BRNO UNIVERSITY OF TECHNOLOGY

Faculty of Mechanical Engineering

Energy Institute

Department of Power Engineering

GASIFICATION OF PINE WOOD CHIPS WITH AIR-STEAM IN FLUIDIZED BED

(Summary of doctoral thesis)

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Opponents :

Brno 2014

Keywords

Steam, air, gasification, biomass, fluidized bed , tar, steam to biomass ratio, equivalence ratio.

Klíčová slova

Para , vzduchu, zplynování, biomasa, fluidní lože, dehet, , poměru páry a biomasy, ekvivalentního poměru

Place of work:

Brno University of Technology, Department of Power Engineering, Faculty of Mechanical Engineering, Energy Institute

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Introduction

Biomass energy is the oldest energy source used by humans. Biomass has evolved as one of the most promising sources of energy for the future. This has spurred the growth of research and development efforts. Because of lower fossil fuels and increase need of energy security, environmental concerns and promotion of socio economic benefits to rural areas, and there is important fact that Biomass somewhat uniformly distributed nature worldwide which means it is available locally and is helpful in reducing the dependence upon the fossil fuel. Biomass is a desirable feedstock for producing transportation fuels as its use contributes little or no net carbon dioxide to the atmosphere. Renewable biomass resources are short-rotation woody crops, herbaceous biomass, and agricultural residues. Biomass is available for using for conversion to the biofuels as well as for power generation applications[5]. There are various conversion technologies that can convert biomass resources into power, heat, and fuels for its use in UEMOA countries. The most used of this conversion are thermal conversions, bio-chemical and chemical conversions and direct combustion. The thermal conversion processes consist of fast and slow pyrolysis and biomass gasification, the bio-chemical conversion is fermentation and anaerobic digestion; chemical conversions are trans-esterification and other processes to convert plant and vegetable oils to biodiesel, and direct combustion of wood and other biomass is being used for a very long. Thermal processing of biomass has the potential to offer a major contribution to provide the increasing demands of the bio-energy and renewable energy sectors and to meet the targets for CO_2 mitigation [2].

Biomass gasification is one of the most promising routes for syngas or combined heat and power production because of the higher efficiency cycles. The gasification and combustion processes convert carbonaceous material to gases. Gasification processes operate in the without oxygen or with a limited amount of oxygen, but combustion processes operate with excess oxygen [5].

Gasification is using of heat, pressure, and steam to convert solid biomass or other carbonaceous solids into gas (flammable fuel), this gas consist of primarily of carbon monoxide and hydrogen [12]. Through gasification, we can convert nearly any dry organic matter into a clean burning, carbon neutral fuel that can replace fossil fuel in most use cases. Whether wood chips or walnut shells, construction debris or agricultural waste, gasification will convert waste into a flexible gaseous fuel which can be used to run internal combustion engine, cooking stove, flamethrower [1].

1. Summary and Objectives of this Study

The main point of my full work will be focused on:

1. carrying out experiments of gasification of pine wood chips obtained from a local timber mill as the feedstock [48] at fluidized bed gasifier called Biofluid100 that exist in lab of the Institute of Power Engineering, Brno University of Technology, by using air as agent of gasifier taking into account its flow and temperature of the reactor and steam- air as agent of gasifier taking into account ratio of steam to air and steam temperature at different value of temperatures and flows , and compare between the properties of the gas produced by both of the two methods (hydrogen content - Lower heating value (LHV) - formed Tar content)and study whether use of air-steam as agent gasification in fluidized bed gasifier will improve the gas quality for our feedstock or not, and define the suitable ratio of air to steam and feed steam temperature for the best properties of the product gas , or suggestion of another feedstock to study.

2. The study of effects of steam to biomass ratio $\frac{S}{B}$, equivalence ratio (ER) and air/steam ratio to gas composition, gas yield, tar content, low heating value (LHV) and carbon conversion efficiency.

3. Proper utilization of biomass through gasification can increases the energy security and creates opportunities in the renewable energy sector.
4. Dissemination of the results of these studies and research in scientific journals and interested research sites.

Previously in our laboratory was carried out a number of experiments which aimed to gasification of thermal fluidized of wood biomass by using air as gasification agent and was involved in the measurement. Measurements should be carried out methodically on a similar basis and measured data are available for comparing the performance characteristics for different gasification agents (air, air-steam).

