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Characteristic of tar content and syngas composition during beech updraft gasification

Abstract
This work aims at study the effect of the operating conditions like equivalence ration and temperature on the updraft gasification of beech wood. The main aspects was to analyze the influence of temperature distribution in the reactor and equivalence ratio on the fuel consumption, syngas composition as well as tar formation characteristics during the gasification process. The light tar content and composition were analysed using gas chromatography coupled with mass spectrometry (GC-MS). Experimental results have shown that the amount of air supplied does not affect the parameters of the gasification process linearly. For lower ER value there was high fuel consumption and high bed temperature in the gasifier, which results in high caloric value of syngas. The results showed that tar yield during updraft gasification depends on the temperature and equivalence ratio. With the increase value of ER and the decrease of temperature on the surface of the bed, the total amount of tar yield increased. The highest temperature on the surface of the bed leads to the smallest tar yield, which can be associated with thermal cracking. The results indicate that both light and heavy tar are changing nonlinearly with different operating conditions. In addition, with decreasing temperature and increasing ER values, the amount of phenol and oxidized aliphatic compounds in the tar samples increased while the BTEX amount decreased. The amount of PAHs, in relation to the temperature and ER, was kept low in all cases.

Keyword: gasification tar, updraft gasifier, beech wood, GC-MS spectrometry.

1. Introduction

Gasification is a complex thermochemical process, which convert biomass or another carbonaceous solid fuel like coal and waste to gaseous fuel. This process takes place at high temperatures (700–1500°C) and in the presence of air or oxygen as a gasifying agent (McKendry, 2002; Chen et al., 2012). Gas produced in gasification process can be used for power generation in gas engine or directly combusted in boiler, which could minimize the pollutants emission and allows for CO_2 reduction (Ma, 2012). Furthermore, syngas can be used as feedstock for synthesis of fuels and chemicals. These advantages generated considerable interest in the gasification of biomass. However, the problem of tar formation significantly slows down the development of gasification technology. The main technical aspects are associated with tar condensation which leads to plugging and fouling problems. Tars can be define as a complex mixture of organic compounds (Li & Suzuki, 2009; Hernández et al., 2013; Yu et al., 2014), which composition depends on the feedstock, type of gasifier and operating conditions like temperature, pressure and gasification agent (McKendry, 20002; Devi et al., 2003; Li et al., 2009; Hernández et al., 2012; Yu et al., 2014; Kihedu et al., 2016) or sampling procedure and analysis of tars (Li & Suzuki, 2009; Hernández et al., 2013; Nakamura et al., 2015; Edinger et al., 2016).

One of the most important parameters influencing the gasification in the updraft reactor is the bed temperature and the distribution of the individual zones. This aspect was presented by Ismail and El-Sala (2017) and it was indicated that equivalence ratio (ER) significantly affects the temperature of the bed in the gasifier. Furthermore, temperature and ER are closely related to fuel consumption and this aspect must be taken into account. Temperature profile in the updraft gasifier was also analyzed by Chen et al. (2012). Mesquite and juniper wood were subjected to gasification. It was found that syngas composition was very sensitive to moisture content, ER and temperature peak in the gasifier.

Influence of bed temperature and ER on tar during cellulose, hemicellulose and lignin gasification presented by Yu et al. (2014) showed that with increasing reaction temperature the tar yields dropped for all three materials. In addition, the results indicated that the main constituent of the tar is PAHs and its relative content increased with temperature. Lignin, due to its chemical structure gives much higher tar yield than cellulose and hemicellulose. The composition of gasification tar was investigated using GC-MS.

Effect of operating conditions on the tar yield from updraft gasification of dealcoholized marc of grape was discussed in the work of Hernández et al. (2013). The results indicated that increase of fuel-to-air ratio leads to non-linear rise of tar production and the constituents are phenol and BTEX. The influence of temperature showed that the total tar yield was reduced as the temperature increased and reduction in phenol proportion and increase in the PAH and BTEX fractions was observed. In this work to analyze the tar composition an analytical HPLC (High Performance Liquid Chromatography) method has been used.

In this work, a updraft gasification of beech wood has been studied. Experiments were carried out to investigate the influence of bed temperature and equivalence ratio on the feeding rate, syngas yield and its calorific value and especially on the tar production.

2. Materials and methods

2.1. Proximate and ultimate analysis of fuel

The beech wood samples were first dried and moisture content was determined using an MAC moisture analyzer (RADWAG). The analysis of elementary composition were carried out using a CHNS-O Flash 2000 analyzer (Thermo Scientific). The determination and calculation of the calorific value was executed using a KL-11 calorimeter. The results of the proximate and ultimate analyses are presented in Table 1.

Table 1. Proximate and ultimate analyses of hardwood pellet.

HHV [MJ/kg]	19.6
Moisture [wt.%. as delivered]	6.1

Proximate [wt. %$_{db}$][1]	
Volatiles	76.3
Fixed Carbon	21.4
Ash	2.3
Ultimate [wt. %$_{db}$]	
C	48.5
H	5.3
O[2]	45.8
N	0.4

[1] db = oven-dry basis
[2] by difference

2.2. Experimental setup

The updraft gasification stand is presented in Fig. 1. The total high of gasifier is 135 cm and the internal radius is 22 cm. The air inlet nozzles were installed 52 cm from the bottom of the reactor, and the syngas outlet was installed 111 cm from the bottom.

