INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 5, Issue 5, 2014 pp.631-642
Journal homepage: www.IJEE.IEEFoundation.org

Improve of produced gas quality by using air/steam in fluidized bed gasifier

Salami N, Skala Z

Energy institute, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic.

Abstract
The aim of this work is to determine the best operating parameters of system air- steam gasification in in fluidized bed gasifier,which achive the best gas quality. To accomplish this task, many experiments have been performed to study the effect of reactor temperature(T101), steam to biomass ratio ($\frac{S}{B}$) and temperature of provided steam (Tf1), low heating value(LHV), gas yield, carbon conversion efficiency and gasifier efficiency.
Copyright © 2014 International Energy and Environment Foundation - All rights reserved.

Keywords: Gasification; Gasifying agent; Air; Steam.

1. Introduction
The renewable energy sources, as solar, wind, hydraulic and biomass energies, have been used since many centuries and their applications continued until the "industrial revolution", at which time, because of the low price of petroleum, they were abandoned [1].
Biomass energy is an important source of energy for majority of the world's population. The use of biomass energy is expected to increase in the near future, with growth in population. In developing nations, biomass is an even more important resource providing as much as 35 % of the energy needs in some areas of the globe, particularly in isolated areas where it is often the only resource available [3].
Biomass is available for exploitation for conversion to the bio-fuels as well as for power generation applications. There are various conversion technologies that can convert biomass resources into power, heat, and fuels. In view of this a variety of processes exists for biomass conversions [5]. 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. Gasification is a process for converting carbonaceous materials to a combustible or synthetic gas (H_2, CO, CO_2, CH_4)[1].
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 [5].

2. Chemical reactions in the gasification process
Table 1 includes the reactions that take place in a gasifier during the gasification process [1].

Table 1. Reactions that take place in a gasifier during the gasification process

	NO		heat of reaction $\Delta H_r^0\left(\frac{kJ}{mol}\right)$
The combustion reaction	1	$C+O_2 \rightarrow CO_2$	+393,5
	2	$2H_2+O_2 \rightarrow 2H_2O$	+482,3
partial combustion	3	$C+\frac{1}{2}O_2 \rightarrow CO$	+110,5
gasification reaction	4	$C+H_2O \leftrightarrow CO+H_2$	-131,3
	5	$C+2H_2O \leftrightarrow CO_2+H_2$	-90,2
	6	$C+CO_2 \leftrightarrow 2CO$	-172,4
Methanation reaction	7	$C+2H_2 \leftrightarrow CH_4$	+74,8
	8	$2CO+2H_2 \rightarrow CH_4+CO_2$	+247,3
	9	$CO+3H_2 \rightarrow CH_4+H_2O$	+206,1
	10	$CO_2+4H_2 \rightarrow CH_4+H_2O$	+165,0
	11	$CO+3H_2 \leftrightarrow CH_4+H_2O$	+205,1
	12	$CH_4+2O_2 \rightarrow CO_2+2H_2O$	+801,0
	13	$2CO+O_2 \rightarrow 2CO_2$	+576,3
Water gas reaction	14	$CO+H_2O \leftrightarrow CO_2+H_2$	+41,1

3. Gasification medium

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[2].

3.1 Air gasification

The using of air as a gasifying agent is not complex way, however the produced gas is with lower calorific value primarily approximately (3.5-7.8$\frac{MJ}{Nm^3}$), with little amout of hydrogen and carbon monoxide and high amount of nitrogen.The produced gas by this method it suitable for boiler and engine applications but not for uses that require its transportation through pipelines [6]. Air gasification is widely used compared to oxygen and steam due to its economical and operational advantages, However this technology produces a gas with a low heating value 4 ($\frac{MJ}{Nm^3}$) and an 8-11 vol.% H_2 content only [7].

3.2 Steam gasification

Steam gasification needs an external heat source, if it is used alone as gasifying agent [7]. Provide steam will enhance gas quality, which it enhance hydrogen content and heating value. The high temperature will enhance devolatilization process of biomass to produce gas [8]. Steam will react with carbon monoxide to produce hydrogen and carbon dioxide it is called the water-gas shift reaction Equation 14, Table 1. However the excessive increase of steam provided, will be lowered the gas quality [8].

3.3 Steam-air gasification

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 the exothermic nature of burning biomass. Reducing the Nitrogen content of the product gas will increase the heating value of the gas [7].

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

4. Experimental study

4.1 Experimental unit biofluid 100

Experiments are carried out at fluidized bed atmospheric gasifier with stationary fluidized bed called Biofluid 100. The experimental set-up, shown in (Figures 1 and 2), consists of six main parts: (i) a fluidized bed reactor of atmospheric pressure, (ii) biomass feeding section, (iii) steam, air providing and preheating section, (iv) gas metering, cleaning and sampling section, (v) temperature control section, (vi) gas offline analysis section. A mixture of air and steam was used as the fluidizing agent and introduced into the reactor. Air was supplied by a compressor and was heated to 200 °C in a preheater. The steam of 150 °C was produced in a steam generator and its mass flowrate was measured by a steam flowmeter then the steam heat in reheater to 450 °C Blower-compressed air is delivered to the gasifier, to under its grate, as primary air ensuring partial oxidization of fuel and maintaining the fluidized bed. Moreover, air can be supplied at two other levels as secondary air and tertiary air. The parameters of the gasifier are as follows:

- Output (in generated gas) 100 (kW)
- Input (in fuel) 150 (kW)
- Fuel consumption max. 40 $\left(\frac{kg}{h}\right)$
- Air flow max. 50 $\left(\frac{m^3}{h}\right)$
- Air temperature 200 (°C)
- Output (steam generator) 18 (kW)
- Steam temperature (output steam generator 150 °C, then it will be heated to 450 °C)
- Steam flow 18 $\left(\frac{kg}{h}\right)$

Measured quantities: T 101-104…temperatures in the gasifier, T105...temperature inside the cyclone Tf1...temperature of the incoming primary air (the temperature of the mixture of incoming primary air and steam), T107...gas temperature at jacket outlet, F 1-3…air flows, F107...gas flow,P107…outlet gas pressure, Ppal... tank pressure, DPfv...fluidized bed pressure difference.

