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Investigation of fuel effect on biomass gasification process using equilibrium model

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Abstract. Gasification is one of the most promising technologies of converting biomass into energy. Different type of biomass can be used for gasification process since there are no strict limitations for parameters of used fuel. Various types of biomass are used in Latvia for production of energy. Wood fuels make up the main part of used biomass in Latvia. However, many non-wood biomass types are available as well.

This study presents the comparison of wood and non-wood biomass use in gasification process. Biomass gasification model based on thermodynamic equilibrium was used to simulate gasification process with various biomass types. All input parameters were constant in model except fuel properties. In general gasification process was simulated with seven types of biomass – draff from beer production, common reed, middling from oats and wheat sieving, straw from grain cultivation, buckwheat hulls, rapeseed by-product from biofuel production, as well as wood. These non-wood biomass types are available in Latvia.

Produced syngas calorific value and gasification process efficiency are taken as the indicators to examine the gasification performances using various biomass types. The regression model was proposed to describe relation between fuel properties and efficiency of the gasification process. Results show that non-wood biomass can be successfully used for gasification process. Ash content growth in the fuel promotes temperature decrease in the reactor. Fuel chemical composition has effect on the produced syngas composition and heating value.

Key words: biomass gasification, non-wood biomass, thermodynamic model, syngas.

INTRODUCTION

The use of fossil fuels for energy production generates the overwhelming amount of CO_2. Biomass is one of the dominant sources of alternative energy to substitute fossil energy use (Berndes et al., 2003). Wood is the most frequently used biomass type. However, there are many other non-wood biomass resources available for energy production. Different methods exist to convert biomass into energy. Nowadays rapid progress in biomass gasification technology became one of the most perspective methods. Biomass gasification is economically favourable and environmentally friendly technology. One on the advantages is that there are no strict limitations in biomass properties of its use in gasification process. Resource availability, economical substantiation and suitability for use in definite technology for biomass conversion in the energy are the main factors which should be taken into consideration choosing non-wood material.

The diversity of non-wood biomass is very high, and types of available raw material vary between world regions and countries. Rice straw is one of frequently used material for gasification process in the Southeast Asia (Suramaythangkoor & Gheewala, 2010). The amount of available rice straw and husk are notable in Japan as well. Potato, corn, sugarcane, sorghum and some other agricultural residue can be used as an energy resource in Japan, too (Matsumura et al., 2005). Some amount of energy is produced using olive and olive oil residues in Greece. Typically simple combustion technologies were used. Syngas with calorific value more than 8 MJ Nm^{-3} can be produced using olive residues as fuel (Skoulou et al., 2008).

From all energy source consumption in Latvia, 59,274 TJ or 34.6% related to the oil products, 50,269 TJ or 29.3% to the natural gas and 53,106 TJ or 31.0% to the wood fuels in year 2013 (Energy balance, 2013). It follows that the fossil fuel has determinant role in the energy production. However, the amount of used wood fuel increased by 13.9% from 45,646 TJ in 2010 up to 53,106 TJ in 2013, but fossil fuels amount decreased conversely. The fastest growth is seen in the use of wood chips from 8,596 TJ up to 14,182 TJ by 39.4% and pellets from 562 TJ up to 1,728 TJ by 67.5%. Unfortunately, no regulation to control quality of the produced pellet is available. It promotes the accessibility of pellets with various properties in the market in Latvia (Beloborodko et al., 2012).

The amount of non-wood biomass consumed in the energy production is minimal, 80 TJ produced from peat and 58 TJ from straw. The amount of non-wood biomass use for energy production can increase using herbaceous material from agricultural sector and using industrial by-products. Availability and energy potential of herbaceous and fruit biomass resources in Latvia are described in study done by Beloborodko et al (2013). Total amount of energy from straw and hogweed exceeds 3,000 TJ and can be used for the energy production.

The biomass updated technologies use before gasification process can noticeably improve produced syngas properties. The pyrolysis of the biomass is a frequently used method to produce fuel with high energy content. The torrefaction of biomass can improve gasification process as well. Torrefaction is a mild pyrolysis process at the temperature typically between 200 and 300 °C. The oxygen/carbon ration of torrefied biomass decreases, but energy content of wood increases after the torrefaction process. Hydrogen and carbon monoxide content in the syngas goes up using torrefied fuel (Couhert et al., 2009). Tar content typically is lower in the syngas produced from torrefied fuel. The growth of temperature in the gasifier reactor using torrefied fuel is one of the main reasons of it. Another reason is that torrefaction process provides partial devolatilisation and lower production of water fractions (Dudynski et al., 2015).

