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Biomass gasification thermodynamic model including tar and char

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Abstract. Biomass gasification is a thermochemical process in which feedstock is heated to high temperatures in a condition of absence of oxygen. As a result, biomass is converted into the combustible syngas, which typically consists of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), nitrogen (N_2) and water vapour (H_2O). Biomass gasification process simulation plays an important role in gasification process comprehension and optimization. Typically, gasification models have only one output flow in the process mass balance, which represents the amount of the produced syngas. Tar and char also are significant products of gasification process. This study presents a thermodynamic biomass gasification model. The fundamental distinction of the proposed model, comparing to other available models, is that tar and char also are taken into account in developed model. Gasification process is affected by many factors. Similarly, the amount of produced tar and char can significantly vary depending on gasifier operation conditions. Literature review on the previous studies is done to determinate the most critical factors which affect tar and char formation. Results show that temperature in the gasifier, equivalence ratio and fuel properties have dominant effect on the products yield. Two regression models are elaborated to present the amount of the produced tar and char depending on independent variables. The achieved mathematical equations are added to the developed thermodynamic model of the gasification process. Biomass gasification process is simulated with different values of fuel moisture and equivalence ratio. The results show that produced syngas amount, calorific value and biomass energy conversion efficiency are more realistic after tar and char including in the model.

Key words: biomass gasification, syngas, tar, char, mathematical model.

INTRODUCTION

Gasification is a complex process for conversion of solids into to gaseous fuels. Gasification process consists of drying, pyrolysis, partial combustion and gasification or reduction sub-processes. Produced gas typically contains 70% to 80% of the initial biomass energy, but residual energy is lost. (Blumberga et al., 2011) Efficiency of the gasification process and produced gas properties depend on many mutual factors. Simulation tools are widely used for understanding and optimization gasification process. Nowadays many gasification models exist and describe the effect of operational parameters of the process, as well as fuel properties. Thermodynamic equilibrium and kinetic models are the two most frequently used simulation tools. In the study done by Baruah & Baruah (2014) these simulation approaches are discussed and compared. The influence of gasifier design on the gasification process can be analysed using kinetic models. Produced gas composition at specific place in gasifier and definite time can also be determined. (Gordillo & Belghit, 2011; Saravanakumar et al., 2011) Thermodynamic models are useful to predict chemical composition of the produced gas. The influence of equivalence ratio, temperature in reactor and fuel properties on the gasification process can be successfully simulated using thermodynamic models. (Jarungthammachote & Dutta, 2007; Sharma, 2008; Azzone et al 2012) This is one of the main advantages of the thermodynamic modelling. The global gasification reaction is a base of the thermodynamic model. Fuel chemical composition, moisture content and equivalence ratio are the main input parameters determining composition of produced gas.

Syngas is the main product of the gasification process. Some amount of fuel was converted to the tar and char also. In general, tar is a complex mixture of condensable organic substances, including light aromatics, polyaromatics, heterocycles, etc, that condense in the low-temperature zones of the gasifier and in downstream equipment. Tar is formed in each zone of gasifier, forming the greatest part in pyrolysis zone, where temperature vary from 200 to 500 °C. Tar is undesired substance and can be a reason for many problems such as plugging the equipment because of condensation, formation of tar aerosols, formation of particulates or polymerizing on the surface of solid particles, as well as metal corrosion. (Ahmed et al., 2011). Char is typically produced at the pyrolysis stage and often is the final solid residue left over from gasification process. Char mainly consists of hydrogen and carbon and has high calorific value. Char porosity is relative high and can vary in the range of 40 to 50% (Basu, 2010).

Only in several models include tar and char in the gasification process mass balance, typically as constant value. The aim of this study is get empirical relation of tar and char yield depending from gasifier operation parameters and achieved equation including in the mathematical model. The determination of main factors which have effect on the tar and char yield must be done before. Many studies available about tar and char formation in the gasification process. Sometimes different and even opposite effect of different factors on the tar and char yield can be find. Tar and char formation are depended from many factors. This can be one of the main reason of different results between studies. Only results from studies where one type gasifiers with similar gasification agent used can be compared.