Figure 1. Atmospheric fluidized bed gasifier Biofluid 100

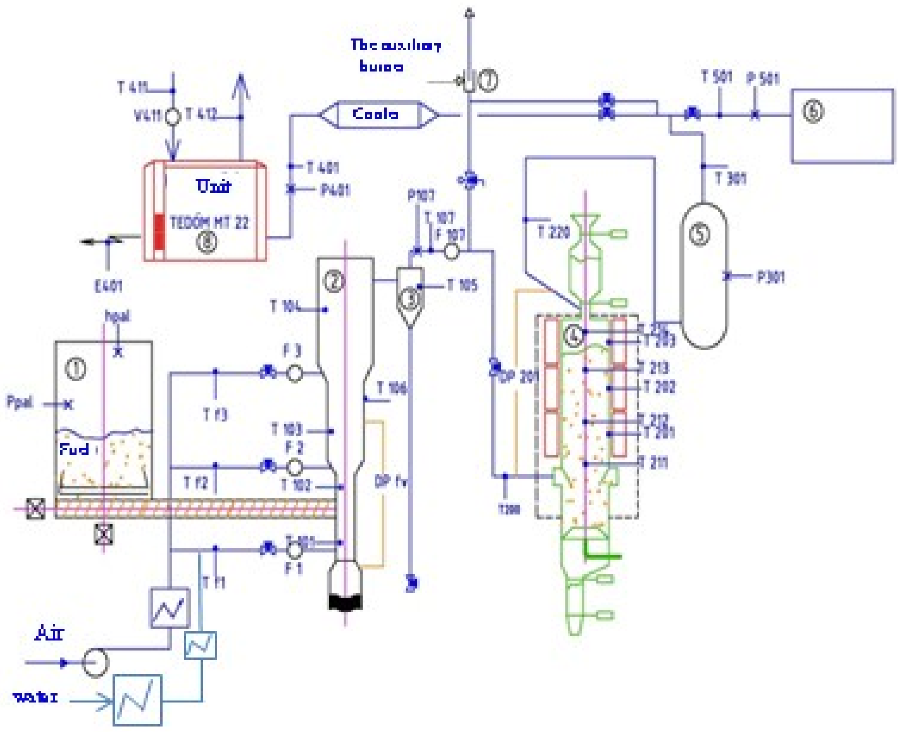

Figure 2. Simplified layout of the gasifier connections

4.2 Fuel material

The fuel material used in this experiment is pine wood chips obtained from a local timber mill were used as the feedstock. The analyses of the feedstock were reported in Table 2.

Table 2. The analyses of the feedstock by RWTUV Praha, Spol.sr.o. Laboratories and test Olomoucka 7/9 656 66 Brno [9]

Specified	Sample in delivered stat	Water-free sample	Sample inflammable matter
Total water %	11.00	-	-
Ashes %	0.47	0.53	-
Caloric value LHV at 25C kJ.kg^{-1}	16426	18760	18860
Hydrogen H %	5.46	6.13	6.16
Carbon C %	44.56	50.07	50.34
Nitrogen N %	0.11	0.12	0.12
Oxygen O_d %	38.38	43.13	43.36
Chlorine Cl %	<0.01	<0.01	<0.01
Volatile sulphur S_{vk} %	<0.01	<0.01	<0.01
Sulphated ash S_A %	<0.01	<0.01	-
Total sulphur S_t %	0.01	0.01	-

5. Results and discussion

5.1 Steam to biomass ratio S/B, reactor temperature T101

The first goal is determination the optimum temperature of the reactor T101 and optimal ratio of steam to biomass. To achieve this goal, many experiments have been done 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 $\left(\frac{kg}{h}\right)$, thus steam to biomass ratio varied from 0 to 0.85 $\left(\frac{kg_{steam}}{kg_{biomass}}\right)$ Steam temperature was about Tf1 =261 (°C), equivalence ratio ER about 0.29, air flow

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2014 International Energy & Environment Foundation. All rights reserved.

rate avaried from 14 to 24 $\left(\frac{\text{kg}}{\text{h}}\right)$ and biomass flow rate also avaried from 15 to 26 $\left(\frac{\text{kg}}{\text{h}}\right)$. Samples for mutual comparison are selected at similar gasification conditions, for every reactor temperature separately.The results of this testes were reported in Figures 3 to 11.