The biomass torrefaction and gasification can be successfully united into one combined process. Different technological methods to unite these processes are available. Oxygen-blown gasification of torrefied wood can be one of the most promising methods (Prins et al., 2006). Biomass pretreatments methods as pyrolysis and torrefaction as well as drying and dissolution were analysed in the study done by Svoboda et al. (2009) to dominate effect on the gasification process.

At the same time gasification process is considerably dependent on fuel properties. Fuel chemical composition, calorific value, ash and moisture content are prior factors which effect produced syngas properties. The calorific value of produced syngas depends on heating value of used biomass. The higher is biomass heating value the higher calorific value of syngas can be achieved (Antonopoulos et al., 2012). Tar content in the syngas typically is higher for fuel richer with ash (Wei et al., 2007). However, small-scale difference in the amount of carbon and hydrogen in fuel doesn't cause constitutive changes in produced syngas composition (Andre et al., 2005).

The moisture content of fuel has more crucial effect on the gasification process. CO content goes down sharply due to the moisture increase. It provides decrease of the heating value of the produced syngas. This tendency proves gasification process with sawdust (Altafini et al., 2003), cashew nut shell (Ramanan et al., 2008), sugarcane mills (Pellegrini & de Oliveira, 2007), paddy husk and wood (Zainal et al., 2001).

The main objective of this paper is to compare the gasification process efficiency and syngas properties produced from different wood and non-wood fuels. Only the non-wood biomass types accessible in Latvia were considered. Determination of biomass types for energy production and fossil fuel replacement is one of the goals. The second goal is to identify the independent variable parameters of the fuels that cause the highest influence on the gasification process.

MATERIALS AND METHODS

Fuel description

The gasification process was simulated using seven different biomass types available in Latvia. Draff from beer production (DR), common reed (CR), middling from oats and wheat sieving (OWM), straw from grain cultivation (ST), buckwheat hulls (BH), rapeseed by-product from biofuel production (RB) were chosen to present non-wood biomass. One wood (WO) sample was used as benchmark to compare produced syngas quality and the gasification process in general. The analysis of fuel samples was done in the Environmental Monitoring Laboratory of Riga Technical University (see Table 1). The ultimate and proximate properties of the biomass were presented in the study done by Žandeckis also (2014).

Table 1. The ultimate and proximate properties of the biomass samples

	DR	CR	OWM	ST	BH	RB	WO
Ash, w-%,dr*	4.91	4.89	3.61	4.72	2.19	11.3	0.82
C, w-%,dr af**	46.3	44.5	43.6	45.1	47.2	48.2	50.2
H, w-%, dr af	7.26	5.84	7.52	5.77	6.15	8.00	6.98
N, w-%, dr af	4.05	0.38	1.84	0.42	0.65	3.05	0.14
S, w-%, dr af	0.05	0.04	0.09	0.10	0.08	0.06	0.01
O, w-%, dr af	42.3	49.2	47.0	48.6	45.9	40.7	42.7
HHV, MJ kg^{-1}***	19.2	16.4	18.4	18.0	18.5	19.2	21.1
LHV, MJ kg^{-1}****	15.6	13.2	14.9	14.6	15.0	15.8	17.2

* – on dry basis; ** – dry and ash free basis; *** – calculated value from the model; **** – calculated value from the model at similar moisture 10% for all samples.

The gross calorific value of the fuels was calculated in model using following equation:

$$HHV_f = 339.1C_{dr} + 1178.3H_{dr} + 100.5S_{dr} - 103.4O_{dr} - 15.1N_{dr} - 21.1A_{dr} \quad (1)$$

where: HHV_f – gross calorific value of the fuel on dry basis, kJ kg^{-1}; C_{dr}, H_{dr}, O_{dr}, S_{dr}, N_{dr} – the fuel chemical composition on dry basis, %; A_{dr} – ash content in the fuel on dry basis, %.

It was decided to take the similar moisture content 10% for all biomass samples. Tipically raw material firstly undergoes the pretreatments stage before use. The fuel moisture content 10% can present real amount of water in biomass after pretreatments stage. It was done to exclude the effect of the water content and present the influence of fuel chemical properties and ash content. Lower calorific values were calculated by:

$$LHV_f = 339.1C_{af} + 1029H_{af} + 109S_{af} - 109O_{af} - 25W \quad (2)$$

where: LHV_f – lower calorific value of the fuel as fired basis kJ kg^{-1}; C_{dr}, H_{dr}, O_{dr}, S_{dr}, N_{dr} – the fuel chemical composition as fired basis, %; A_{af} – ash content in the fuel as fired basis, %.