2. Chemical Reactions in the Gasification Process

Table 1 include the reactions that take place in a gasifier during the gasification process

Table 1 : Chemical Reactions in 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

Note.: The above values of the reaction heat ΔH_r^0 are determined at standard conditions (T_0 = 298.15 [K]; P_0= 101,325 [kPa]) and for endothermic reactions are positive, negative for exothermic reactions

3. Description of the experimental apparatus and equipment

3.1 Experimental unit Biofluid 100

Research has been done at the Institute of Power Engineering, Brno University of Technology, Brno, into fluidized bed gasification of biomass and separated municipal waste. Experiments are carried out at fluidized bed atmospheric gasifier with stationary fluidized bed called Biofluid 100[22].

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 and heat 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

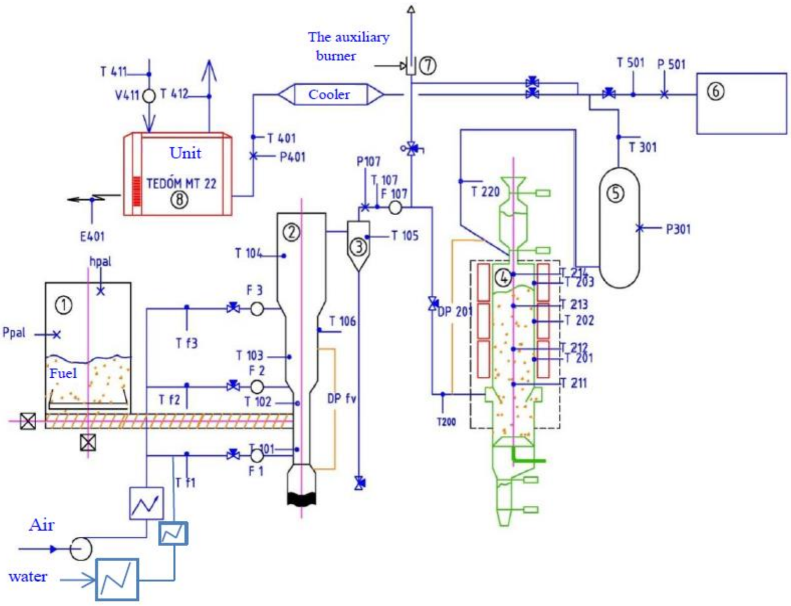

Figure 2 : Simplified layout of the gasifier connections

3.2 Analysis of Samples

Analysis of the sample gas and tar compounds had been carried by gas chromatography. The analysis of samples, especially tar sample was taken relatively long time. Analysis of the samples tar were conducted in the Institute of Chemical Technology, Prague (ICT), and gas samples analyses were conducted in Mechanical Engineering Faculty in the Technical University in Brno (BUT). Especially the tar samples were needed long time for analysing due to capacity of laboratory so it had been waiting for several months.

4. Evaluation of the Composition of Product Gas

This chapter summarizes the results of analysis of samples of the gas mixture and tar content, which had been taken during experiment. A series of experiments have been done in fluidized bed gasifier called Biofluid 100, to choose the best parameters of: reactor temperature T101, steam to biomass ratio $\frac{S}{B}$, temperature of steam TF1 , equivalence ratio ER and steam to air ratio which achieved the best quality of produced gas . Gas and tar samples have been taken during the experiment in different condition according to the aim of this work.

4.1 The Determine of Optimal Reactor Temperature T101 and the Optimal Steam to Biomass Ratio

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 rate avaried from 14 to 24 $\left(\frac{kg}{h}\right)$ and biomass flow rate also avaried from 15 to 26 $\left(\frac{kg}{h}\right)$. Samples for mutual comparison are selected at similar gasification conditions, for every reactor temperature separately. Table 6 shows the results of gas samples analysis at reactor temperature T101 = 829(°C), the same samples has been taken for temperatures 770, 790,810,841 and 861C at same values of steam to biomass ratios approximately.

The results of this testes were reported in figures 3 to 11.