The developed mathematical model describes gasification process in the downdraft gasifier where air was used as gasifying agent. Only studies which analyse tar and char yield from downdraft gasifier with air medium were used for regression model derivation. Tar yield from downdraft gasifiers is lower in comparison with updraft and fluidized bed gasifiers. Biomass gasification with air agent promote higher tar concentration in the syngas than with steam or oxygen gasification.

The temperature increase promotes total tar content decrease in the syngas. Hydrocarbons conversion becomes more active because of heat released by the combustion reactions. (Basu, 2010; Erkiaga et al., 2014). The char yield also reduces due to temperature growth and is converted into gas through Boudouard reactions and thermal cracking reaction (Luo et al., 2012). On the other side, the significant growth of the temperature favours the decrease of the low heating value of the syngas. By increasing temperature, more carbon is oxidized to CO_2, which is incombustible. Syngas heating value goes down in the result. It is important to find optimal temperature range for gasifier operation to produce high syngas yield without significant decrease of the syngas heating value (Sanz & Corella, 2006).

From the other side gasification temperature is affected by many parameters, like equivalence ratio, moisture content of fuel, fuel chemical composition, reactor design, etc. Temperature in the gasifier cannot be changed without changing one or several input parameters and has strong correlation with mentioned parameters. Temperature should be considered as a dependent variable in the result. In the thermochemical models interactive calculation is applied to determine gasification temperature at which energy balance of the global gasification reaction is fulfilled.

Equivalence ratio is one of the most significant parameters affecting gasification process efficiency and syngas composition. Equivalence ratio is the ratio of the actual air/fuel ratio to the stoichiometric air/fuel ratio. Equivalence ratio is 1 for the ideal combustion and typically ranges from 0.2 to 0.4 for biomass gasification. The growth of the air/fuel ratio promotes increase of the activity of the combustion reactions. Temperature in the reaction zone goes up in the result. Many studies' results present that there is a strong correlation between equivalence ratio and temperature (Pellegrini & Oliveira, 2007; Ghassemi & Shahsavan-Markadeh, 2014). Ji et al. (2009) and Guo et al. (2013) determined tar content decreasing, but Fiaschi & Michelini (2001) present char reduction with air/fuel ratio increase.

The similar situation is with fuel moisture. The effect of moisture has influence on tar and char yield and temperature in the gasifier reactor (Pellegrini & Oliveira, 2007; Karamarkovic & Karamarkovic, 2010). The higher the fuel moisture, the higher energy amount is used to evaporate water from the biomass and less energy is available for endothermic reactions. The temperature in the gasifier goes down in the result and promotes growth of the tar and char yield. The tar content growth from 14.4 g m^{-3} to 20.7 g m^{-3} and temperature decrease from 795 °C to 748 °C was found out when the fuel moisture increased from 15% to 34% in the study done by Guo et al. (2013).

There are also some another factors which have influence on the tar and char yield - feedstock particle size (Mohammed et al., 2011), high concentration of volatile matters (Min et al., 2003), lignin content in the fuel (Saw & Pang, 2013; Amirabedin et al., 2014) and fuel chemical composition. Model represent gasification process of wood chips with constant properties. The effect of fuel chemical composition was presented in the previous study (Kirsanovs & Žandeckis, 2015a). It was determined that chemical composition and ash content in the fuel have effect on the gasification temperature. Therefore, the fuel chemical composition influence on the gasification process can be represented due relationships of temperature in the gasifier and tar and char yield.

MATERIAL AND METHODS

Literature review confirm that tar and char formation depends from temperature in gasifier, equivalence ratio and fuel properties. Table 1 summarizes the studies which present effect of gasification operation parameters and fuel properties on the tar and char formation. Table present the ranges of gasification temperature, air/fuel ratio, biomass moisture and ash content in biomass in the studies. Fuel moisture and ash content in some studies are constant in the experiments.

