Use of the Steam as Gasifying Agent in Fluidized Bed Gasifier

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This work has studied the impact of gasification mediums (air and steam air mixture) on syngas components (H_2, CO) and low heating value LHV.

This study has been based on previous research and experimental studies conducted in fluidized bed by using air-steam as gasification agent and pine wood chips as feedstock.

According to the results of the experiments and discussion, it has been found, that the gas quality is improved with the use of the steam and air mixture. The parameters, with which to achieve the best quality of the produced gas at experimental conditions (ER = 29, $Tf1$ = 261 °C) are as follows: T_{101} = 829 °C, $\frac{S}{B} = 0.67$, where hydrogen is increased from 10.48 to 19.68 % and low heating value from 3.99 to 5.53 MJ m^{-3} and tar is decreased from 1964 to 1046 mg m^{-3} by increasing S/B from 0 to 0.67 at T_{101} = 829 °C.

Key words:
gasification, gasifying agent, air, steam

Introduction

Biomass energy is the oldest energy source used by humans. Biomass has evolved as one of the most promising sources of fuel for the future[1]. This has spurred the growth of research and development efforts in both federal and private sectors. This impetus is motivated by several factors; dwindling fossil fuels and thus an increased need of energy security, environmental concerns and promotion of socioeconomic benefits to rural areas. Another important fact is the somewhat uniformly distributed nature of biomass worldwide which means it is available locally and is helpful in reducing dependence on fossil fuel[1]. Biomass is potentially an attractive feedstock for producing transportation fuels as its use contributes little or no net carbon dioxide to the atmosphere[2]. Renewable biomass resources include short-rotation woody crops, herbaceous biomass, and agricultural residues. Biomass is available for exploitation for conversion to bio-fuels as well as for power generation applications. There are various conversion technologies that can convert biomass resources into power, heat, and fuels for potential use in UEMOA countries[3]. In view of this a variety of processes exists for biomass conversions. The most used of these are thermal conversions, bio-chemical and chemical conversions and direct combustion. The thermal conversion processes consist of fast and slow pyrolysis and biomass gasification. Biomass gasification is considered as one of the most promising routes for syngas or combined heat and power production because of the potential for higher efficiency cycles Gasification is a process for converting carbonaceous materials into a combustible or synthetic gas (H_2, CO, CO_2, CH_4)[4]. In general, gasification involves the reaction of carbon with air, oxygen, steam, carbon dioxide, or a mixture of these gases at 700 °C or higher to produce a gaseous product that can be used to provide electric power and heat or as a raw material for the synthesis of chemicals, liquid fuels, or other gaseous fuels such as hydrogen[1].

Gasification media

Thermochemical gasification of biomass is a well-known technology that can be classified depending on the gasifying agent: air, steam, steam–oxygen, air– steam, .., etc[5].

Gasification with air

The use of air as a gasifying agent is not a complex method; however, the produced gas possesses low heating value of primarily approximately (3.5 – 6 MJ m^{-3}), with little amount of hydrogen and high amount of nitrogen[5]. The gas produced by this method is suitable for boiler and engine applications but not for applications requiring its transportation through pipelines[6]. Gasification with air is widely used compared to oxygen and steam because of its economic and operational advantage. Howev-

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er, this technology produces a gas possessing a low heating value of (3.5–6 MJ m^{-3}) and an H_2 content of only 8–11 (vol.%) content[5].

The study results of an air gasification system in a fluidized bed by using sawdust, indicated that under optimum operating conditions, a fuel gas could be produced at a rate of about 1.5 m^3 kg^{-1} biomass and heating value of about 4 MJ m^{-3}. The concentration of hydrogen, carbon monoxide and methane in the gas produced were 9.27 %, 9.25 % and 4.21 %, respectively[7].

Gasification with oxygen

Gasification oxygen is one of the most effective ways to improve syngas quality. It produces gas with heating value of approximately 12 MJ m^{-3} and without nitrogen. This gas can be economically transported pipeline and therefore, be used for process heat[2]. In this case, an oxygen plant or a nearby source of oxygen is required, thus raising the capital cost of the plant which is a disadvantage to its popularization[8].

Gasification with steam

Gasification with steam needs an external heat source if it is used alone as a gasifying agent[5]. The provided steam will enhance gas quality; it enhances hydrogen content and heating value. The high temperature will enhance the devolatilization process of biomass to produce gas[7]. Steam will react with carbon monoxide to produce hydrogen and carbon dioxide, which is called the water–gas shift reaction equation[7]:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (1)$$

However the excessive increase of steam provided, will lower the gas quality[7]. Steam gasification produces gas with higher heating value compared to air gasification[7].