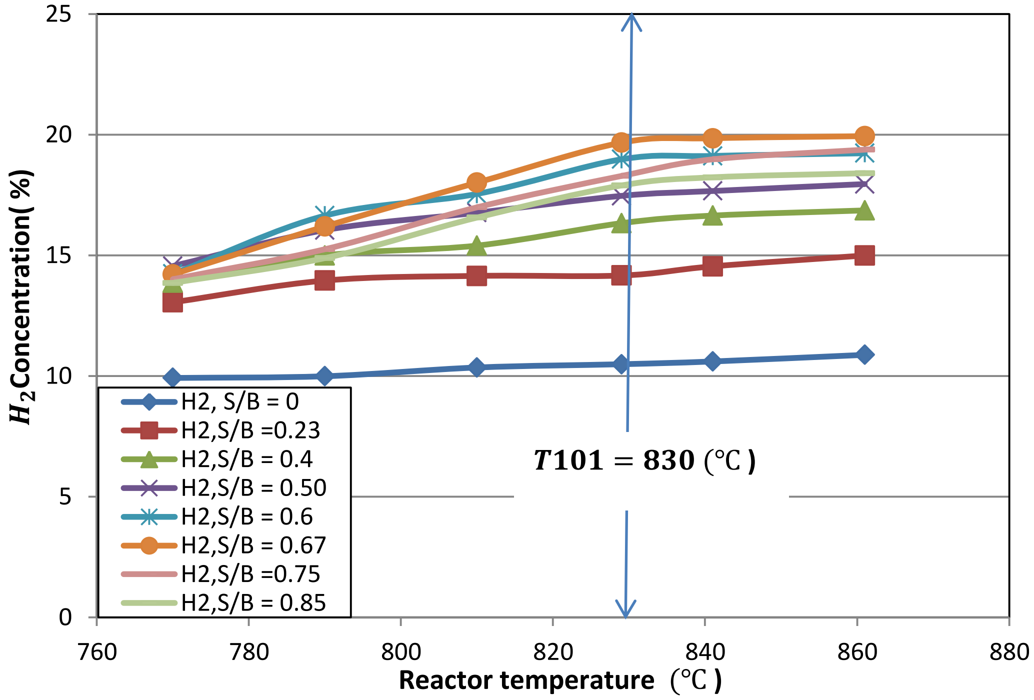

Figure 3. The effect of S/B and T101 on hydrogen content in produced gas

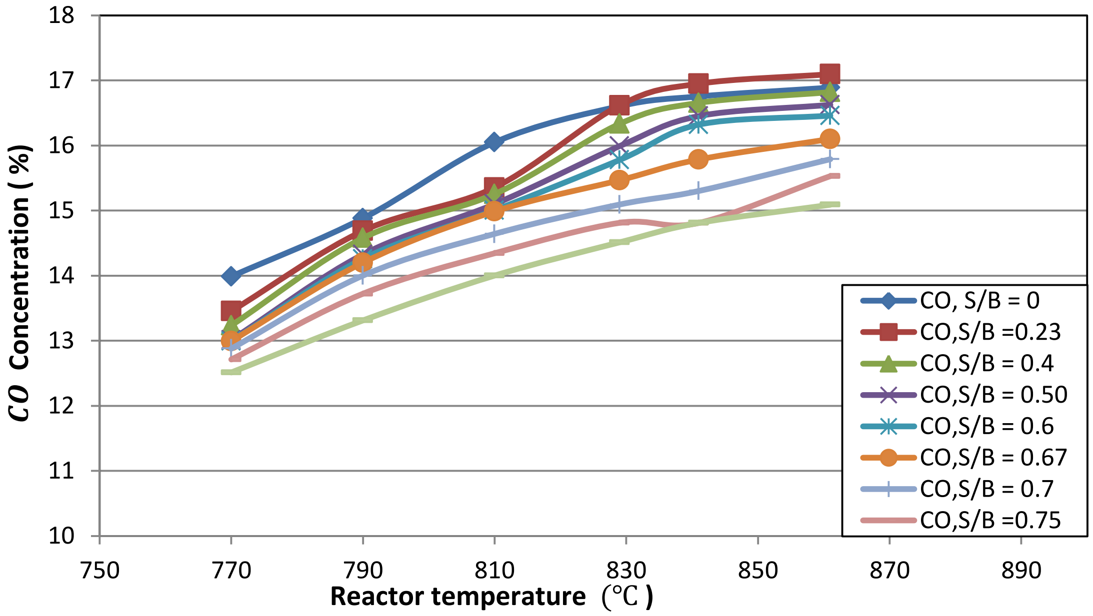

Figure 1. The effect of S/B and T101 on Carbon monoxide content in produced gas

It has been calculated each of Low heating value, gas yield, Carbon efficiency, gasifier efficiency and Equivalence ratio depend on conditions and results of experiment for every gas samples due to:

- Low heating value LHV $\left(\frac{\text{MJ}}{\text{m}^3}\right)$ has been calculated by this flowing equation [7]:

$$\text{LHV} = (30\ \text{CO} + 25.7\text{H}_2 + 85.4\text{CH}_4 + 151.3\ \text{C}_n\text{H}_m).4.2/1000 \quad (15)$$

where: CO, H_2, CH_4 and C_nH_m are the gases concentrations of the product gas.

- gas yield ($V_{gas}, \frac{m^3}{h}$),which has been calculated by this equation[5]:

$$V_{gas} = \frac{0.79}{N_2} . F_1 \tag{16}$$

where: Air contains 79 % nitrogen by volume.
N_2 (%): Content of nitrogen in produced gas.
$F1\left(\frac{m^3}{h}\right)$: primary air flow rate, it has been measured during the experiment.

- Carbon efficiency $\eta_c(\%)$, which has been calculated by equation [5]:

$$\eta_c = \frac{\sum \text{mass of carbout in gas produce}}{\sum \text{mass of carbon in biofuile}} \text{ X100}$$

$$\eta_c = \frac{(CO+CO_2+CH_4+2\ .C_2H_2).M_{gas}\ X\ 12}{C} \text{ X100} \tag{17}$$

where: CO, CO_2, CH_4 and C_2H_6 (%): are the gas concentrations in produced gas
C (%): The carbon content in the ultimate analysis of biomass (Table 2).

- Gasifier efficiency η_{geff} (%), which has been calculated by flowing equation [6]:

$$\eta_{geff} = \frac{\sum HHV_{gas}}{HHV_{biomass}} \text{ X100} \tag{18}$$

where:
$HHV_{biomass}\ \left(\frac{MJ}{kg_{biomass}}\right)$: High heating value of biomass
$\sum HHV_{gas}\ \left(\frac{MJ}{kg\ biomass}\right)$: High heating value of produced gas

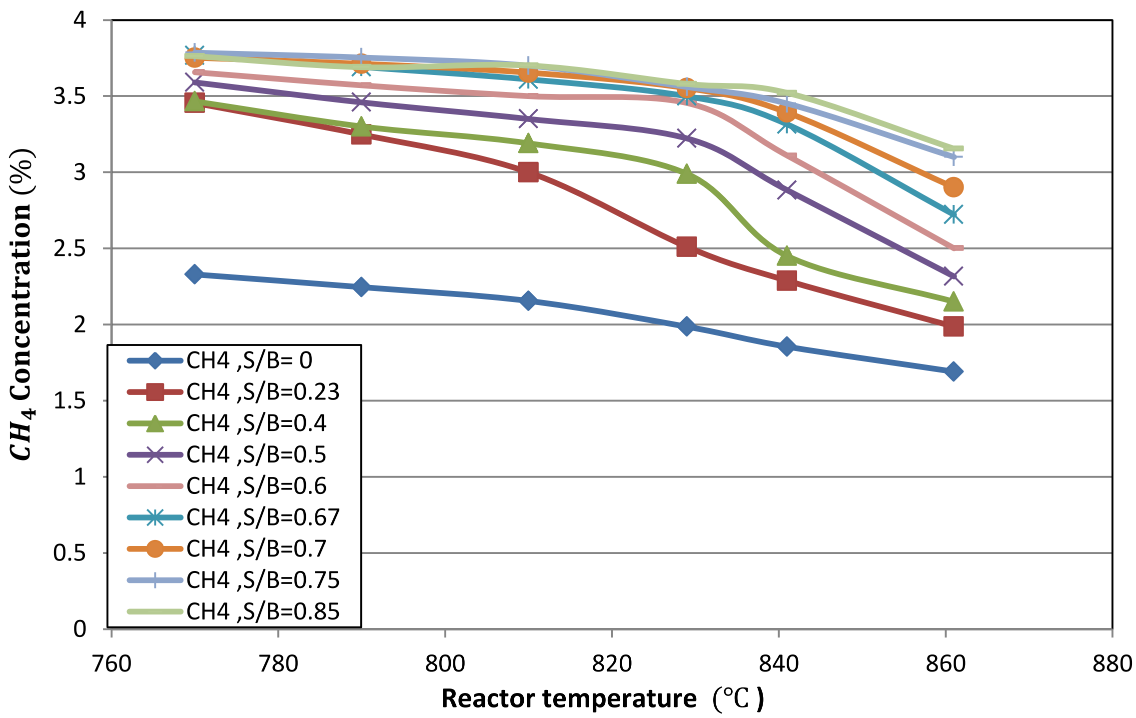

Figure 2. The effect of S/B and T101 on methane content in produced gas

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2014 International Energy & Environment Foundation. All rights reserved.