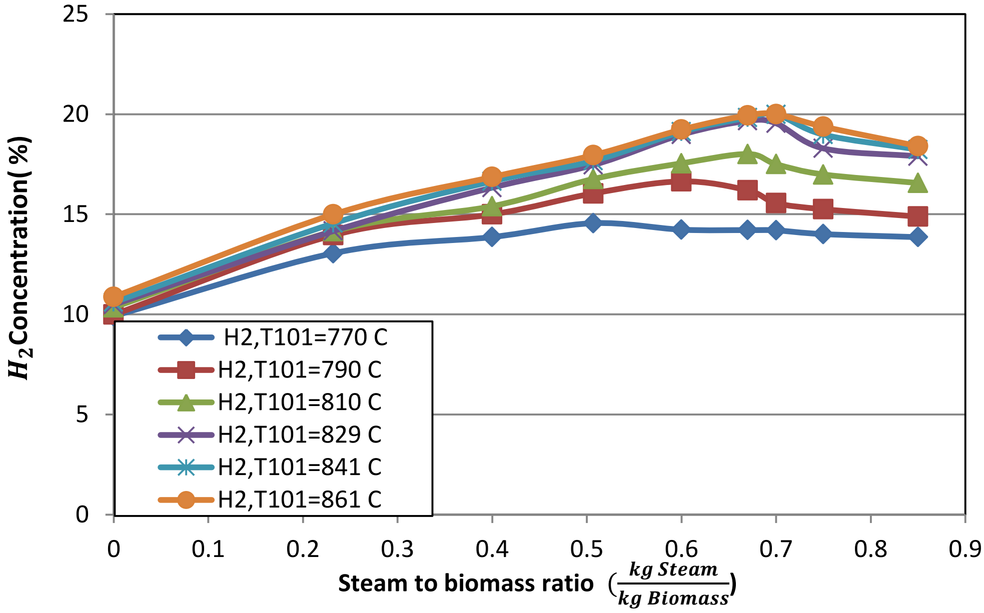

Figure 3 : The effect of $\frac{S}{B}$ and T101 on hydrogen content in produced gas

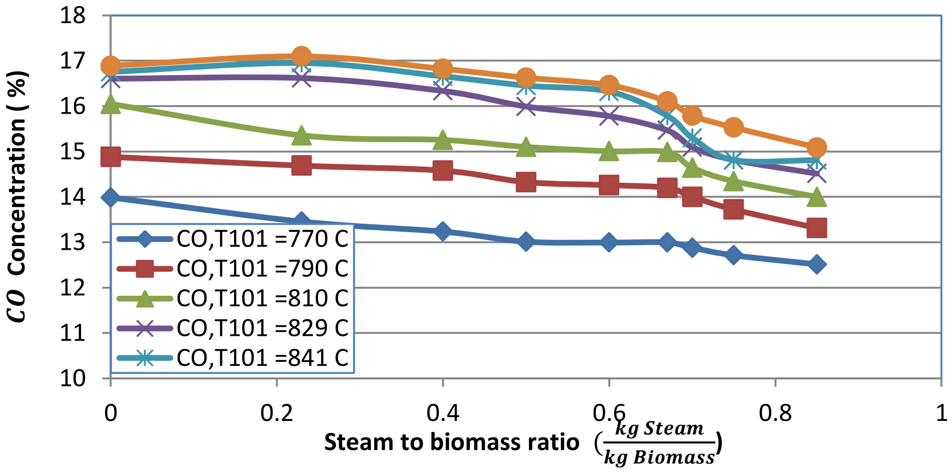

Figure 4 : The effect of $\frac{S}{B}$ and T101 on Carbon monoxide content in produced gas

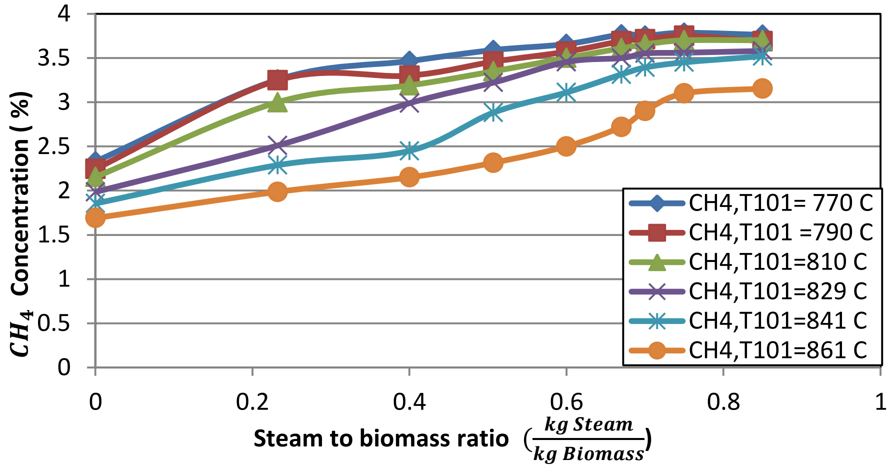

Figure 5: The effect of $\frac{S}{B}$ and T101 on methane content in produced gas