Table 1. Summary of previous studies which present tar and char formation at the biomass gasification process

Gasification temperature	Air/fuel ratio	Biomass moisture, %	Ash content in biomass, w-%, dr	References
930–1,040	1.29–2.88	6.17	5.93	Gai & Dong, 2012
821–1,206	1.37–1.64	12.5	0.77	Dogru et al., 2002a
553–755	1.04–1.63	6.00–11.0	0.50–1.4	Sarket & Nielsen, 2015
705–920	0.87–1.85	4.37–15.2	3.90	Sheth & Babu, 2010
830–1,120	0.96–1.83	4.40–14.9	0.40–21.8	Striūgas et al., 2014
1,009–1,077	2.28–2.69	11.8	23.5	Dogru et al., 2002b
870–1,108	1.11–1.28	8.00	0.55	Lv et al., 2007
773	1.88	18.0	1.3	Atnaw et al., 2013

Data analysis is performed using STATGRAPHICS Centurion 16.1.17 software and shows that there are correlations between tar and char yield and gasification operation parameters and fuel properties. The first mathematical equation below represents gasification temperature, air/fuel ratio and biomass moisture effect on the tar yield. (see Eq. 1) Tar yield was presented as relation of tar mass at the exit of gasifier to total fuel and air mass input. The mass of the fuel and air injected in the gasifier is similar with total product mass output from gasifier. The second equation shows the connection between char yield and gasification temperature, air/fuel ratio, fuel moisture and ash content (see Eq. 2). Char yield was presented as relation of char mass at the exit of gasifier to total fuel mass input.

$$w_{tar} = (6.411 - 0.203 \cdot sqrt(T))^2 + 0.248 \cdot AF - 0.024 \cdot W \quad (1)$$

$$w_{Char} = (6.643 - 0.006 \cdot T)^2 + 2.108 \cdot AF + 0.193 \cdot W + 0.487 \cdot A \quad (2)$$

where: w_{tar} is tar mass concentration, wt%; w_{char} is char mass concentration, wt%; T is temperature in the gasifier, °C; AF is ait/fuel ratio; W is fuel moisture content, wt%; A is ash content in the fuel, wt%, on dry basis.

Analysis of both models is presented in Table 2. Results show that temperature is most influential parameter on the indicator in Model I and II. This is mostly due to significant influence of temperature on the tar and char yield. R-Squared statistic indicates that the model as fitted explains 77.60 and 68.24 variability of tar and char yield. Standard error of the estimate is low and especially for model I, so it can be used to predict limits for new observations. The mean absolute error is the average value of the residuals and also is lower for model I.

Table 2. Data analysis of the regression model

Reg. model	Depended variable	R^2, %	Adjusted. R^2, %	Standard error of estimate	Mean absolute error
I	Tar	77.60	75.81	0.51	0.30
II	Char	68.24	63.67	2.13	1.43

Two achieved equations are integrated in the modified thermodynamic model of the gasification process. Model detailed description can be found in the previous studies (Kirsanovs & Žandeckis, 2015a; Kirsanovs & Žandeckis, 2015b). Global gasification reaction is a base of the created thermodynamic model. CO, CO_2, H_2, CH_4, N_2 and H_2O vapour make syngas composition in the model. The inclusion of tar and char in the model is the main difference from previous models. Air is used as gasification agent in this model. Fuel and ambient temperatures are constant. Fuel properties like chemical composition and ash content are constant in the model for all scenarios and represent typical wood from forest with or without bark. Model validation with others studies also was described in the earlier papers. Model was based on the global gasification reaction, where tar and char were also included (Eq. 3):

$$\begin{aligned} & CH_xO_yN_z + wH_2O + m(O_2 + 3.76N_2) = n_1H_2 + n_2CO + \\ & + n_3CO_2 + n_4CH_4 + n_5HO_2 + (\frac{1}{2}z + 3.76m)N_2 + n_6tar + n_7char \end{aligned} \quad (3)$$

The carbon, hydrogen and oxygen balances in the model were presented as (Eq. 4–6):

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

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

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

The mass balance consists from two input and for output flows. Fuel and air are input flows, but syngas, tar, char and ash are output flows (Eq. 7). Tar and char mass were calculated using achieved equations 1 and 2.

$$m_f + m_{air} = m_s + m_t + m_c + m_{ash} \quad (7)$$

where: m_f – fuel mass; m_{air} – air mass; m_s – syngas mass; m_t – tar mass; m_c – char mass; m_{ash} – ash mass.