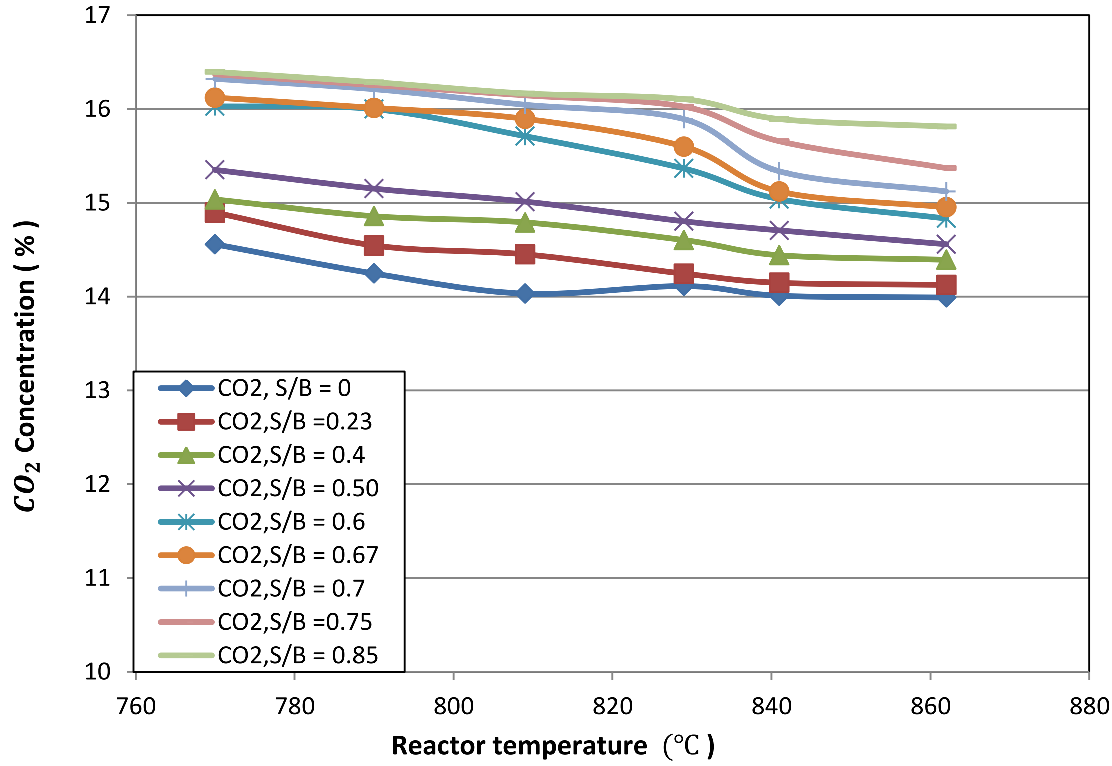

Figure 3. The effect of S/B and T101 on carbon dioxide content in produced gas

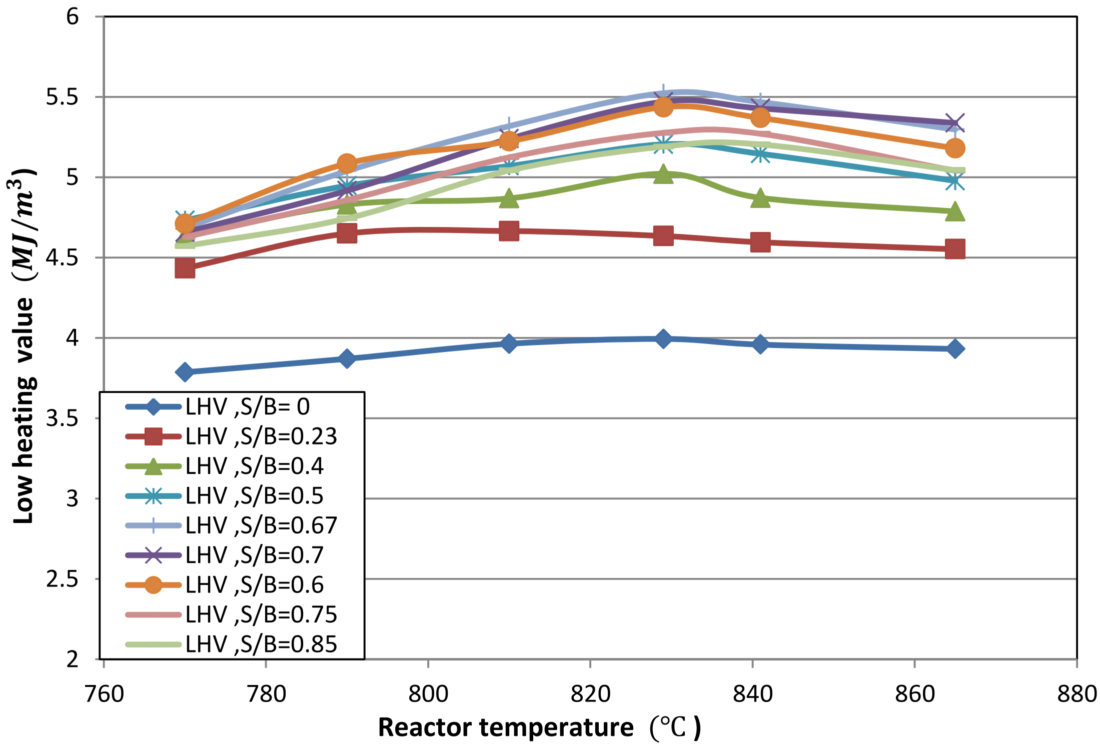

Figure 4. The effect of S/B and T101 on low heating value of produced gas

5.2 The optimal temperature of the steam

The objective of these experiments is to determine the temperature of the feed steam that achieves the best properties of produced gas. It has been depended on the results of experiments that have been carried out previously. These experiments has been done at constant reactor temperature T101= 829 (°C) and different values of the steam temperature Tf1: (180,200,220,240 and 260 °C), which Tf1 is Temperature

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2014 International Energy & Environment Foundation. All rights reserved.

of steam and air mixture. Primary air during the experiment about F1= 20-21$\left(\frac{m^3}{h}\right)$, feed flow rate was about B = 23$\left(\frac{kg}{h}\right)$. Steam to biomass ratio value was 0.68 ($\frac{\text{kg Steam}}{\text{kg Biomass}}$). Equivalence ratio was about 0.29.Samples for mutual comparisons are selected at similar gasification conditions, for every reactor temperature separately.