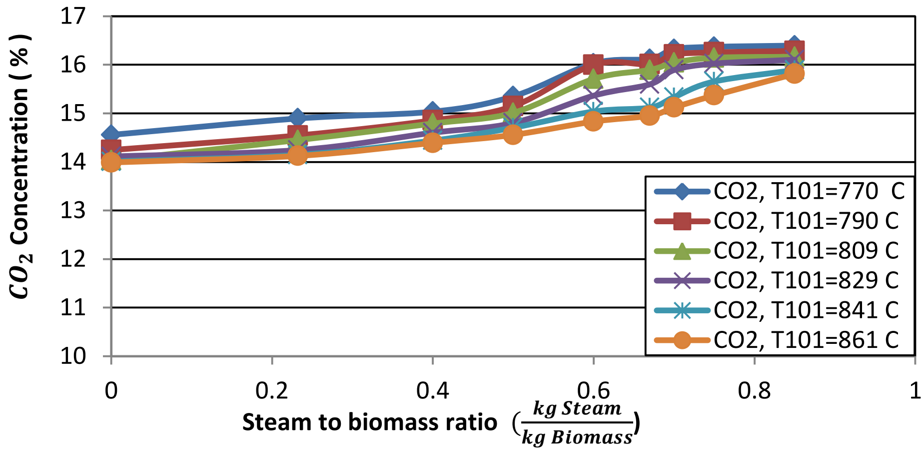

Figure 6 :The effect of $\frac{S}{B}$ and T101 on carbon dioxide content in produced gas

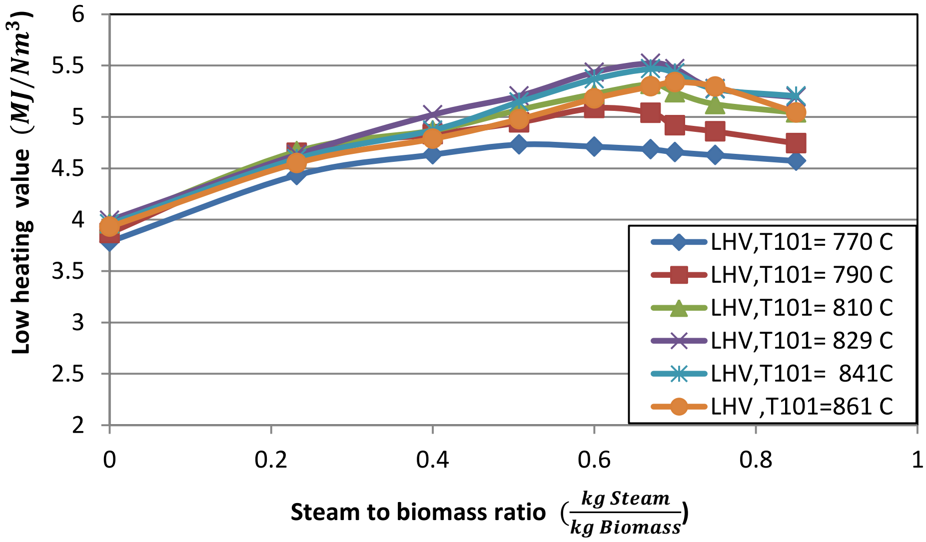

Figure 7 : The effect of $\frac{S}{B}$ and T101 on low heating value of produced gas