Model description

The mathematical model of gasification process was created to determine the possibilities of non-wood biomass use for syngas production. Model was based on the thermodynamic equilibrium reactions. Model describes gasification process for the downdraft gasifier where air was used as gasifying agent. The oxygen and nitrogen make 100% of air in the model. It was decided take the constant equivalence ratio 0.25 for all biomass types to make comparison more credible. The efficiency of gasification process typically achieves maximum values when equivalence ratio lies between 0.2 and 0.3 (Pellegrini et al., 2007). Similarly the fuel and ambient temperatures were chosen as constant in the model for all biomass types. The produced syngas comprise only from CO, CO_2, H_2, CH_4, N_2 and H_2O vapour.

The model was based on the global gasification reaction:

$$\begin{aligned} & CH_xO_yN_z + wH_2O + m\cdot(O_2 + 3.76N_2) = \\ & n_{H_2}H_2 + n_{CO}CO + n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{CH_4}CH_4 + (\frac{z}{2} + 3.76m)\cdot N_2 \end{aligned} \quad (3)$$

where: n_{H2}, n_{CO}, n_{CO2}, n_{H2O}, n_{CH4} and n_{N2} – the numbers of moles of H_2, CO, CO_2, H_2O, CH_4 and N_2 in the syngas; m – the air moles; w – the moisture associated with the biomass.

Based on global gasification reaction carbon, hydrogen and oxygen balances are calculated using the following equations:

$$n_{CO} + n_{CO_2} + n_{CH_4} - 1 = 0 \quad (4)$$

$$n_{H_2} + 2n_{H_2O} + 4n_{CH_4} - x - 2w = 0 \quad (5)$$

$$n_{CO} + 2n_{CO_2} + n_{H_2O} - w - 2m - y = 0 \quad (6)$$

The mass balance consists of two input and two output flows. The input flow includes biomass consumption on dry ash free basis, mass of the water and ash contained in the fuel. The produced syngas and ash are the output flows.

The fuel heating value, fuel sensible heat and sensible heat of gases form the input flow in the energy balance of the gasification process. The majority of energy is injected in the gasifier with fuel heating value. The sensible heat of fuel and air depends on fuel and air temperatures. The heat losses aren't divided into types, but are only calculated as total amount. Heat losses are basically formed by heat losses from gasifier to surrounding, heat from condensation and from energy removed with tar and char.

The model validation was created to make certain of verity of results obtained from model. Two models done by Zainal et al. (2001) and Jarungthammachote et al. (2007) and experimental study of biomass gasification (Gai & Dong, 2012) were used for validation (see Table 2). The similar biomass chemical composition, water content and equivalent ratio were used in present model for validation. Models comparison shows that acquired results were in close range with the results from others models. For this reason the created model can be used to simulate gasification process with various biomass types.

Table 2. Model validation

Model	Biomass properties				ER	Syngas composition, %				
	C, %	H, %	O, %	M, %		CO, %	CO_2, %	CH_4, %	H_2, %	N_2, %
Gao & Dong (2012)	43.0	5.83	44.1	6.17	0.32	19.8	11.6	3.70	20.8	55.7
Present						24.8	9.80	1.03	20.4	44.0
Zainal et al. (2001)	40.0	4.80	35.2	14.0	0.39	20.0	10.4	0.31	14.0	56.6
Present						22.4	9.03	0.31	18.1	50.2
Jarungthammachote et al. (2007)	43.9	5.83	33.7	14.0	0.44	18.5	11.7	1.06	16.8	51.9
Present						20.9	8.57	0.11	15.3	55.1

Model calculates such parameters as amount of produced syngas, syngas chemical composition and heating value, sensible heat of each syngas components, efficiency of gasification process and other values. The efficiency of gasification process is expressed in model as:

$$\eta = \frac{LHV_g \cdot V_g + Q_s \cdot V_g}{LHV_f \cdot m_f} \quad (7)$$

where: η – the efficiency of the gasification process, %; LHV_g – lower calorific value of the syngas, kJ Nm^{-3}; V_g – volume of the produced syngas, Nm^3; Q_s – sensible heat of syngas, kJ m^{-3}; m_f – the mass of the fuel as fired basis kg.