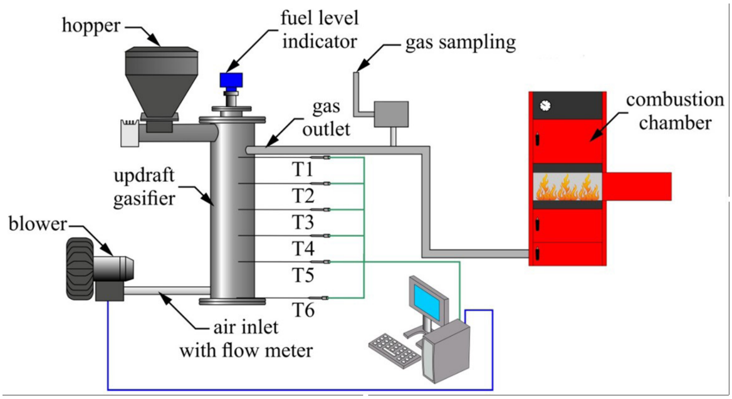

Fig. 1. Schematic diagram of the experimental setup

During experimental investigation hardwood pellet were loaded by a screw feeder to the reactor 10 cm below the syngas outlet. The thermocouples (Type N and S) were installed along of the gasifier high respectively 30, 55, 72, 88, 90 and 119 cm from the bottom of the reactor. The air was supplied to gasifier by an electric blower and controlled using the inverter and the thermal mass flow meter. The syngas left the reactor and passing through an outlet tube to the combustion chamber. On the outlet tube part of the syngas is directed to the sampling system in order to perform tar and gas analysis.

2.3. Experimental procedure

Before starting of gasification process a batch of 3-kg feedstock was loaded into the gasifier during each experiment. The initial level of the feedstock was maintained at the level of the air inlet nozzles until the high bed temperature was obtained. After reaching the high temperature of the bed the gasifier has been filled up to the level of the indicator. In each experiment the height of the fuel bed was kept at the same level using a rotary fuel level indicator — 112 cm from the bottom. Experiments were carried out for the four values of equivalence ratio 0.16, 0.17. 0.23 and 0.30, which corresponds successively to 12, 15, 17 and 20 Nm^3/h of supplied air. The duration of each experiment was 120 minutes from the time when the gasification process reached the steady-state condition (constant temperature in each zone and constant syngas composition).

2.4. Gas composition measurement

The samples of syngas were sampled using tedlar bags. The analysis of the syngas composition were performed using a SRI Instruments 310 gas chromatograph with a thermal conductivity detector (TCD). The gas analyzer was pre-calibrated using a standard mixture of gas to determined CO, CO_2, CH_4 and H_2 and the argon was used as a carrying medium.

2.5. Tar sampling

Tar sampling stand was based on the guideline for sampling and analysis of tars from the gas producer and consists of series of six impinger bottles (Good et al., 2005). The set-up is based on the use of isopropanol as a tar collecting solvent in first five bottles; last impinger bottle is empty. The first three bottles are placed in the heated batch, while the last three bottles are inserted into a cryostat (T = -20°C). This method can also be find in literature (Phuphuakrat et al. 2010; Pedroso et al., 2013).

3. Results and Discussion

3.1. Temperature profile in the gasifier

All of the presented experimental results are characterized by the similar trend of temperature profiles, which is consistent with literature (Chen et al., 2012; Kihedu et al. 2016). Temperature increases along the height of the gasifier and reach maximum temperature above the air nozzles and next decreases gradually along with the height of the fuel bed in the gasifier.

Experimental results of beech wood updraft gasification indicated significant impact of amount of supplied air on the height of the individual gasification zones. It should be emphasized that gasification is a complex process and defining the height of the zones is very difficult due to the heterogeneity of the gasification bed and the complexity of the chemical reactions. Based on the literature the boundary of temperature for the combustion zone was established at 1000°C (Chen et al., 2012) and 750°C for the reduction zone (Mani et al., 2011; Sircar et al., 2014). The results show that for the 10, 12 and 15 Nm^3/h of supplied air the maximum peak of temperature in the combustion zone reached about 1000°C, while for the 17 Nm^3/h reached about 1100°C (Fig. 2). In the combustion zone char reacts with oxygen to produce carbon monoxide and carbon dioxide and generate heat for the reduction and pyrolysis process. Temperature in this zone highly depends on the concentration of O_2, CO, and CO_2. Lower temperatures for the first three cases may be associated with the insufficient amount of air supplied to the combustion zone.