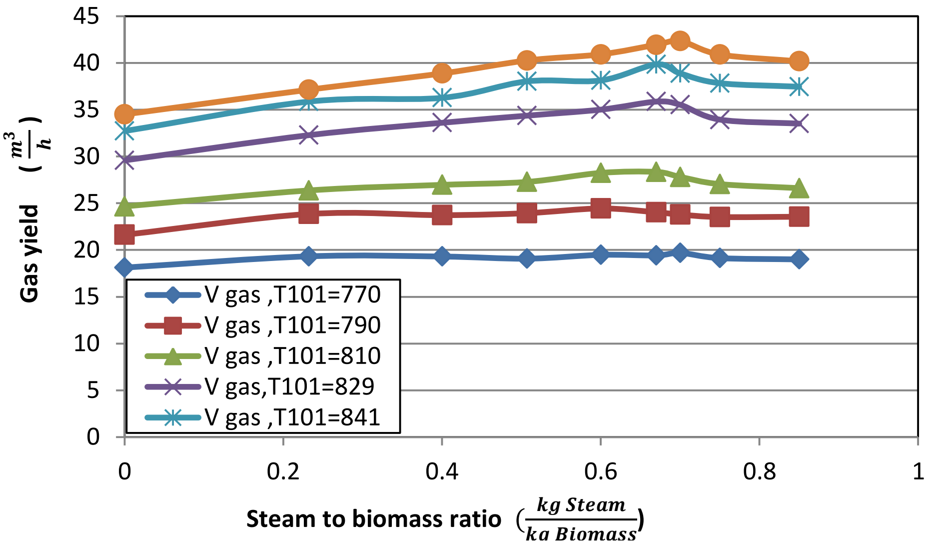

Figure 8: The effect of $\frac{S}{B}$ and T101 on the gas yield

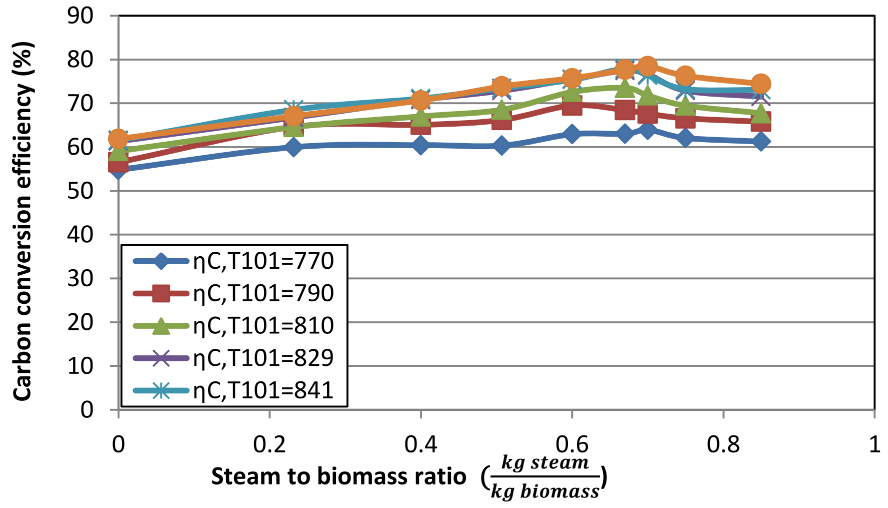

Figure 9 : The effect of $\frac{S}{B}$ and T101 on carbon conversion efficiency

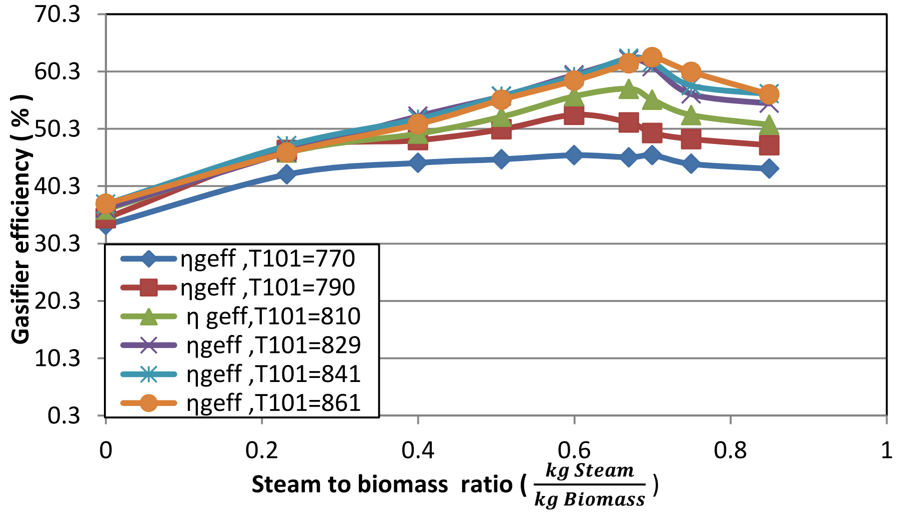

Figure 10: The effect of $\frac{S}{B}$ and T101 on gasifier efficiency

4.2 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 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 changed from 0 to 0.85 ($\frac{kg\ Steam}{kg\ Biomass}$). Equivalence ratio was about 0.29.Samples for mutual comparison are selected at similar gasification conditions, for every reactor temperature separately.

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 thesis, but here the results are reported for best value of steam to biomass ratio; $\frac{S}{B}$ = 0.68 in Table 3 and Figure 11 .

Table 2: the effect of Tf1 on $\left(LHV, V_{gas}, \eta_C and\ \eta_{geff}\right)$

$TF1$ (°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$\left(\frac{m^3}{h}\right)$					