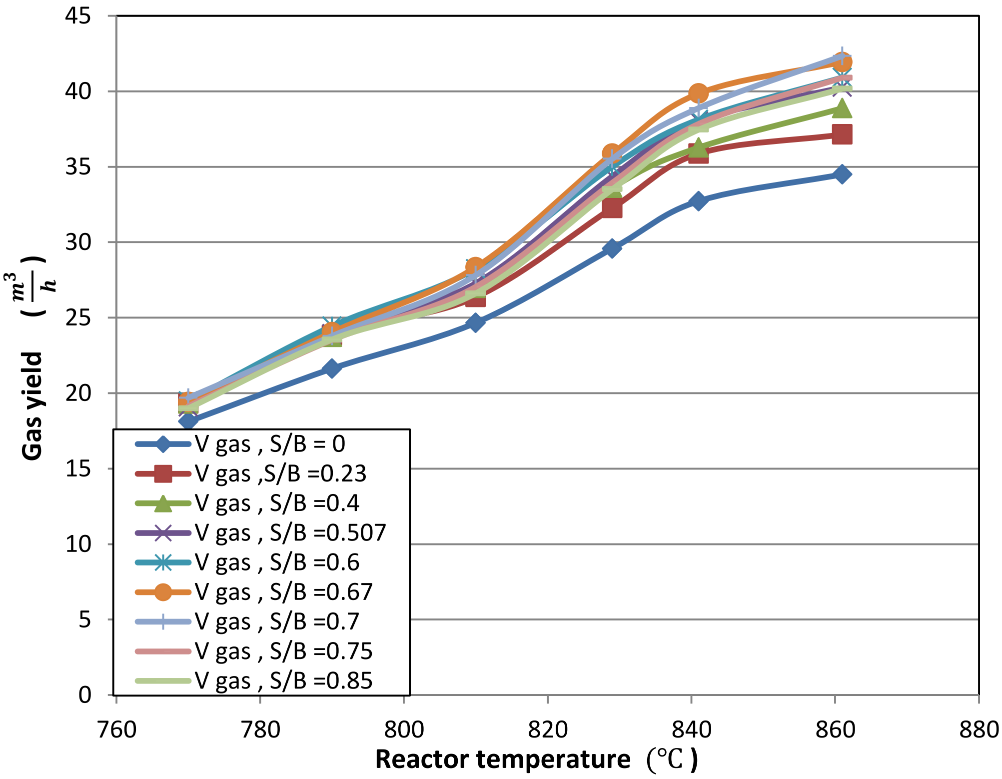

Figure 5. The effect of S/B and T101 on the gas yield

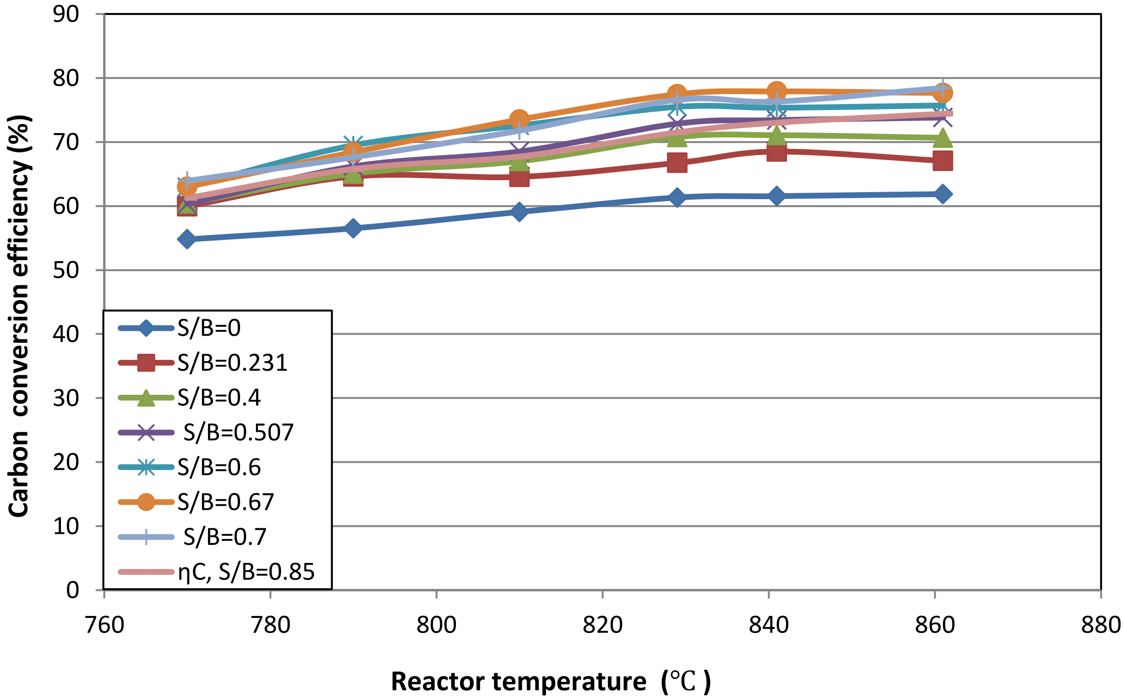

Figure 9. The effect of $\frac{S}{B}$ and T101 on carbon conversion efficiency

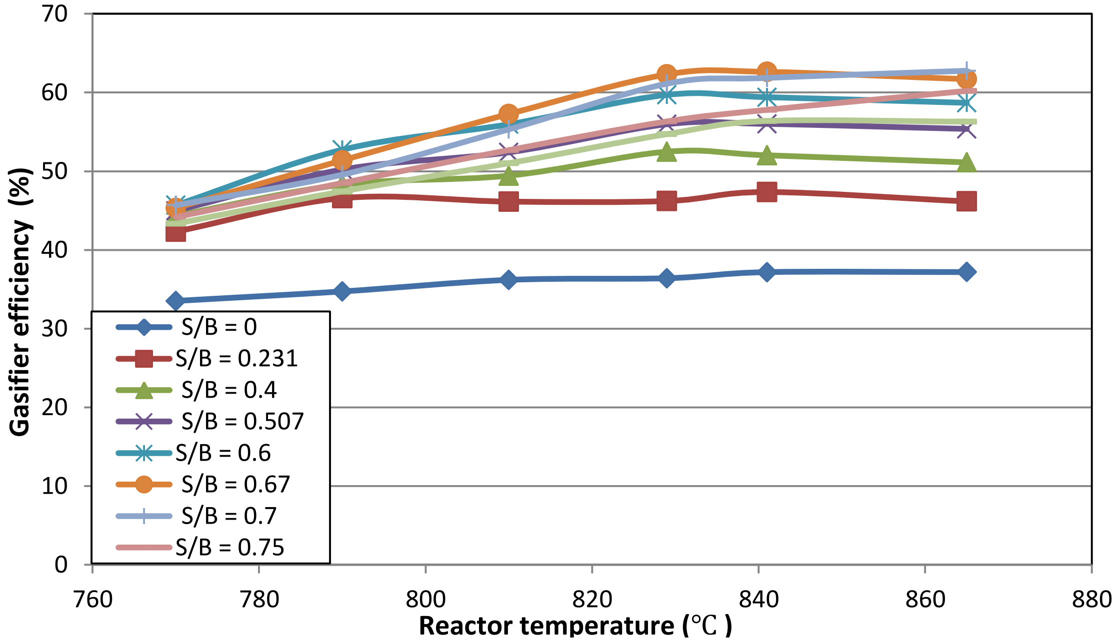

Figure 10. The effect of $\frac{S}{B}$ and T101 on gasifier efficiency

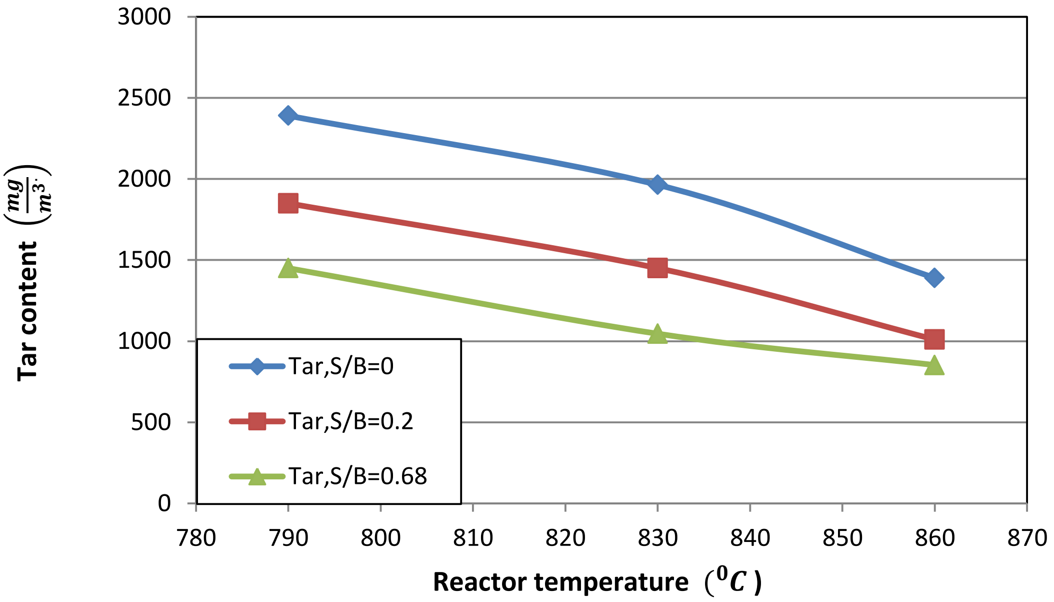

Figure 11. The effect of $\frac{S}{B}$ and T101 on tar content

It has been calculated each of Low heating value, gas yield, Carbon efficiency and gasifier efficiency, as it have been discussed in the previous paragraph for each gas samples.The results of samples analysis were reported in Table 3 and Figures 12 and 13.

5.3 The evaluation of experiments and discuss the results

- From Figures 3 to 11, it can be observed, that the increasing in reactor temperature T101 lead to increase in hydrogen, carbon monoxide, gas yield and carbon conversion efficiency, and decrease in methane and tar content and carbon dioxide. But Low heating value and gasifier efficiency at the first increase with T101, until reach to temperature 829 ℃, they start decreasing by increasing T101. And this due to:
  - By depending on Le Chatelier's principle, higher temperatures improve the reactants in exothermic reactions and improve the products in endothermic reactions [7]. Therefore the

 ©2014 International Energy & Environment Foundation. All rights reserved.

endothermic reactions (19) and (20) will be enhanced with increase of temperature, which leads to increase of hydrogen concentration and decrease of CH_4 concentration.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \; - 206 \text{ KJ} \quad (19)$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 - 165 \text{ KJ} \quad (20)$$

- The Boudouard reaction Equation 6, it can be seen that this reaction will be improved by high temperature, so activity so the carbon dioxide decreasing and carbon monoxide increasing and this lead to enhance gas yield [4].
- The methane formation reaction Equation 7 is improved by low temperature therefore decrease methane by increasing temperature.
- By increasing temperature this due to increasing of combustible gases (CO, H_2), but the heavier hydrocarbons as (tar, ethane, ethane and methane), which have high low heating value have been cracked at high temperature and produce carbon and hydrogen, that conversion to combustible gases and non-combustible gas therefore low heating value decreases at high temperature.