Extensive experimental studies reported in literature (Delgado *et al.*, 1996; Aznar *et al.*, 1998; Gil *et al.*, 1999; Rapagna *et al.*, 2000; Courson *et al.*, 2000; Schuster *et al.*, 2001; Mathieu and Dubuisson, 2002) show, that fluidized-bed, steam-gasification processes are also able to produce gas with possessing heating value of about 10 MJ m^{-3} and hydrogen content of about 30 (vol.%). However, this technology requires steam temperature to be above 700 °C, which implies additional costs for the steam generator[5].

Gasification with steam-air mixture

Using a mixture of steam and air as a gasifying agent will enhance syngas quality. Oxygen in the air will help to provide the needed energy because of the exothermic nature of burning biomass. Reducing the nitrogen content of the produced gas will increase its heating value[6].

This work has studied the effect of steam and air gasification in a fluidized bed on syngas quality, and the optimal parameters of the air-steam-gasification system to achieve best quality have been chosen[7].

Experimental study

Experimental unit Biofluid 100

Research has been conducted at the Institute of Power Engineering, Brno University of Technology, Brno, into fluidized bed gasification of biomass and separated municipal waste called Biofluid 100. Pine wood chips were used as fuel.

The experimental set-up, shown in Figure 1, consists of six main parts: atmospheric fluidized bed reactor, biomass feeding section, steam and air providing and preheating section, gas metering, cleaning and sampling section, temperature control section, and gas offline analysis section.

The parameters of the gasifier are as follows:

- Output (in generated gas) 100 kW
- Input (in fuel) 150 kW
- Fuel consumption max. 40 kg h^{-1}
- Air flow max. 50 m^3 h^{-1}
- Air temperature 200 °C
- Output (steam generator) 18 kW
- Steam temperature (output steam generator 150 °C and heat to 450 °C)
- Steam flow 18 kg h^{-1}