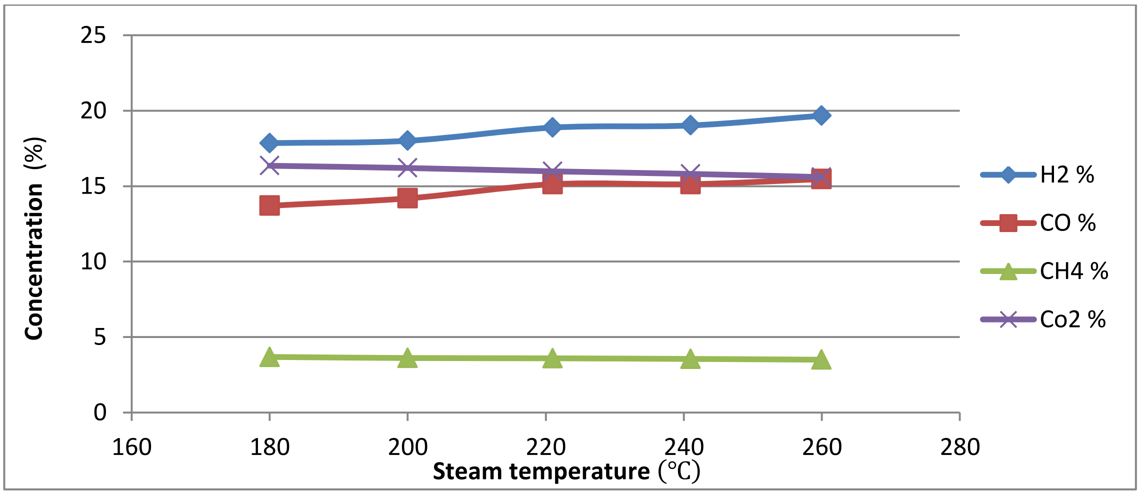

Figure 11 : the effect of $Tf1$ on the basic components of the produced gas gas at $\left(\frac{S}{B} = 0.68, T101 = 830\ ℃, ER = 0.29\right)$

4.3 Optimal of Equivalence Ratio (ER)

Equivalence ratio (ER) has been varied from 0.26 to 0.33 through changing the air flow rate from 18-24 $\left(\frac{m^3}{h}\right)$. Changing of the steam flow rate was from 0-20 $\left(\frac{kg}{h}\right)$ by holding the other conditions (reactor temperature T101=829 (°C),biomass flow rate B=23 $\left(\frac{kg}{h}\right)$,steam temperature Tf1=260 (°C)).

The experiments has been done for three values of equivalence ratio (0.26,0.29 and 0.32)on three stage , the values of equivalence ratio have been selected depending on the previous studies[49], in each stage has been tested constant value of equivalence ratio at a gradual increase in the values of the ratio of steam to biomass from (0 to 0.85) . The results of samples analysis were reported in thesis, but here the results are reported for best value of steam to biomass ratio; $\frac{S}{B}$ = 0.68 in Table 4 and Figure 13.

Table 3: the effect of ER on on $\left(LHV, V_{gas}, \eta_C and\ \eta_{geff}\right)$

Air $\left(\frac{m^3}{h}\right)$	18.5	21.1	23.7
ER	0.26	0.29	0.32
Gas LHV$\left(\frac{MJ}{m^3}\right)$	5.100	5.52	4.96
Gas yield $\left(\frac{m^3}{h}\right)$	30.97	35.86	39.55
Carbon conversion efficiency (%)	64.54	77.46	75.43
Gasifier efficiency (%)	50.23	62.30	62.82
B = 23 $\left(\frac{kg}{h}\right)$; T101= 829 °C; S = 15.6 kg/h; $\frac{S}{B}$=0.68			

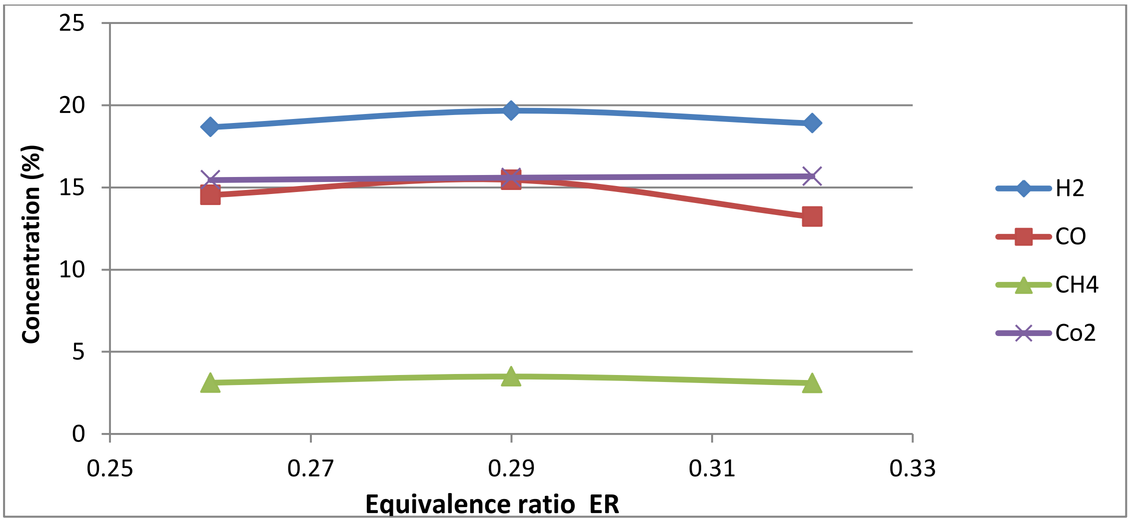

Figure 12: the effect of ER on the basic components of the produced gas at $\left(\frac{S}{B} = 0.68,\ T101 = 830\ ℃, Tf1 = 261\ ℃\right)$