Table 3. The effect of Tf1 on $(LHV, V_{gas}, \eta_C \text{and } \eta_{geff})$

TF1 (°C)	180	200	220	240	260
Gas LHV$\left(\frac{MJ}{m^3}\right)$	5.180	5.23	5.35	5.42	5.52
Gas yield $\left(\frac{m^3}{h}\right)$	34.12	33.894	35.35	35.38	35.00
Carbon conversion efficiency (%)	71.9	73.05	75.66	76.19	77.46
Gasifier efficiency (%)	55.62	56.56	58.9	60.36	62.30
B = 23 $\left(\frac{kg}{h}\right)$; T101= 829 °C; S = 15.6 $\left(\frac{kg}{h}\right)$; $\frac{S}{B}$ = 0.68, ER=0.29,F1= 21.1$\left(\frac{m^3}{h}\right)$					

- From Figures 3 to 11, it can be observed, that the increasing in values of ratio of steam to biomass lead to increases each of hydrogen and methane, carbon dioxide, gas yield, low heating value, conversion efficiency and gasifier efficiency and decreased tar, but to decreases carbon monoxide. However, the excessive increase in the provided steam lead to the reduction of the concentration of hydrogen and thus leads to the lower of the value of each (low heating value, gas yield). The best ratio of steam to biomass, which achieve the best gas quality increases by reactor temperature, it can be calculated by equation (28) for our experimental conditions (Tf1=261 °C and ER =29), it was $\frac{S}{B} = 0.67\left(\frac{\text{kg steam}}{\text{kg biomass}}\right)$ at T101 =829°C and this due to:
  - The water–gas shift reaction, Equation 14, will be more activate with steam and it leads to increase in the ratio of hydrogen and carbon dioxide to carbon monoxide in the gas [5].
  - The water–gas reaction Equation 4 will be more activity reaction by steam [5] so it enhance gas yield.
  - The excessive increase of steam at steam temperature 260 °C (according to our experiments) leads to a reduction reaction temperature, so it leads to decreasing in hydrogen, low heating value and gas yield during the experiment after a certain value of steam to biomass ratio.
- From Figure 11, it can be seen, that tar content decreases by increases T101 and S/B, where tar content decreased from 2390 to 1390 $\left(\frac{mg}{m^3}\right)$ by increased temperature from 770 to 861°C when used only air, but tar content decreased from 1450 to 853 $\left(\frac{mg}{m^3}\right)$ by using steam and air mixture at $S/B = 0.67\left(\frac{kg_{steam}}{kg_{biomass}}\right)$ in the same range of increasing temperature. And this due to:
  - Steam converts high molecular weight hydrocarbons of tar into smaller gas products including H_2, CH_4, CO and CO_2 [8].Also cracking of the heavier hydrocarbons as (tar, ethane, ethane and

 ©2014 International Energy & Environment Foundation. All rights reserved.

methane) will be done by high temperature and produce carbon and hydrogen, part of carbon converts to carbon monoxide [5]. Therefore Tar content will be decreased by increasing each of reactor temperature T101 and steam to biomass ratio S/B.

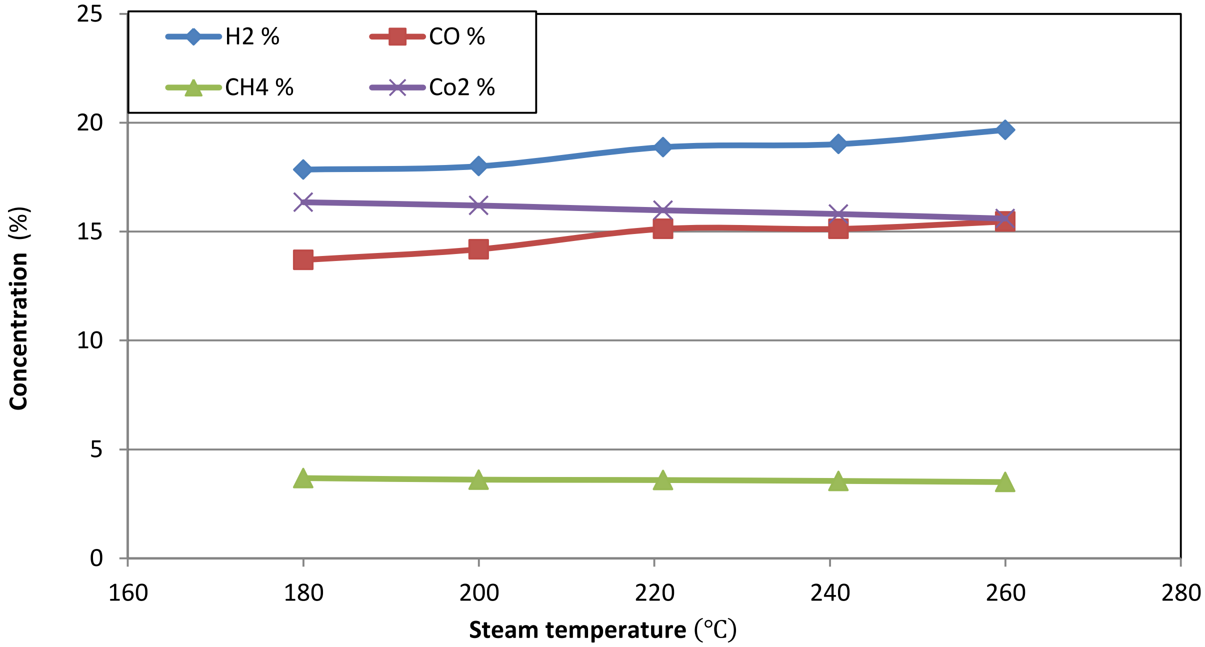

Figure 12. The effect of Tf1 on the basic components of the produced gas at $\left(\frac{S}{B} = 0.68, T101 = 830\ ℃, ER = 0.29\right)$