RESULTS AND DISCUSSION

Gasification process was simulated using the model with six non-wood and one wood biomass samples. Fig. 1 displays syngas composition for the various type of biomass. In general syngas composition is relatively similar for all biomass samples. The CH_4 content of syngas produced from rapeseed by-product is 12.2%, but average CH_4 content for all samples is 6.85%. N_2 content is high as well in comparison to other acquired syngas. However, H_2 and CO content in the syngas from rapeseed by-product is noticeably lower. Syngas produced from wood have the highest CO and H_2 content comparing with other syngas samples.

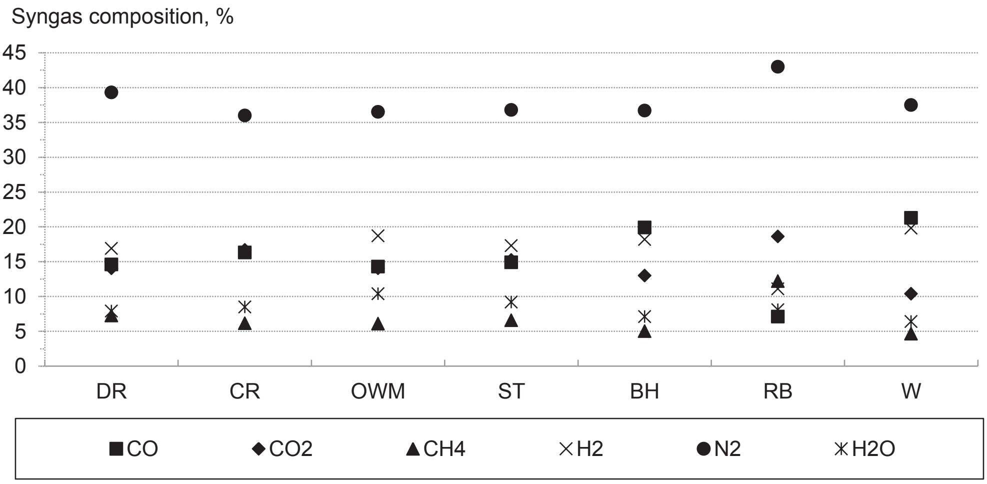

Figure 1. Syngas composition depending on the biomass types.

Gasification process efficiency and produced syngas lower calorific value changes between various biomass types have similar tendencies (see Fig. 2). Gasification efficiency is near 80% for majority of samples including wood. Only gasification process efficiency using middling from oats and wheat sieving is comparatively low about 76.4%, but the use of rapeseed by-product is contrariwise high about 87.8%. The lower calorific value of syngas produced from wood, draff and buckwheat hulls is about 5.5 MJ Nm^{-3}. The calorific value of syngas from common reed, middling from oats and wheat sieving and straw from grain cultivation is lower. The energy value of the syngas from rapeseed by-product is conversely higher and exceeds 6.0 MJ Nm^{-3}. The elevated amount of CH_4 in the syngas from rapeseed by-product is the main reason of it.

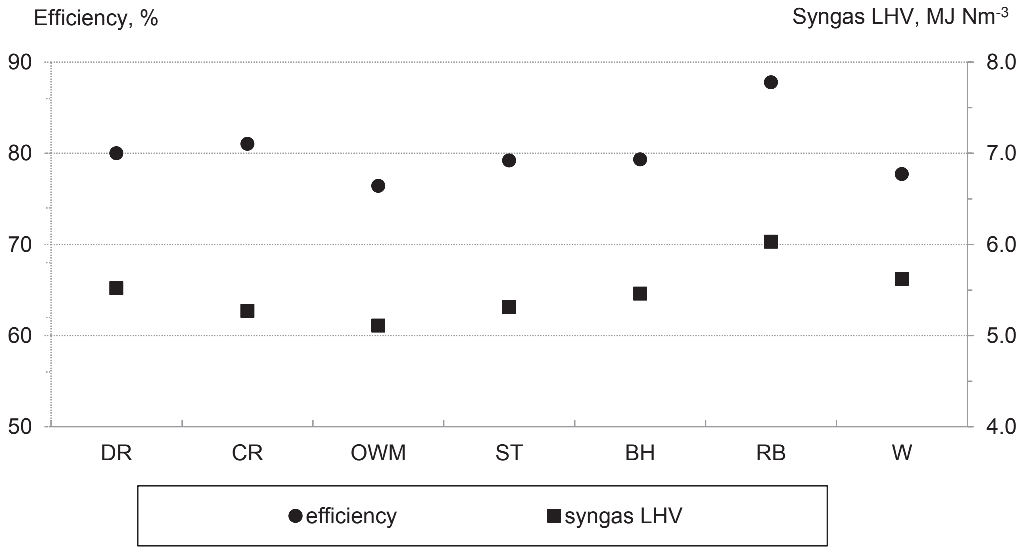

Figure 2. Syngas lower heating value and gasification efficiency depending on the biomass types.