Fig. 1 – *Atmospheric fluidized bed gasifier Biofluid 100*

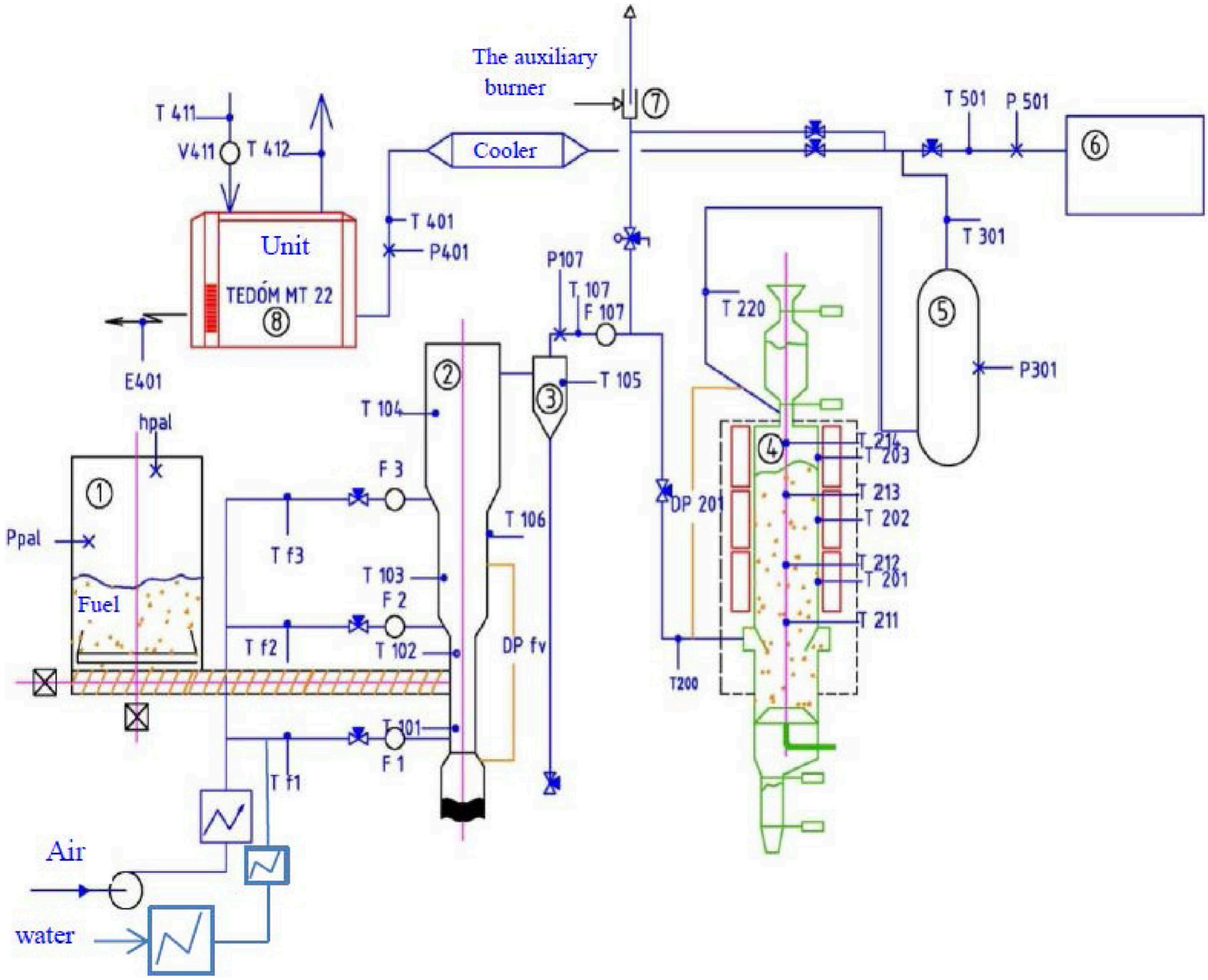

Fig. 2 – *Simplified layout of the gasifier connections; measured quantities:* $T_{101} – T_{104}$*...temperatures in the gasifier,* T_{105}*...temperature inside the cyclone Tf1...temperature of the incoming primary air (temperature of incoming primary air and steam mixture),* T_{107}*...gas temperature at jacket outlet, F 1–3...air flows,* F_{107}*...gas flow,* p_{107}*...outlet gas pressure, Ppal... tank pressure, DPfv...fluidized bed pressure difference.*

Results and discussion

Steam to biomass ratio *S/B*, reactor temperature T_{101}

The first goal is to determine the optimum temperature of the reactor T_{101} and optimal ratio of steam to biomass.

To achieve this goal, many experiments have been conducted at different reactor temperatures and different values of steam to biomass ratio. Reactor temperature was varied from 770 to 861 °C in 20 °C increments. Steam rate was varied from 0 to 20 kg h^{-1}, thus steam to biomass ratio varied from 0 to 0.85 kg steam kg^{-1} biomass.

Steam temperature was about *T*f1 = 261 °C equivalence ratio ER about 0.29, air flow rate varied from 14 to 24 kg h^{-1}, and biomass flow rate also varied from 15 to 26 kg h^{-1}.

Samples for mutual comparison were selected at similar gasification conditions, for every reactor temperature separately. The results of these tests are given in Figures 3 to 9.

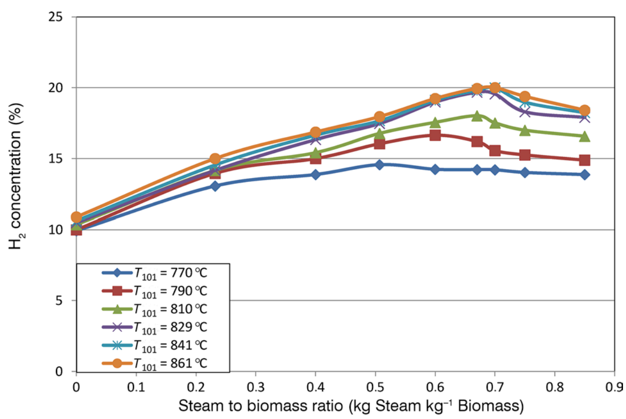

Fig. 3 – *Effect of S/B and T101 on hydrogen content in the produced gas*

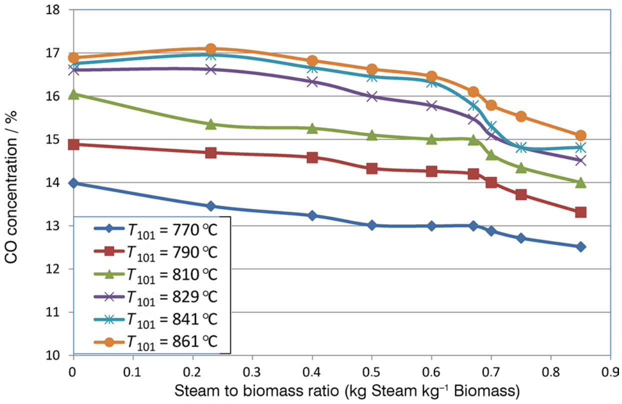

Fig. 4 – *Effect of S/B and T_{101} on carbon monoxide content in the produced gas*