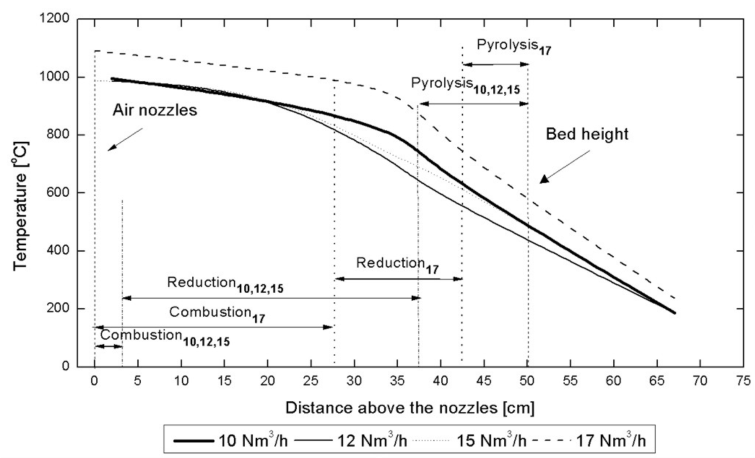

Fig. 2. Characteristic of temperature profile in the gasifier

Table 2. Syngas composition

Amount of supplied air [Nm³/h]	Fuel consumption [kg/h]	ER	Syngas composition [%]				LHV of gas [MJ/Nm³]
			CO	CO_2	H_2	CH_4	
10	14.8	0.16	36.3	6.9	10.0	2.4	6.6
12	9.6	0.30	28.3	10.7	9.5	2.3	5.4
15	16	0.23	34.1	9.6	11.1	2.5	6.4
17	24	0.17	37.4	5.8	10.0	2.1	6.6

Combustion zone reached height about 4 cm from the air nozzles for 10, 12 and 15 Nm³/h of supplied air and 27 cm for 17 Nm³/h. For lower values of the amount of air supplied reduction zone reached about 33 cm, while for the highest amount of supplied air about 16 cm. The pyrolysis zone reached height at 13 cm for the 10, 12 and 15 Nm³/h of supplied air and 7 cm for 17 Nm³/h. Low temperatures in pyrolysis zone are associated with the supply of fresh fuel and consumed heat, as well as by oxidation of biomass at the lower part of the reactor, in endothermic pyrolysis reactions (Yang et al., 2007).

3.2. The gas caloric value

The results of updraft gasification of beech wood showed the significantly influence of amount of supplied air, equivalence ratio and temperature on the syngas composition (Table 2).

Experimental investigation showed importance of interplay between all parameters: amount of air supplied, fuel consumption and temperature. Despite the increase in amount of supplied air (from 10 to 12 Nm³/h), which promotes oxidation reactions and leads to more heat released in the gasifier, the fuel consumption and temperature on the surface of the bed dropped down to 9.6 kg/h and 440°C (ER = 0.30). This is caused by imbalance between pyrolysis and combustion/reduction process in the gasifier. The increase the amount of supplied air caused an increase in the intensity of the combustion process, but the amount of generated heat was not sufficient to raise the temperature in the reduction and pyrolysis zone (Fig. 2) and part of the biomass, which has not completed degassing, went to the reduction and combustion zone. The increase in the amount of air to 17 Nm^3/h caused a significant increase in temperature and fuel (Fig. 3).

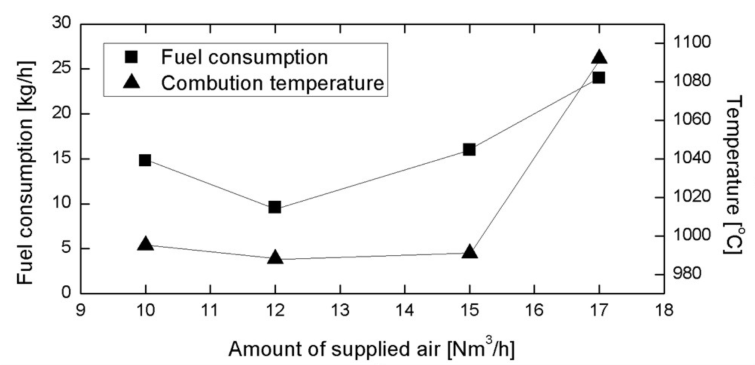

Fig. 3. Relationship amount of supplied air, fuel consumption and temperature in the combustion zone

For this reason it is important to operate with the equivalence factor, which is defined as the air-to-fuel-to-air weight ratio divided by the air-to-fuel weight ratio of stoichiometric combustion (Erlich & Fransson, 2011) and compare it with fuel consumption and temperature. This relation is presented in the Fig. 4 and Fig. 5. For the ER = 0.17 temperature in the gasifier reached maximum value both in the combustion zone (1092°C) and on the surface of the bed (575°C) and at the same time reach the maximum value of fuel consumption (24 kg/h).

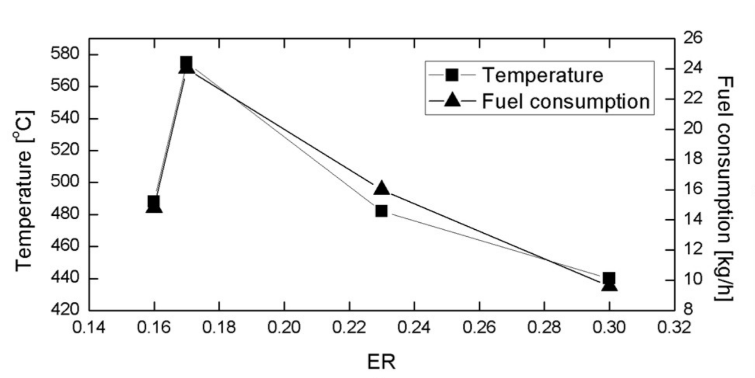

Fig. 4. Relationship between ER, temperature on the surface of the bed and fuel consumption