The relations between different parameters of the gasification process were determined based on the acquired data (see Fig. 3.) Close correlation between ash content in the fuel and temperature in the gasifier reactor was discovered. The ash content growth promotes the temperature decrease. The problems of carbon and char conversion can be the main reason of it. The reduction of the temperature promotes the growth of CO and H_2 concentration in the syngas and the decrease of CH_4 content. The increase of temperature causes primary and secondary water gas reactions, secondary cracking and reforming of heavy hydrocarbons activity. The content of produced H_2 in the syngas goes up in the result. The activity of water gas and Boudouard reactions also increases due to temperature growth. Therefore, carbon reacts with CO_2 and H_2O vapour and produces higher amounts of CO. On the other hand, the temperature growth promotes combustion reactions and CH_4 amount decrease.

The lower is the content of oxygen in the fuel the higher amount of air should be injected in the gasifier to acquire the required equivalent ratio for the gasification process. Nitrogen content in the air is about 78.1%. Therefore, the N_2 content in the produced syngas increases if injected amount of air goes up. The N_2 content in the syngas is not recommended and promotes the decrease of the calorific value of produced syngas. That is why there is correlation between amount of oxygen content in the fuel and energy content of syngas.

The carbon amount in the fuel has effect on the CO content in the syngas. However, the correlation is not so strong, because some amount of carbon was converted in the CO_2, but some amount cannot be converted in general. The stronger connection is between carbon to oxygen ratio and heating value of syngas. The higher is the carbon to oxygen ratio of fuel the higher is heating value of produced syngas.