Three input and three output flows form the energy balance in the model (Eq. 8). The main energy was injected with fuel heating value. Some energy goes to gasifier with air and fuel sensible energy. The dominant share of energy leaves gasifier with syngas heating value, but some energy was removed from syngas sensible heat. The remaining energy belong to heat losses. Heat losses from gasifier hot surfaces, heat removed from tar and char are main energy losses ways.

$$E_f + E_{f_s} + E_{a_s} = E_s + E_{s_s} + E_l \quad (8)$$

where: E_f – fuel energy; E_{f_s} – fuel sensible energy; E_{a_s} – air sensible energy; E_s – syngas energy; E_{s_s} – syngas energy; E_l – heat losses.

The cold-gas efficiency of gasification process is relation between produced syngas heat of combustion to input energy with biomass and expressed in model as (9) (Basu, 2010):

$$\eta_{cold} = \frac{LHV_g \cdot V_g}{LHV_f \cdot m_f} \tag{9}$$

where: η_{cold} – 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.

The hot-gas efficiency take into account produced gas sensible heat also. Sensible heat is depending from syngas temperature after gasifier and after cooling (10) (Basu, 2010):

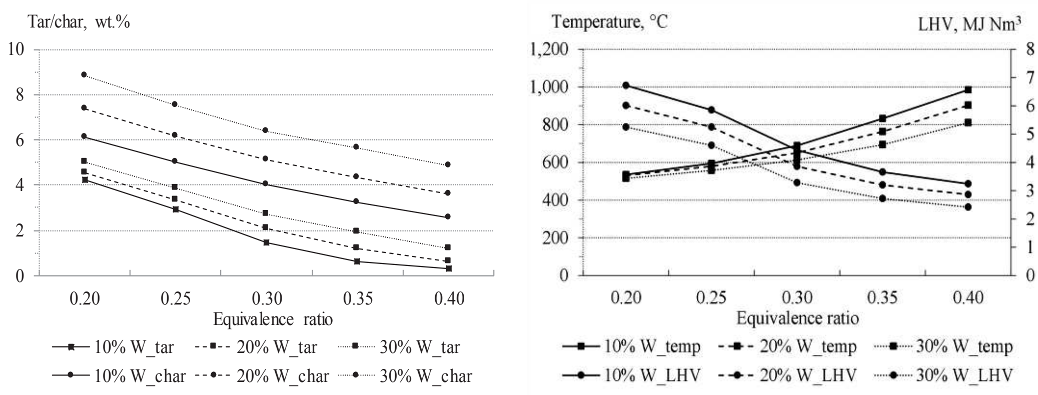
$$\eta_{hot} = \frac{LHV_g \cdot V_g + Q_s \cdot V_g}{LHV_f \cdot m_f} \tag{10}$$

where: η_{hot} – the efficiency of the gasification process, %; Q_s – sensible heat of syngas.

RESULTS

The effect of gasification operational conditions on the gasification temperature, produced syngas amount, syngas heating value and syngas sensible or latent heat, as well as gasification process efficiencies are analysed. Gasification process is simulated using previous model without tar and char and modified model, which includes gasification process subproducts. It is done to compare models and to represent the difference between the results of modelling. Equivalence ratio and fuel moisture are chosen as independent variables. Equivalence ratio vary in range from 0.2 to 0.4. Three typical values of the amount of water in the biomass – 10%, 20% and 30% – were taken for fuel moisture.