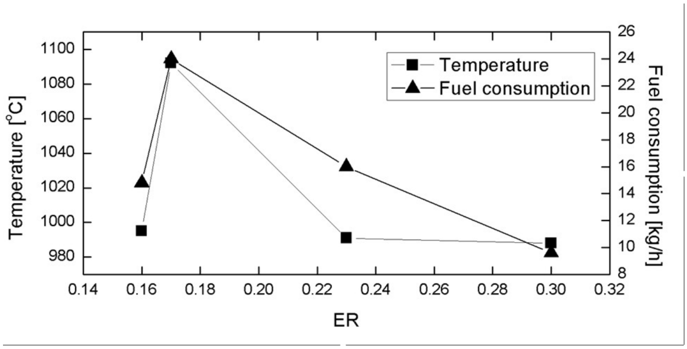

Fig. 5. Relationship between ER, temperature in the combustion zone and fuel consumption

Figure 6 presents that the increasing ER resulted in an increase in CO_2 from 6.9 to 10.7%, while CO molar fraction decreased from 37 to 28%. Higher temperature in the combustion zone for the lower values of ER shifts the equilibrium of the endothermic reaction (e.g. Boudouard's reaction) to the products and increase in CO molar fraction from 28% at 988°C to 37% at 1092°C (Fig. 7).

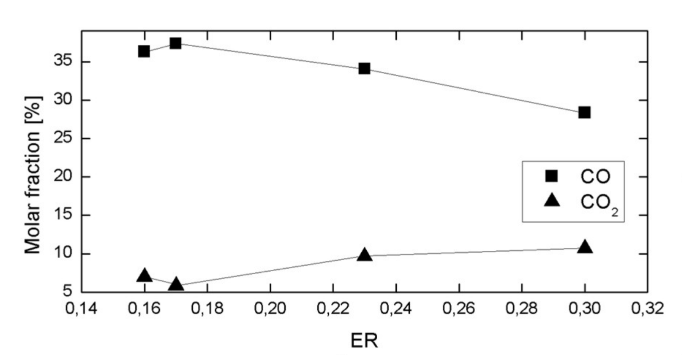

Fig. 6. Influence of ER on the CO and CO_2 content in the syngas

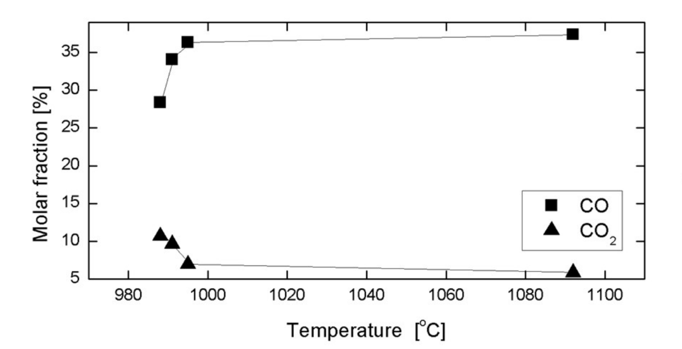

Fig. 7. Influence of bed temperature on the CO and CO_2 content in the syngas

In the updraft gasifier carbon dioxide is generated by oxidation of beech wood at the lower part of the reactor while carbon monoxide is produced by char reduction reaction (*Boudouard's reaction*) in the reduction zone. To understand the effect of temperature on the gasification process, a series of heterogeneous gasification reactions in the reduction zone should be analysed (Devi et al., 2003; Chen et al. 2012; Pedroso et al. 2013):

$$C + O_2 \leftrightarrow CO_2 \quad \Delta H = -393{,}180 \text{ kJ/kmol} \tag{1}$$

$$C + 0.5\, O_2 \leftrightarrow CO_2 \quad \Delta H = -110{,}180 \text{ kJ/kmol} \tag{2}$$

$$C + CO_2 \leftrightarrow 2CO \quad \Delta H = 172{,}320 \text{ kJ/kmol} \tag{3}$$

Increasing temperature, due to the increase of the amount of air-supply and reactions (1) and (2), results in equilibrium of reaction (3) and favour for the CO formation.

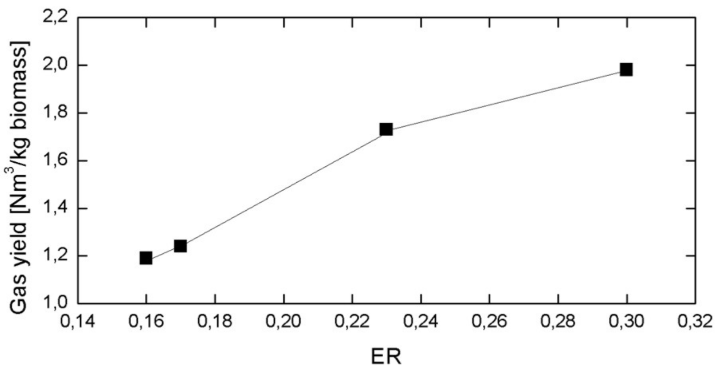

Fig. 8. Influence of ER on the gas yield per kg of biomass

The amount of produced gas can be calculated using nitrogen tracer method (Thanapal, 2010; Chen et al. 2012). Knowing the amount of nitrogen in the supplied air, the amount of the syngas can be calculated from the percentage of nitrogen in the produced gas. The results showed that the gas yield from per kg biomass increased from 1.2 Nm^3/kg biomass for the ER = 0.16 to 1.98 Nm^3/kg biomass for ER = 0.30 (Fig. 8). The increase of gas yield from per kg biomass with increasing ER are similar to the finding by Chen et al. (2012).