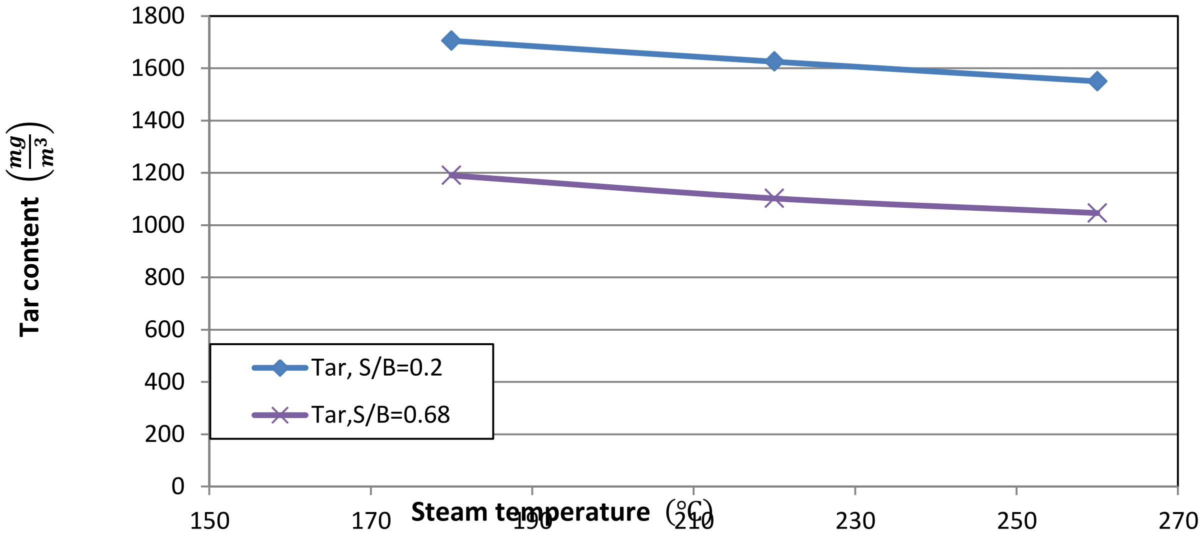

Figure 13. The effect of Tf1 on tar content

- Figure 12 and Table 3 show, that the effect of steam temperature Tf1 on the quality of gas. Steam temperature is important for the biomass gasification process.The increasing in temperature Tf1, which is the temperature of a mixture of steam and air at the inlet of the reactor, enhances the reaction temperature and thus improves the production of endothermic reactions according to Le Chatelier's principle. Therefore the Equations 19 and 20, the water-gas reaction Equation 4, Boudouard reaction Equation 6, were improved with rising temperature of steam but the methane formation reaction equation 7 was favored by low temperature. This explains, that the increase in concentration of hydrogen and carbon monoxide in produced gas by increasing steam temperature,

 ©2014 International Energy & Environment Foundation. All rights reserved.

while the concentration of methane and carbon dioxide decrease with rising steam temperature Figure 12, also increase each of low heating value, gas yield, carbon conversion efficiency and gasifier efficiency with steam temperature, as it is clear in Table 3. From Figure 13 show that tar content decreases with increasing Tf1. By depending on results discussion, it can be seen, that the best value of steam temperature is the higher value, it can be.

6. Conclusion

From the results of the experiments and discussion, it has found, that by using of the mixture of steam and air, the gas quality will be improved, and the parameters, which achieved the best quality of produced gas at the experimental conditions ($\mathbf{ER = 0.29.}$).are $\boldsymbol{T101 = 830}$℃, $\mathbf{S/B = 0.68}$ and $Tf1$., is the higher value, where $\boldsymbol{H_2}$ increased from 10.3 to 19.67 %, $\boldsymbol{CH_4}$ from 2 to 3.5 %, $\boldsymbol{LHV}$ from 3.9 to 5.55 $\left(\frac{\boldsymbol{MJ}}{\boldsymbol{m^3}}\right)$ and tar content decreased from 1970 to 1050 $\left(\frac{\boldsymbol{mg}}{\boldsymbol{m^3}}\right)$ by using only air and by using mixture of steam and air at the best conditions respectively.

References

[1] DEMIRBAS, Ayse Hilal a Imren DEMIRBAS. Importance of rural bioenergy for developing countries. Energy Conversion and Management. 2007, roč. 48, č. 8, s. 2386-2398. ISSN 01968904.DOI:10.1016/j.enconman.2007.03.005.Dostupnéz: http://linkinghub.elsevier.com/retrieve/pii/S0196890407000763.

[2] BASU, Prabir. Combustion and gasification in fluidized beds. Boca Raton: CRC, 2006, 473 s. ISBN 08-493-3396-2.

[3] GEK PROJECT. Gasifier Experimenters Kit: pushing wood gas beyond the Imbert [online]. [Cit. 2012-09-02]. Available from http://gekgasifier.com/.

[4] ARENA, Umberto. Process and technological aspects of municipal solid waste gasification. A review. Elsevier: Waste Management. roč. 35, č. 4, 625-639.

[5] GIL, Javier, Jose CORELLA, María P AZNAR a Miguel A CABALLERO. Biomass gasification in atmospheric and bubbling fluidized bed: effect of the type of gasifying agent on the product distribution. Elsevier: Biomass and Bioenergy. 2009, roč. 17, s. 389-403.

[6] Handbook biomass gasification. Enschede: BTG Biomass Technology Group, 2005, xxii, 378 s. ISBN 90-810-0681-9.

[7] LV, Z.H XIONG, J CHANG, WU, Y CHEN a J.X ZHU. An experimental study on biomass air-steam gasification in a fluidized bed. Bioresource Technology. 2004, roč. 95, č. 101, 95–101.

[8] Sadaka, S.S., Ghaly, A.E., Sabbah, M.A., 2002a. Two phase biomass air–steam gasification model for fluidized bed reactors. Part I: model development. Biomass Bioenergy 22, 439-462.

[9] Test report n.861/05-698/Ves laboratory RWUV Praha, spol.sr.o Laboratories and test Olomoucka 7/9 656 66 Brno 30.11.2005.

Najdat Salami, PhD student in Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, Brno, Czech Republic. He graduated from Energy Department, Faculty of mechanical Engineering, Al-Baath University, Homs, Syria in 2000 and he had M.Sc. degrees in renewable energy, Energy Department, Al-Baath University, Homs, Syria 2008. He worked as assistant teacher in Mechanical Energy Department, faculty of mechanical and Electrical Engineering, Al Baath University, Homs, Syria in 2000.
E-mail address: y127450@fme.vutbr.cz

Zdeněk Skála, Head of Institute of Energy, Faculty of Mechanical Engineering, Brno University of Technology, Brno, Czech Republic. He had Master degree, Faculty of Mechanical Engineering, Brno University of technology, subject field-Power Engineering 1961. He had PhD degree, Faculty of Mechanical Engineering, Brno University of Technology, subject field - Power Engineering 1976 and in year1979, habilitation, Faculty of Mechanical Engineering, Brno University of Technology, subject field - Power Engineering. He worked as associate professor from 1965, Institute of Energy.
E-mail address: skala@fme.vutbr.cz

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2014 International Energy & Environment Foundation. All rights reserved.