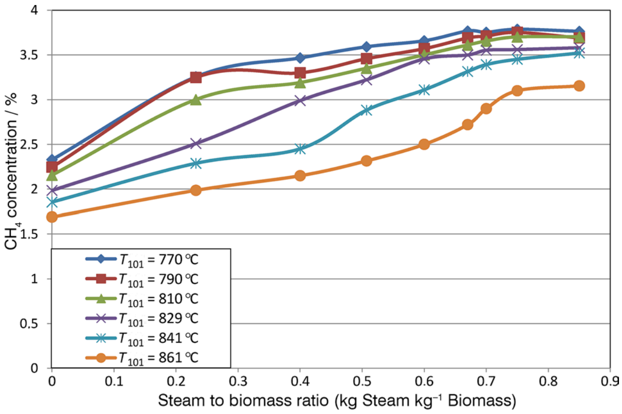

Fig. 5 – *Effect of S/B and T_{101} on methane content in the produced gas*

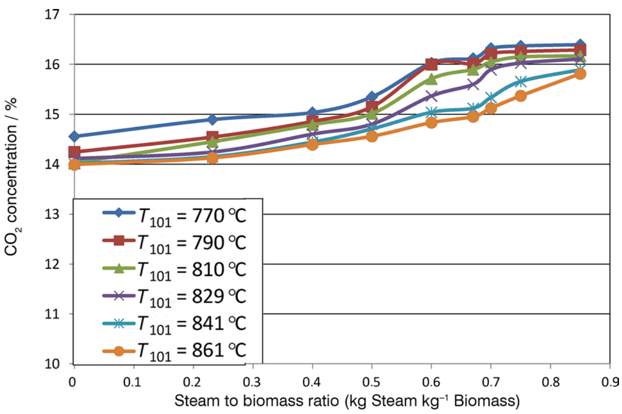

Fig. 6 – *Effect of S/B and T_{101} on carbon dioxide content in the produced gas*

From Figures 3 to 9, the following can be observed:

The increase in reactor temperature T_{101} leads to the increase in hydrogen, carbon monoxide, gas yield, and a decrease in methane, tar, and carbon dioxide content. The low heating value first increases with T_{101} up to the temperature of 829 °C, after which it starts to decrease with the further increase in T_{101}. This is due to the following:

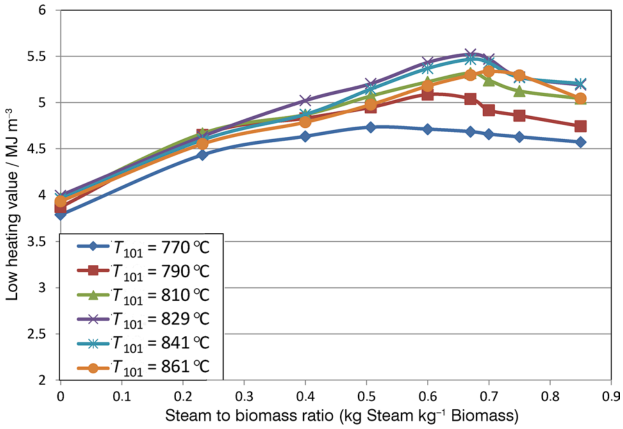

Fig. 7 – *Effect of S/B and T_{101} on low heating value of the produced gas*

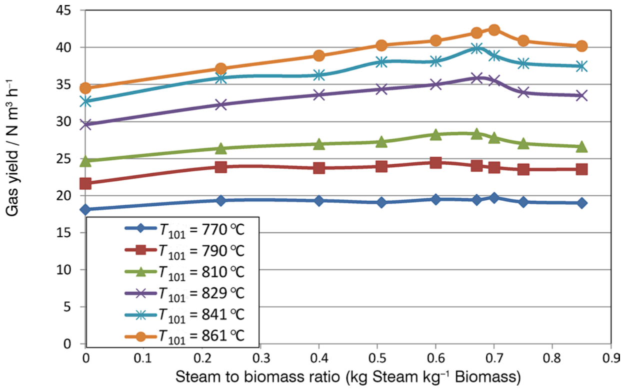

Fig. 8 – *Effect of S/B and T_{101} on the gas yield*

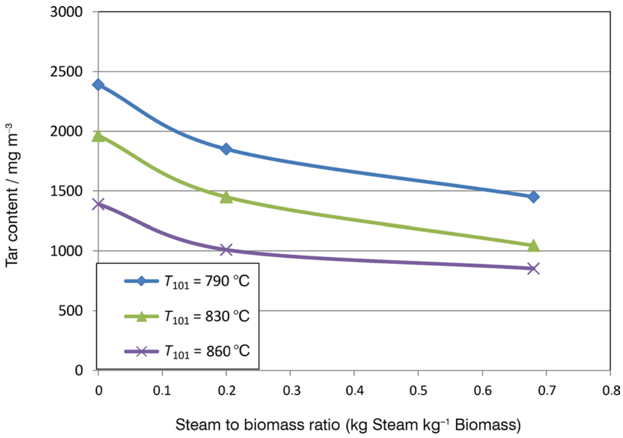

Fig. 9 – *Effect of S/B and T_{101} on tar content*

– By depending on Le Chatelier's principle, higher temperatures improve the reactants in exothermic reactions and improve the products in endothermic reactions[5]. Therefore, the endothermic reactions (2) and (3) will be enhanced with an increase in temperature, which leads to an increase in hydrogen concentration and a decrease in CH_4 concentration.

$$CH_4 + H_2O \rightarrow CO + 3H_2 - 206 \text{ kJ} \qquad (2)$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 - 165 \text{ kJ} \tag{3}$$

– The water–gas reaction, Equation 4, will be more active by high temperature[8]. But this equation produces hydrogen and carbon monoxide at the same molar rate; they have the same molar concentration at balance state.

$$C + H_2O \rightarrow CO + H_2 - 131.38 \text{ kJ} \tag{4}$$

– The Boudouard reaction, Equation 5, shows that this reaction will be improved by high temperature; carbon dioxide decreases and carbon monoxide increases, thus enhancing the gas yield also.

$$C + CO_2 \rightarrow 2CO - 172.58 \text{ kJ} \tag{5}$$

– The methane formation reaction, Equation 6, is improved by low temperature; therefore decreases methane by increasing temperature.

$$C + 2H_2 \rightarrow CH_4 + 74.90 \text{ kJ} \tag{6}$$

The increase in the values of the steam to biomass ratio lead to the increase in hydrogen and methane, carbon dioxide, gas yield, low heating value, and to the decrease in tar content, but also carbon monoxide. However, the excessive increase in provided steam leads to a reduced concentration of hydrogen, and thus to lower values of each (low heating value, gas yield). The optimum steam to biomass ratio for achieving the best gas quality increases with reactor temperature in our experimental conditions ($Tf1 = 261$ °C and ER = 28), was $\frac{S}{B} = 0.67$ kg steam kg^{-1} biomass at T_{101} = 829 °C and this is due to the following:

– The water–gas shift reaction, Equation 1, is more active with steam and thus leads to an increase in the ratio of hydrogen and carbon dioxide to carbon monoxide in the gas[8].

– The water–gas reaction, Equation 4, is a more active reaction with steam, so it enhances gas yield[4].

– The excessive increase of steam at steam temperature 260 °C (according to our experiments) leads to a reduction in reaction temperature, which thus leads to a decrease in hydrogen, low heating value, and gas yield during the experiment after a certain value of steam to biomass ratio.

Figure 9 indicates that the tar content decreases with increasing T_{101} and S/B, the tar content decreased from 2390 to 1390 mg m^{-3} by increasing the temperature from 770 to 861 °C when using only air, but the tar content decreased from 1450 to 853 mg m^{-3} with the use of the steam and air mixture at $\frac{S}{B} = 0.67$ kg steam kg^{-1} biomass in the same range of the temperature increase. This is due to the following:

Steam converts high molecular weight hydrocarbons of tar into smaller gas products including H_2, CH_4, CO and CO_2[7]. Also, the heavier hydrocarbons such as tar, ethane and methane, will be cracked by high temperature, producing carbon and hydrogen; part of the carbon converts to carbon monoxide[8]. Therefore, the tar content will decrease by increasing both reactor temperature T_{101} and steam to biomass ratio S/B.

Comparison of the properties of gas produced with air-steam and air gasification

From the results of the experiments and discussion, it has been found that the optimum parameters for achieving the best quality of produced gas at the experimental conditions (ER = 0.29, $Tf1 = 261$ °C), are T_{101} = 830 °C and — 0.68.