4.4 Optimal of Steam to Air Ratio

To determine the best of the steam to air ratio, it has been depended on results of the experiments that has been explained in paragraph 15.1, Steam to air ratio was varied from 0 to 0.75 through changing the steam flow rate from 0-20 $\left(\frac{kg}{h}\right)$ by holding the other conditions (reactor temperatureT101=829(℃),biomass flow rate B=23 $\left(\frac{kg}{h}\right)$,steam temperature Tf1=260 (℃) and air flow rate F1 = 20 (m^3/h)).

The values of the ratio of steam to biomass has been increased from (0 to 0.85) . The results of samples analysis have been reported by: Figure 13 shows produced gas composition, Figure 14 shows Low heating value of gas , Figure 15 shows gas yield rate and figure 16 shows gasifier efficiency and carbon efficiency.

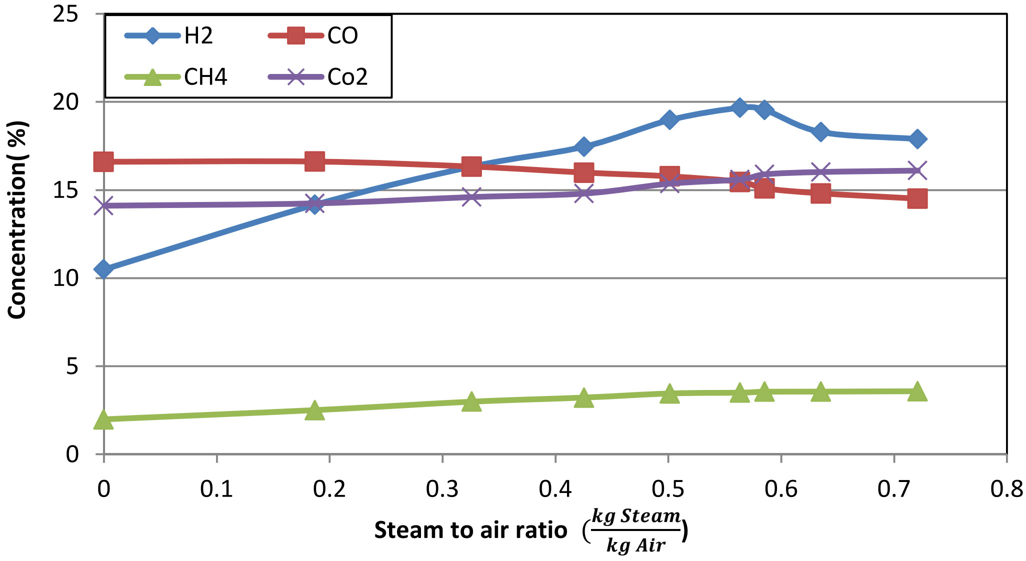

Figure 13 : The effect of $\frac{S}{A}$ on gas composition

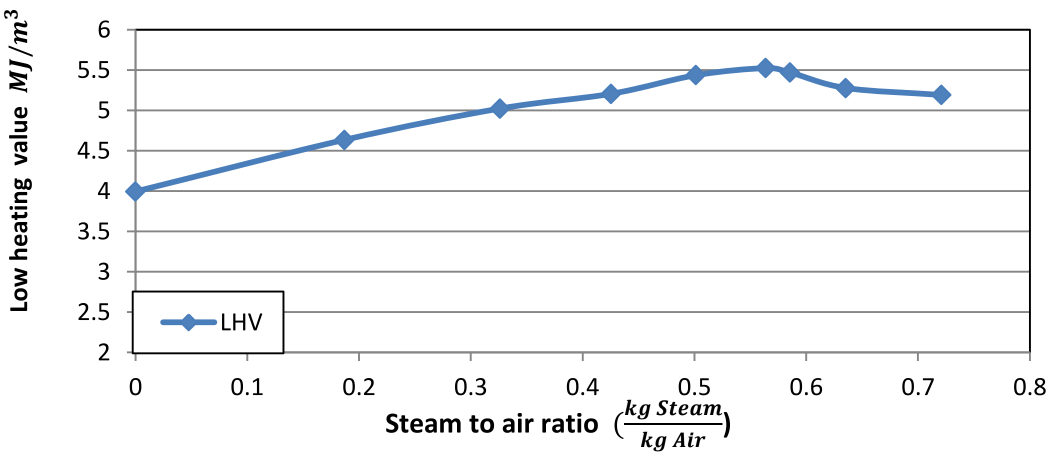

Figure 14 : The effect of $\frac{S}{A}$ on low heating value