3.3. Tar component analysis

3.3.1. Tar characteristic

Tars are one of the most important technical problems during biomass gasification process. The tars definition covers a wide range of organic compounds which concentrations and measurement methods are heavily dependent on the definitions. It is assumed that these are primarily aromatic compounds. Based on the literature (Hernández et al., 2013; Yu et al., 2014) tars can be classified according to the molecular weight and chemical properties as follows:

- PAHs — polycyclic aromatic hydrocarbons, organic compounds containing only carbon and hydrogen like naphthalene, acenaphthylene, fluoranthene, pyrene, etc.,
- BTX — refers to mixture of benzene, toluene, ethylbenzene and xylene,
- phenols and its derivatives,
- miscellaneous hydrocarbons.

3.3.2. Tar yield

The literature (e.g. Kihedu et al., 2016) and experimental results tar was mainly generated at the upper part of gasifier, in the pyrolytic zone which occurs above combustion and reduction zone (Fig. 2). It is related to However, some tar generation may occur in the reduction zone which is associated with inhomogeneity within the packed bed in the reactor.

The tar yield, defined as the weight of tar generated from 1 kg of feedstock (Yu et al., 2014), for different value of equivalence ratio in relation to temperature on the surface of the bed and fuel consumption are shown in Fig. 8 and 9. The results indicates that tar yield during updraft gasification depends on the temperature and fuel consumption. For lower ER values there is high fuel consumption and high bed temperature in the gasifier (Fig. 4 and 5), which results in high values of tar yield 134 g/kg biomass for ER = 0.17 (Fig. 9). Maximum value of tar yield reached 267 g/kg biomass for ER = 0.23, which is the point of inflection depending on the amount of tars from ER; it is similar to the finding by Yu et al. (2014) and Hernández et al. (2013). It is worth noting that both, the amount of tar and fuel consumption, are similar function of the ER (Fig. 9 and 10). For higher ER values imbalance between pyrolysis and combustion and reduction process in the gasifier caused a temperature drop in the reactor and decreased the yield of tar (193 g/kg biomass).

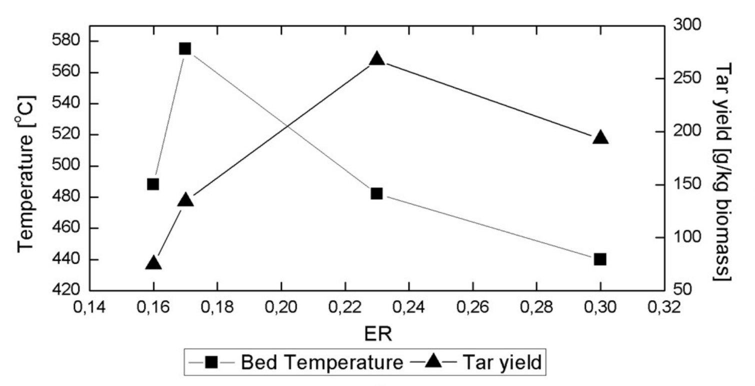

Fig. 9. Relationship between ER, temperature on the surface of the bed and tar yield

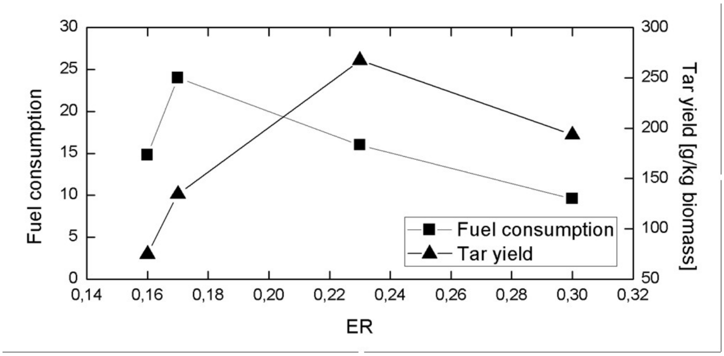

Fig. 10. Relationship between ER, fuel consumption and tar yield

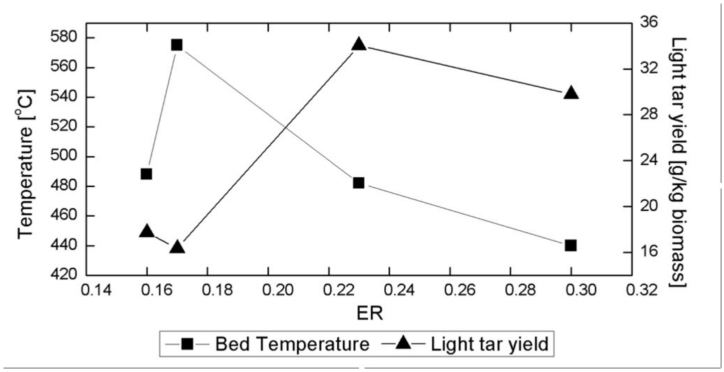

Fig. 11. Relationship between ER, temperature on the surface of the bed and light tar yield

Figure 11 shows that in the case of light tar yield, the bed temperature is one of the most important parameters. Experimental results indicate that for the highest temperature on the surface of the bed the smallest amount of light tar yield was obtained (16 g/kg biomass for 575°C). For the lowest temperatures, yield of light tar increased to about 30 g/kg biomass. The results indicate that tar is mainly composed of the heavy tar and both light and heavy tar are changing nonlinearly for different operating conditions.

