conditioned corresponding to requirements of the engine producers in order to avoid malfunctions and accelerated wear.

Real volume of gas produced in technical scale using reactor HR-200

The calculation algorithm is the same as with the small reactor. The amount of material used in this trial was too small for this reactor and the results are not satisfying. However, some results are helpful for understanding of the process and its optimisation in the future. The material mass parameters of gasification carried out in HR-200 in the temperature of 650 °C are listed in Tab. 6.

Table 6. Material mass parameter of gasification at 650 °C in HR-200

Parameter	Amount
Throughput	12 kg/h
Weight loss = 76 %	9.12 kg/h
Remaining residues	2.88 kg/h
Tar and dust content	14.5 g/m^3

The content and densities of each syngas components and mix at standard pressure and temperature (STP) are listed in Table 7.

Table 7. Density of syngas from biomass gasification at SRC

Gas composition	Content in dry gas [%]	Content in humid gas [%]	Density of components at STP [kg/m³]	Resulting gas density at STP [kg/m³]
H_2O	-	28.2	0.864	0.244
Methane+Ethane	8.577	6.2	0.717	0.044
CO	20.057	14.4	1.250	0.180
CO_2	14.99	10.84	1.977	0.213
Nitrogen	46.143	33.1	1.250	0.414
Hydrogen	9.471	6.8	0.090	0.006
Density of gas mix at STP (273,15K, 101.325 kPa) - ρ_1				1.101

The volumetric flow rate of humid gas in the real conditions at 750 °C and 100 kPa is 0.321 kg/m^3.This experiment was carried out with a throughput of only 12 kg/h. Usage of the total capacity of the reactor, which is at 200 kg/h, was not possible in this experiment mainly from economic reasons.

Table 8. Volumetric flow rates of syngas at different conditions

Condition of gas	Volumetric flow of gas	Unit
Q_1 - Humid gas at STP (273 K, 101.325 kPa)	8.28	$[m^3_N/h]$
Q_{1d} - Dry gas at STP (273 K, 101.325 kPa)	5.95	$[m^3_N/h]$
Q_2 - Humid gas at real conditions (750 °C, 100 kPa)	28.37	$[m^3/h]$
Volumetric flow of gas per 1 kg load		
q_1 - Humid gas at STP (273 K, 101.325 kPa)	0.69	$[m^3_N/h]$
q_{1d} - Dry gas at STP (273 K, 101.325 kPa)	0.50	$[m^3_N/h]$
q_2 - Humid gas at real conditions (750 °C, 100 kPa)	2.36	$[m^3/kg]$

Theoretical volume of gas produced in technical scale using reactor HR-200

This calculation assumed that the performance of the small reactor is able to reproduce also using the reactor HR-200. Some technical improvements like optimisation of material feeding and usage of total capacity in order to reduce the amount of oxygen inside of the reactor will enhance the syngas quality and composition. It is very likely to achieve or exceed the performance of the small reactor.

The real parameters of gas have been transferred from the experiment with HR-Lab at 800 °C and converted to higher throughput. Tab. 9 bellow contains the adapted data.

Table 9. Assumed material mass parameter of gasification at 800 °C in HR-200

Parameter	Amount
Throughput	200 kg/h
Weight loss 75 %	150 kg/h
Remaining residues	50 kg/h
Tar and dust content	12.2 g/m^3

The syngas composition and density were taken from the experiment with HR-Lab and are listed in Tab 10.

Table 10. Assumed density of syngas from biomass gasification at SRC

Gas composition	Content in dry gas [%]	Content in humid gas [%]	Density of components at STP [kg/m^3]	Resulting gas density at STP [kg/m^3]
H_2O	-	28.7	0.864	0.248
Methane+Ethane	17.938	12.8	0.717	0.092
CO	37.787	26.9	1.250	0.337
CO_2	14.528	10.4	1.977	0.205
Nitrogen	8.68	6.4	1.250	0.080
Hydrogen	19.204	13.7	0.090	0.012
Density of gas mix at STP (273,15K, 101.325 kPa) - ρ_1				0.973

The volumetric flow rate of humid gas in the real conditions at 750 °C and 100 kPa is 0.256 kg/m^3.

Table 11. Possible volumetric flow rates of syngas at different conditions

condition of gas	Volumetric flow of gas	Unit
Q_1 - Humid gas at STP (273 K, 101.325 kPa)	154.09	[m^3_N/h]
Q_{1d} - Dry gas at STP (273 K, 101.325 kPa)	109.86	[m^3_N/h]
Q_2 - Humid gas at real conditions (750 °C, 100 kPa)	584.90	[m^3/h]
Volumetric flow of gas per 1 kg load		
q_1 - Humid gas at STP (273 K, 101.325 kPa)	0.77	[m^3_N/h]
q_{1d} - Dry gas at STP (273 K, 101.325 kPa)	0.55	[m^3_N/h]
q_2 - Humid gas at real conditions (750 °C, 100 kPa)	2.92	[m^3/kg]

Conclusions

The most interesting results have been obtained with the process of the wooden pellets at 800 - 850 °C using the small MW reactor HR-Lab. The syngas formed in this trial had a high calorific value – the lower heating value was about 16.28 MJ/m^3 and contained circa 75 % of combustible compounds. Measurements and

analysis of the results clearly indicate that the process at the temperature 650 °C had no positive influence on the calorific value of gases including combustible content, among others methane.

In the process carried out in HR - LAB on the material in the form of wood pellets a much higher content of combustible gas compounds was formed in relation to the other trials. The reason for substantial increasing of the methane content, carbon monoxide and hydrogen was, among others reasons, the reduction of the oxygen content inside of the small reactor and so prevention of oxidation processes. This fact can indicate that for reaching of maximum process performance a complete elimination of oxygen access, which can occur for example during material feeding, significantly affects the percentage and composition of combustible compounds in the emerging gas. Syngas obtained in the small microwave reactor HR-Lab at gasification temperature 800 °C had a high heating value of 16.237 MJ/kg and can be used as a fuel for gas engines.

The results of calculation with assumed values show that the large microwave reactor HR-200 would be able to produce 0.55 m^3_N/h dry gas per each kilogram of gasified biomass and in total 109.86 m^3_N/h. The total amount of produced humid gas at the temperature 750 °C is at 584.90 m^3/h. This gas contains 28.8 % of evaporated water and about 12.2 g/m^3 of tar and dust. Before usage as a fuel this gas has to be conditioned, which includes cooling, de-watering, de-dusting and tar removal.

The calculation of produced gas by HR-200 assumes that the reactor operates at its full capacity. In order to achieve the assumed high caloric value it is necessary to control the oxygen content inside of the reactor properly. It starts already at the material feeding that seems to be the most sensitive part of the process. Therefore it is important to prepare the material before gasification and the construction of the material loading mechanism has to prevent as far as possible an uncontrolled air penetration.

The proper way to increase the economy of the process would be the reduction of energy consumption for microwaves by the controlled combustion of a portion of the gas still in the reactor − auto thermal mode. Ideally, when the process temperature is maintained and the reactor achieves an auto thermal operation, the microwaves are switched on for process control only.

Acknowledgement

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