First of all, the yield of the produced tar and char in comparison to total output flow are calculated (see Fig. 1). The results show that tar and char mass concentration is maximal at low equivalence ratio. Tar and char yields decrease from 4.2% and 6.1% respective at equivalence ratio 0.2 to 0.3% and 2.6% at equivalence ratio 0.4 using biomass with 10% moisture content. Fuel moisture growth promotes the increase of tar and char content. Tar and char yields go up from 4.2% and 6.1% respective with fuel moisture content 10% to 5.0% and 8.8% with moisture content 30% at equivalence ratio 0.2. Significant gasification temperature reducing with fuel moisture growth is the main reason of it.



a) b)

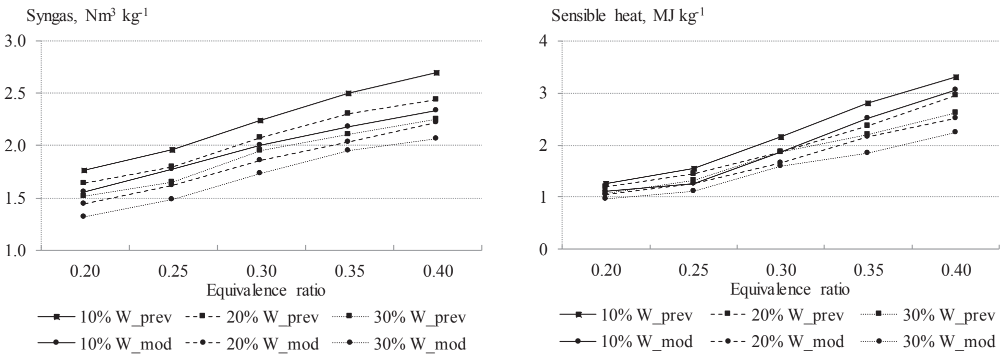
Figure 1. Effect of the equivalence ratio and fuel moisture content on the tar and char yield (a); and temperature and syngas higher calorific value (b), where: 10%W – fuel moisture 10%; 20%W – fuel moisture 20%; 30%W – fuel moisture 30%; temp – temperature in gasifier, °C; LHV – syngas lower calorific value, MJ Nm^3.

Temperature of oxidation zone and temperature in the gasifier in general decrease with biomass moisture growth. More energy from fuel is used to evaporate water. The oxidation reaction activity goes down due fuel moisture increase also. Gasification temperature reduced from 535 °C respective with fuel moisture content 10% to 515 °C with moisture content 30% at equivalence ratio 0.2. At the same time gasification temperature increase from 535 °C at equivalence ratio 0.2 to 985 °C at equivalence ratio using biomass with 10% moisture content.

The carbon monoxide and hydrogen content in the produced syngas goes down with fuel moisture increase. Lower heating value of syngas goes down in the result from 6.7 MJ Nm^3 with fuel moisture content 10% to 5.3 MJ Nm^3 with moisture content 30% at equivalence ratio 0.2. The increase of equivalence ratio promotes the growth of the gasification temperature. Methane concentration rapidly goes down and causes the decrease of syngas heating value too.

The volume of the produced gas is lower after tar and char including in the model. Fig. 2 shows difference in the syngas amount between previous model, where tar and char were not included and modified model with tar and char. The results show that the amount of syngas is lower using modified model. Produced syngas flow increases 1.5 times from 1.5 Nm^3 kg^{-1} to 2.5 Nm^3 kg^{-1} and more with equivalence ratio increase from 0.2 to 0.4. Amount of produced incombustible CO_2 and N_2 also increases due ER growth and promote decrease of heating value of syngas. The amount of produced syngas goes down with fuel moisture growth.