Table 3. Characteristic of light tar from updraft gasification of beech wood

Lp.	Compound	Molecular Formula	ER			
			0.16	0.17	0.23	0.30
			Relative content of the various tar components [wt. %]			
1	1,3-Pentanediol, 2-methyl-	$C_6H_{14}O_2$	16.72	18.97	12.43	32.08
2	Acetic acid	$C_2H_4O_2$	29.78	19.27	35.51	16.47
3	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	$C_6H_8O_2$	1.23	—	1.75	1.48
4	2-Propanone, 1-hydroxy-	$C_3H_6O_2$	5.36	3.36	6.50	3.46

Lp.	Compound	Molecular Formula	ER			
			0.16	0.17	0.23	0.30
			Relative content of the various tar components [wt. %]			
5	Propane, 2,2′-[ethylidenebis(oxy)]bis-	$C_8H_{18}O_2$	12.05	21.91	0.55	1.55
6	Cyclopropyl carbinol	C_4H_8O	0.88	—	1.54	1.84
7	Propanoic acid, 2-oxo-, methyl ester	$C_4H_6O_3$	1.29	—	2.15	—
8	Propane, 1,1-dipropoxy-	C9H20O	0.79	2.38	—	—
9	2-Methyliminoperhydro-1,3-oxazine	$C_5H_{10}N_2O$	1.67	—	—	—
10	1,2-Ethanediol, diacetate	$C_6H_{10}O_4$	—	—	1.30	—
11	1,2-Cyclopentanedione	$C_5H_6O_2$	—	—	1.71	—
12	Oxazolidine, 2,2-diethyl-3-methyl-	$C_8H_{17}NO$	—	—	1.97	—
13	Propane, 2,2′,2′′-[methylidynetris(oxy)]tris-	$C_{10}H_{22}O_3$	—	6.34	—	—
14	Creosol	C_7H_8O	3.09	2.56	2.88	3.67
15	2-Methoxy-4-vinylphenol	$C_9H_{10}O_2$	1.10	1.09	1.38	1.55
16	Phenol, 2,6-dimethoxy-	$C_8H_{10}O_3$	3.94	3.14	4.98	6.36
17	Phenol, 2-methoxy-4-(1-propenyl)-	$C_{10}H_{12}O_2$	1.36	3.48	1.38	4.03
18	Phenol, 2,6-dimethoxy-4-(2-propenyl)-	$C_{11}H_{14}O_3$	2.30	—	3.41	1.77
19	Phenol, 4-ethyl-2-methoxy-	$C_9H_{12}O_2$	0.91	—	1.32	1.34
20	Phenol, 2-methoxy-	$C_7H_8O_2$	—	—	1.67	1.77
21	Phenol, 3-methyl-	C_7H_8O	—	—	0.85	—
22	Benzene	C_6H_6	1.36	1.33	1.48	2.97
23	Toluene	C_7H_8	2.49	—	—	3.53
24	Ethylbenzene	C_8H_{10}	—	—	—	1.70
25	Styrene	C_8H_8	1.39	3.06	—	8.62
26	1,2,4-Trimethoxybenzene	$C_9H_{12}O_3$	4.54	—	4.98	—
27	Benzene, 1,2,3-trimethoxy-5-methyl-	$C_{10}H_{14}O_4$	1.32	—	1.54	—
28	Di-n-octyl phthalate	$C_{24}H_{38}O_4$	1.92	1.15	—	—
29	Furfural	$C_5H_4O_2$	4.48	2.80	5.50	5.16
30	Benzyl methyl ketone	$C_9H_{10}O$	—	2.26	2.32	—
31	Propanedioic acid, oxo-, bis(1-methylethyl) ester	$C_9H_{14}O_5$	—	—	0.89	—
32	2-Butanone, 3-methyl-1-phenyl-	$C_{11}H_{14}O$	—	1.25	—	—
33	Acetic acid, 3,3-dimethylbut-2-yl ester	$C_8H_{16}O_2$	—	5.03	—	—
34	Naphthalene	$C_{10}H_8$	—	0.62	—	0.64

3.3.3. Light tar composition analysis

The composition of tar from beech wood updraft gasification was investigated using GC-MS. The analysis of tar composition showed about 30 different components which shows the complex composition of the tars and it is consistent with literature (Hernández et al., 2013; Yu et al., 2014). Table 3 present details of the light-tar composition (PAHs, BTEX, phenols, oxidized aliphatic compounds and others).

For all cases 1,3-pentanediol, 2-methyl- and acetic acid, which can be classified as aliphatic, were the key components in gasification tar and reached 32.08% content (9.42 g/Nm^3) for 1,3-Pentanediol, 2-methyl- for (ER = 0.17) and 35.01% (14.48 g/Nm^3) for Acetic acid (ER = 0.23). Other substances, such as 2-propanone, 1-hydroxy-, creosol, phenols and furfural also exhibited relatively high concentrations. Some differences between the tar compositions can also be observed. For example, propane, 2,2'-[ethylidenebis(oxy)]bis- constitutes 12% and 21% of the tars for ER = 0.16 and ER = 0.17 respectively and less than 2% for higher values of ER. Furthermore, in the case of BTEX composition, lower values of ER promotes benzene and toluene, while higher ER value promotes toluene and ethylbenzene. The results also indicate non-linear trends for presented compounds, such as propane, 2,2'-[ethylidenebis(oxy)]bis-, phenol, 2-methoxy-, benzene, phenol decrease at higher ER, some of the species present a maximum (e.g. 2-propanone, 1-hydroxy-, oxazolidine, 2,2-diethyl-3-methyl-, 1,2-cyclopenta-nedione, furfural) and minimum (e.g. 1,3-pentanediol, 2-methyl-) at intermediate ER or present a maximum in highest equivalence ratio value (e.g. 1,3-pentanediol, 2-methyl-, cyclopropyl carbinol, creosol).