Compared have been the properties of the gas produced using steam and air as gasifying agent under the optimum parameters as mentioned above, and the gas produced using air as gasifying agent under the same reactor temperature and equivalence ratio. Figure 10 shows this comparison. It is clear that the gas quality improved with the use of the steam and air mixture, where H_2 has been had increased from 10.3 to 19.67 %, CH_4 from 2 to 3.5 %, LHV from 3.9 to 5.55 MJ m^{-3}, and the tar content had decreased from 1970 to 1050 mg m^{-3}.

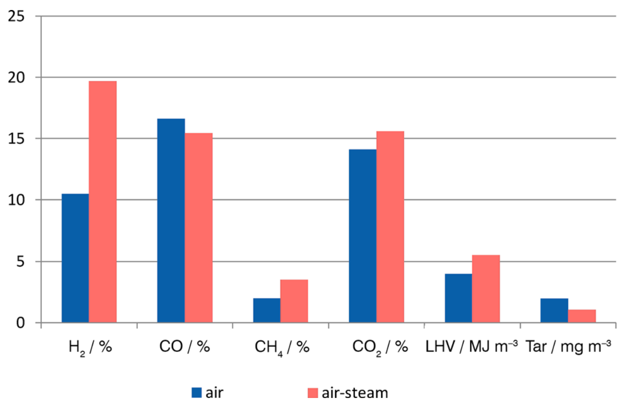

Fig. 10 – *Comparison of the properties of gas produced using steam /air and air as gasifying agent at the best parameters*

Conclusion

The results of the experiments and discussion suggest that gasification with a steam and air mixture will produce a gas of improved quality, while the optimum parameters for the best quality of the produced gas at the experimental conditions

(ER = 0.29, $Tf1$ = 261 °C), are T_{101} = 830 °C, S/B = 0.68, H_2 increased from 10.3 to 19.67 %, CH_4 from 2 to 3.5 %, LHV from 3.9 to 5.55 MJ m^{-3} and tar content decreased from 1970 to 1050 mg m^{-3} at the best parameters.

List of symbols and abbreviations

T_{101} – Temperature measured at the bottom of reactor (primary zone), °C

T_{102} – Temperature measured in mid-section of reactor, °C

T_{104} – Temperature measured at top of reactor, °C

T_{107} – Gas temperature measured at outlet of reactor, °C

$Tf1$ – Temperature of air or steam and air mixture at inlet of reactor, °C

ER – Equivalence ratio, %

$\frac{S}{A}$ – Steam to air ratio kg steam kg^{-1}air

$\frac{S}{B}$ – Steam to biomass ratiokg steam kg^{-1} biomass

References

1. *Demirbas, A. H., Demirbas, I.*, Importance of rural bioenergy for developing countries, Energy Conversion and Management **48** (2007) 2386.
doi: http://dx.doi.org/10.1016/j.enconman.2007.03.005
2. *Basu, P.,* Combustion and gasification in fluidized beds, VOL.1, CRC Press., California, 2006, Page 473.
doi: http://dx.doi.org/10.1201/9781420005158
3. URL: http://www.gekgasifier.com/2010–05–25/2012–09–02.
4. *Arena, U.,* Process and technological aspects of municipal solid waste gasification, Waste Management **32** (2012) 625.
doi: http://dx.doi.org/10.1016/j.wasman.2011.09.025
5. *Xiong, Z. L., Chang, U., Chen, Y., Zhu, X. J.,* An experimental study on biomass air–steam gasification in a fluidized bed, Bioresource Technology **95** (2004) 95.
doi: http://dx.doi.org/10.1016/j.biortech.2004.02.003
6. *Gil, J., Collera, J., Aznar, P. M., Caballero, A. M.,* Biomass gasification in atmospheric and bubbling fluidized bed, Biomass and Bioenergy **17** (1999) 389.
doi: http://dx.doi.org/10.1016/S0961–9534(99)00055–0
7. *Kneof, M, A. H.,* Handbook biomass gasification, VOL. 2, Enschede, BTG Biomass Technology Group., Netherlands, 2005, Page 900.
8. *Sadaka, S. S., Ghaly, A. E., Sabbah, M. A.*, Two phase biomass air–steam gasification model for fluidized bed reactors. Part I: model development, Biomass Bioenergy **22** (2002) 439.
doi: http://dx.doi.org/10.1016/S0961–9534(02)00023–5