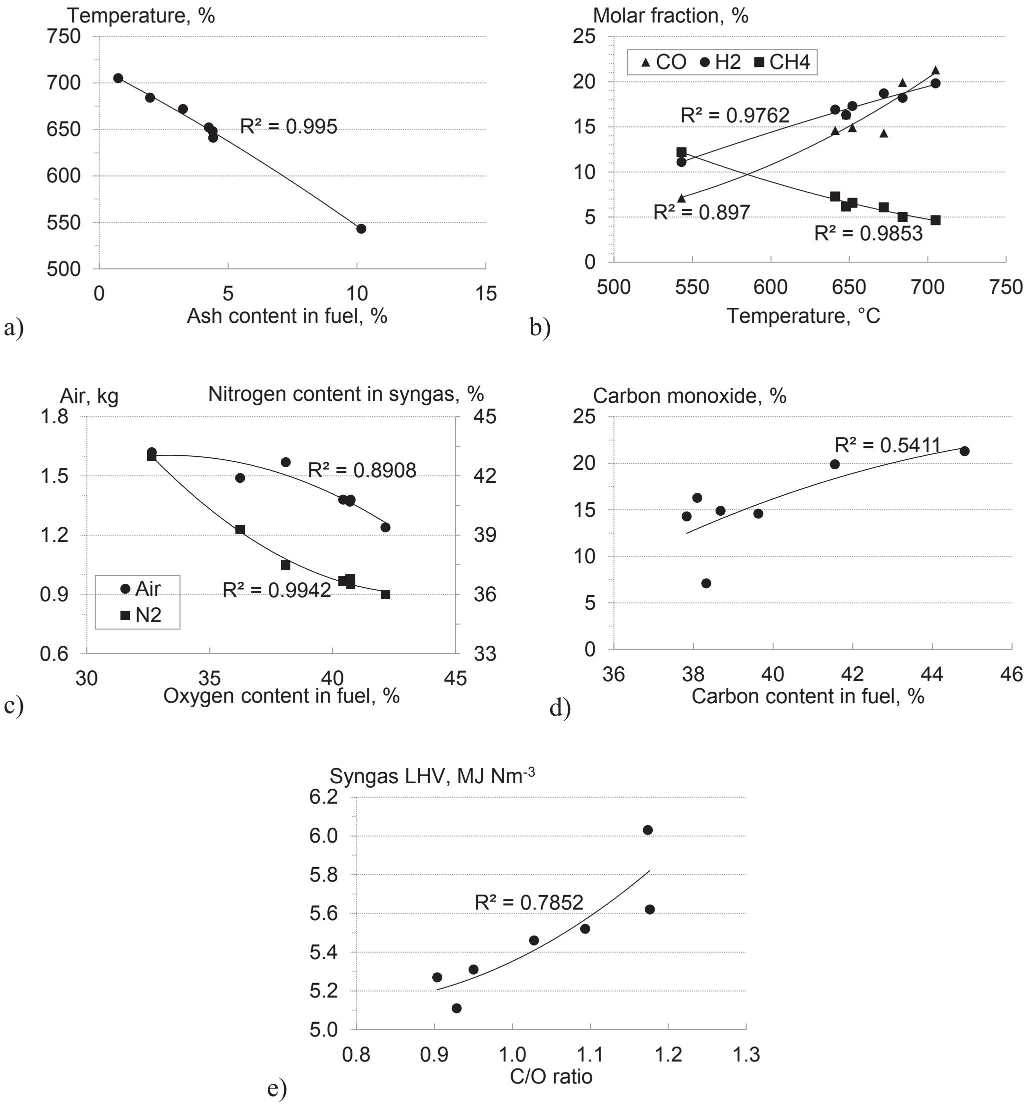

Figure 3. The relation between parameters in the gasification process: a) ash content in the fuel vs temperature in the gasifier reactor; b) temperature in the gasifier reactor vs CO, H_2 and CH_4 content in the syngas; c) oxygen content in the fuel vs required amount of air and nitrogen content in the syngas; d) carbon content in the fuel vs CO content in the syngas; e) C/O ratio of fuel vs produced syngas lower calorific value.

The regression model was elaborated where efficiency of gasification process was dependent on variable. The independent variables were ash, carbon, hydrogen, oxygen content in the fuel as fired basis. The data analysis done in STATGRAPHICS Centurion 16.1.15 environment shows that the efficiency is described by Eq.8:

$$\eta = 56.5309 + 0.711207C_f - 1.8791H_f + 1.56684A_f \quad (8)$$

Data analysis shows that in model all parameters have hight influential on the indicator (see Table 3.). Since P-value in the analysis of the variance (ANOVA) table is less than 0.05, there is statistically significant relationship between the variables. Durbin-Watson statistics is close to 3.1, therefore, there is no autocorrelation observed between independent variables. Coefficient of determination R^2 and adjusted R^2 explains 99.6% and 99.3% of data input for regression model.

Table 3. Data analysis of the regression model

Variables	P-value	P-value for the ANOVA	R^2 & adj. R^2 %[b]	Standard error	Durbin-Watson statistic
Efficiency	0.0003	0.0004	99.644 99.2879	0.3090	3.1194 P = 0.9710
Carbon content	0.0017				
Hydrogen content	0.0043				
Ash content	0.0001				

CONCLUSIONS

The comparison of wood and non-wood biomass for the use in gasification process was done. The thermochemical equilibrium model was used in the study. Produced syngas properties and gasification process efficiency were main criteria in comparison of biomass types. Gasification process was simulated with draff from beer production, common reed, middling from oats and wheat sieving, straw from grain cultivation, buckwheat hulls, rapeseed by-product from biofuel production and wood biomass types. All these herbaceous agricultural and processing industry by-products are available in Latvia.

Results show that all non-wood raw materials can be successfully used in gasification process and on the same basis as wood. Gasification efficiency was about 80% for major samples including wood, but produced syngas calorific value was around 5.5 MJ Nm^{-3}. The consumption of wood fuels for energy production is continuously increasing and non-wood material can be used to satisfy the demand for biomass. In such a way the greater amount of the fossil fuel can substitute with biomass. It is important that one non-wood biomass type can be substituted by another without altering the produced syngas quality.

It was determined that higher ash content results in the process with lower temperature. Temperature reduction promotes the growth of CO and H_2 concentration in the syngas and the decrease of CH_4 content. The lower is oxygen content in the fuel the more air must be injected in the gasifier. Therefore, the low oxygen content in the fuel favours low heating value of syngas. The correlation between carbon content in the fuel and CO content in the syngas was identified as well.

The regression model was proposed to describe the connection between used fuel properties and efficiency of the gasification process. Data analysis shows that the model had sufficient correlation between the variables that will be used to describe the actual situation. Ash and hydrogen content in the fuel is the most influential parameter in model. Coefficient of determination R^2 and adjusted R^2 explains 99.6% and 99.3% of data input for regression model at 95% confidence level.

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