Experimental results showed that aliphatics oxygenated compounds represents the largest component of gasification light tar (Fig. 12). Beech wood is mainly composed of two polysaccharides — cellulose and hemicellulose (Demirbas, 2005). These polysaccharides are made up of many monomers such as simple sugars, mainly glucose. Decomposition of levoglucosan (1,6-anhydro-b-d-glucopyranose), which is a intermediate product of depolymerization, is one of the first significant step during cellulose pyrolysis and for secondary tar reactions stages of thermal decomposition. According to the literature (Kawamoto et al., 2005; Zhang et al., 2012), the distribution of levoglucosan occurs by breaking C-O or C-C bonds or dehydration, which leads to the formation of short-chain oxidized aliphatic compounds. (e.g. 1,3-Pentanediol, 2-methyl- and acetic acid; Table 3). Other aromatics hydrocarbons, phenols and BTEX content in light tars (Fig. 12) is associated with the presence of lignin, which structure contains a large number of aromatic rings connected by short carbon-oxygen chains (Nowakowski et al. 2010; Custodis et al. 2015).

Comparing phenol and derivatives with BTEX and PAHS (Fig. 13), it can also be found that phenol and BTEX constitute the most abundant fraction. It was found that when bed temperature decreases and value of ER increases, the proportion of phenol in the tar samples is increasingly favoured while for the BTEX decreased. PAHs are the least abundant compounds in relation to the temperature and ER, keeping in all cases on a low level (below 2 g/kg biomass). These results indicate that both the temperature and the equivalence ration influence not only the amount of tars, but also their composition, which is consistent with the literature (Hernández et al., 2013).

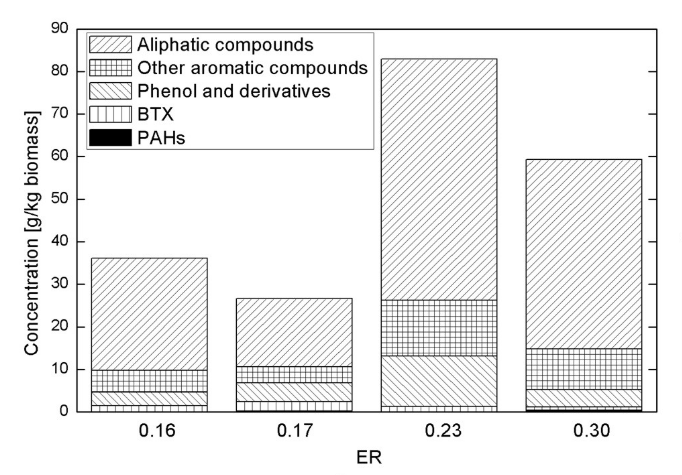

Fig. 12. Relative content of different substance groups in gasification tar

4. Conclusions

Experimental studies shown that the amount of air supplied does not affect the parameters of the gasification process, like temperature, gas composition and tar yield, linearly and a striking is to compare the amount of air supplied with fuel consumption and temperature to analyze the updraft gasification. For lower ER value there was high fuel consumption and high bed temperature in the gasifier, which results in high caloric value of syngas. The tar yields also significantly depends on the temperature and ER. With the increase value of ER and the decrease of temperature on the surface of the bed, the total amount of tar yield increased. The bed temperature is one of the most important parameters influenced on light tars formation, for the highest temperature on the surface of the bed the smallest amount of light tar yield was obtained.

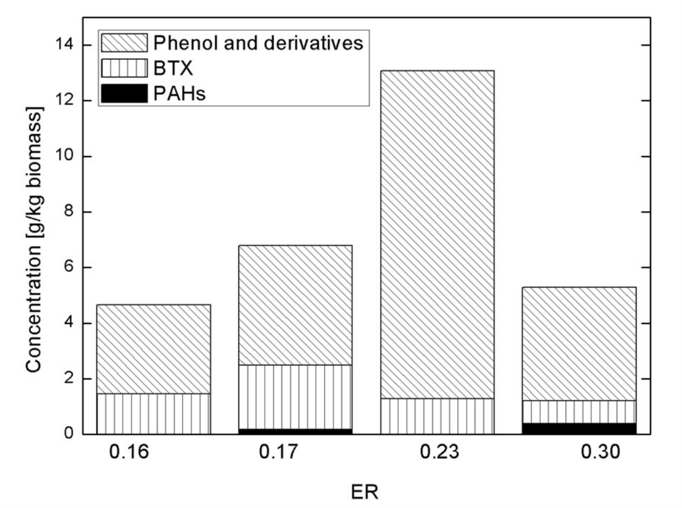

Fig. 13. Relative content of phenols, BTEX and PAHs in gasification tar

Experimental results showed that aliphatics oxygenated compounds represents the largest component of gasification light tar, which was related to high content of cellulose and hemicellulose. Other aromatics hydrocarbons, phenols and BTEX content in light tars was associated with the presence of lignin. When bed temperature decreased and value of ER increased, the proportion of phenol and oxidized aliphatic compounds in the tar samples was increasing, while the BTEX decreased. PAHs, the least abundant compounds in relation to the temperature and ER, were kept in all cases on a low level.