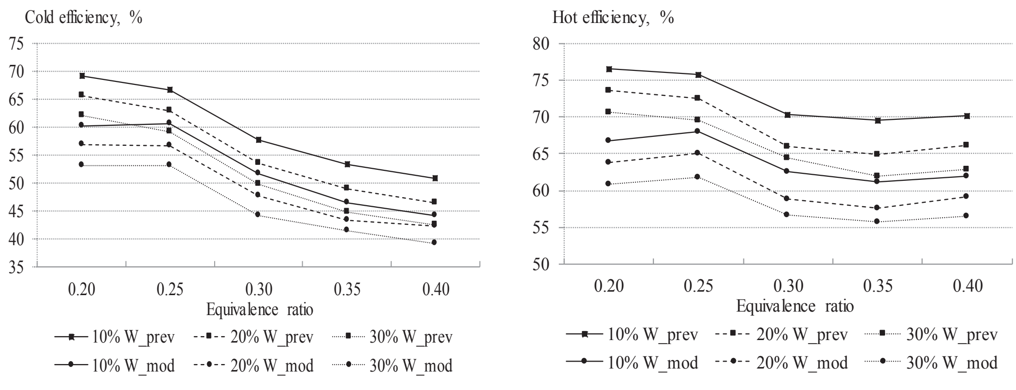
Temperature in the gasifier has dominant effect on the sensible heat of syngas. The higher is gasification temperature the higher is sensible heat of produced gas. This is the main reason that sensible heat of syngas is higher for fuel with lower moisture content and at high equilibrium ratios. Sensible heat of syngas is lower for scenarios where tar and char were included in the model, because the total amount of the syngas goes down.



a) b)

Figure 2. Effect of the equivalence ratio and fuel moisture content(W) on the produced gas volume (a); and syngas sensible heat (b), where: prev – previous model; mod – modified model including tar and char.

The efficiency is one of the main criteria describing performance of the gasification process. Efficiency of the gasification process typically is described using cold gas and hot gas efficiency. Fig. 3 presents calculated cold and hot gas efficiencies of the gasification process for all six scenarios. The syngas calorific value decrease due to equivalence ratio and fuel moisture content growth. Cold gas efficiency of the gasification process goes down in the result. The data from modified model show that cold gas efficiency doesn't go down or opposite go up with equivalence ratio increase from 0.2 to 0.25. The significant tar and char yield decrease is the main reason of it. The fuel moisture increase on 10% promote decrease of cold gas efficiency on the average by 3.5%. The growth of equivalence ratio from 0.2 to 0.4 promote decrease of cold gas efficiency on the average by 19% and 15% using previous and modified models respectively.



a) b)

Figure 3. Effect of the equivalence ratio and fuel moisture content(W) on the gasification process cold efficiency (a); and hot efficiency (b).

Data from previous model show that the hot gas efficiency goes down rapidly at lower equivalence ratio too, but after achieving the critical point was more over constant. Significant syngas volume and sensible heat increase at high equivalence ratios are the main reason of it. The achieved data from modified model present some hot gas efficiency growth with equivalence ratio increase from 0.2 to 0.25. The further effect of equivalence ratio decrease was more over similar with results from previous model.

CONCLUSIONS

The effects of temperature, equivalence ratio and fuel properties on the tar and char formation are analysed, using articles available from literature. Tar and char have a strong impact on the produced syngas properties and gasification process efficiency. Tar and char yield should be included in the mass balance of the biomass gasification process to get achieved data from thermodynamic model closer to real data.

Two models are proposed to present the mathematical connection between temperature in gasifier, air/fuel ratio, fuel properties and tar and char yield during gasification process using collected studies. Data analysis shows that the models have a sufficient correlation between the variable. The achieved equations are integrated in the thermodynamic model of gasification process.

The effect of equivalence ratio and fuel moisture is determined using the developed gasification process model. The results show that air/fuel ratio growth promotes decrease of tar and char yield. The increase of temperature in the reactor is the main reason of it. Growth of the temperature has negative effect on the produced syngas calorific value. Fuel moisture increasing has the opposite influence on the tar and char yield. Temperature in the gasifier reduces due to the biomass moisture growth, that favours the increase of the tar and char yield.

The modified model with included tar and char values is compared with previous model. The results show that efficiency of gasification process lowers. Modified model show that equivalence ratio 0.25 can be optimal value for gasification process. Previous model show that the lower is equivalence ratio the higher is gasification process efficiency, because don't take into account tar and char effect on the process. Data from new model is closer to data from real systems after tar and char including in the model.

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