References

Chen, W., Annamalai, K., Ansley, R.J., Mirik, M. (2012). Updraft fixed bed gasification of mesquite and juniper wood samples. *Energy, 41*, 454–461.

Custodis, V.B.F., Bährle, C., Vogel, F., Bokhoven van, J.A. (2015). Phenols and aromatics from fast pyrolysis of variously prepared lignins from hard- and softwoods. *J Anal Appl Pyrol, 115*, 214–223.

Demirbas, A. (2005), Pyrolysis of ground beech wood in irregular heating rate conditions. *J Anal Appl Pyrol, 73*, 39–43.

Devi, L., Ptasinski, K.J., Janssen, F.J.J.G. (2003). A review of the primary measures for tar elimination in biomass gasi cation processes. *Biomass Bioenerg, 24*, 125–140.

Edinger, P., Schneebeli, J., Struis, R.P.W.J., Biollaz, S.M.A., Ludwig, C. (2016). On-line liquid quench sampling and UV-Vis spectroscopy for tar measurements in wood gasification process gases. *Fuel, 184*, 59–68.

Erlich, C., Fransson, T.H. (2011). Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: Experimental study. *Appl Energ, 88*, 899–908.

Good, J., Ventress, L., Knoef, H., Zielke, U., Lyck Hansen, P., Van de Kamp, W., De Wild, P., Coda, B., Paasen van, S., Kiel J., Sjöström, K., Liliedahl, T., Umger, Ch., Neeft, J., Suomalainen, M., Simell, P. (2005). *Sampling and analysis of tar and particles in biomass producer gases, Technical Report*. BTG biomass technology group, Prepared under: CEN BT/TF 143 "Organic contaminants ("tar") in biomass producer gases".

Hernández, J.J., Ballesteros, R., Aranda, G. (2013). Characterisation of tars from biomass gasification: Effect of the operating conditions. *Energy, 50*, 333–342.

Ismail, T.M., El-Sala, M.A. (2017). Parametric studies on biomass gasification process on updraft gasifier high temperature air gasification. *Appl Therm Eng, 112*, 1460–1473.

Kawamoto, H., Murayama, M., Saka, S. (2003). Pyrolysis behavior of levoglucosan as an intermediate in cellulose pyrolysis: polymerization into polysaccharide as a key reaction to carbonized product formation. *J Wood Sci, 49*, 469–473.

Kihedu, J.H., Yoshiie, R., Naruse, I. (2016). Performance indicators for air and air-steam auto-thermal updraft gasification of biomass in packed bed reactor. *Fuel Process Technol, 141*, 93–98.

Li, C., Suzuki, K. (2009). Tar property, analysis, reforming mechanism and model for biomass gasification — an overview. *Renew Sust Energ Rev, 13*, 594–604.

Ma, Z., Zhang, Y., Zhang, Q., Qu, Y., Zhou, J., Qin, H. (2012). Design and experimental investigation of a 190 kWe biomass fixed bed gasification and polygeneration pilot plant using a double air stage downdraft approach. *Energy, 46*, 140–147.

Mani, T., Mahinpey, N., Murugan, P. (2011). Reaction kinetics and mass transfer studies of biomass char gasification with CO_2. *Chem Eng Sci, 66*, 36–41.

McKendry, P. (2002). Energy production from biomass (part 3): gasification technologies. *Bioresource Technol, 83*, 55–63.

Nakamura, S., Siriwat, U., Yoshikawa, K., Kitano, S. (2015). Development of Tar Removal Technologies for Biomass Gasification using the By-products. *Energy Procedia, 75*, 208–213.

Nowakowski, D.J., Bridgwater, A.V., Elliott, D.C., Meier, D., Wild de, P. (2010). Lignin fast pyrolysis: Results from an international collaboration. *J Anal Appl Pyrol, 88*, 53–72.

Pedroso, D.T., Machín, E.B., Silveira, J.S., Nemoto, Y. (2013). Experimental study of bottom feed updraft gasifier. *Renew Energ, 57*, 311–316.

Phuphuakrat, T., Nipattummakul, N., Namioka, T., Kerdsuwan, S., Yoshikawa, K. (2010). Characterization of tar content in the syngas produced in a downdraft type fixed bed gasification system from dried sewage sludge. *Fuel, 89*, 2278–2284.

Sircar, I., Sane, A., Wang, W., Gore, J.P. (2014). Experimental and modeling study of pinewood char gasification with CO_2. *Fuel, 119*, 38–46.

Thanapal, S.S. (2010). *Gasification of low ash partially composted dairy biomass with enriched air mixture* (Master thesis). Texas: A&M University.

Yang, H., Yan, R., Chen, H., Lee, D.H., Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel, 86*, 1781–1788.

Yu, H., Zhang, Z., Li, Z., Chen, D. (2014). Characteristics of tar formation during cellulose, hemicellulose and lignin gasification. *Fuel, 118*, 250–256.

Zhang, X., Yang, W., Blasiak, W. (2012). Thermal decomposition mechanism of levoglucosan during cellulose pyrolysis. *J Anal Appl Pyrol, 96*, 110–119.