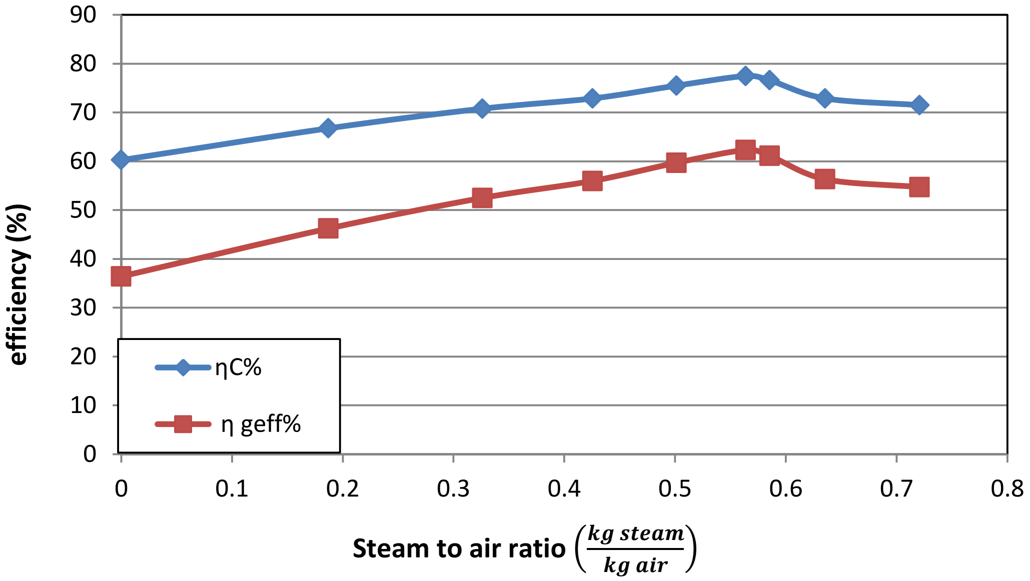

Figure 15 : : The effect of $\frac{S}{A}$ on carbon conversion efficiency and gasifier efficiency

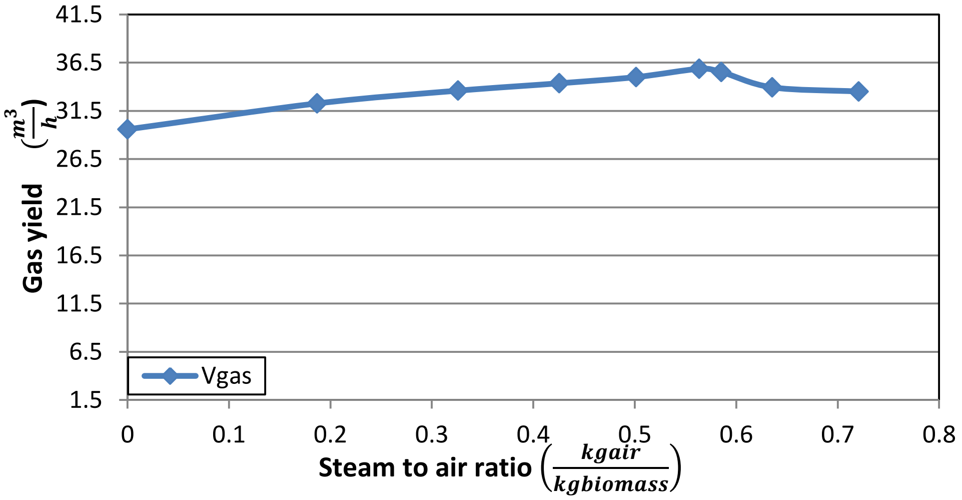

Figure 16 : The effect of $\frac{S}{A}$ on gas yield

4.5 Evaluation of Tar Samples

The tar content of the product gases is depended on different factors like reactor temperature and steam to fuel ratio and steam temperature. Tar sampling has been done for each series of experiments according to the tar protocol.

During the experiments, tar content in produced gas have been measured at different parameters, where tar sampling has been done at different reactor temperature T101 , different value of steam to biomass ratio and different steam temperature. Analysis of the samples tar have been conducted in The Institute of Chemical Technology, Prague (ICT). The impact each of: T101 .$\frac{S}{B}$ and Tf1 on the tar content of the gas produced are shown in figures 17 and 18.

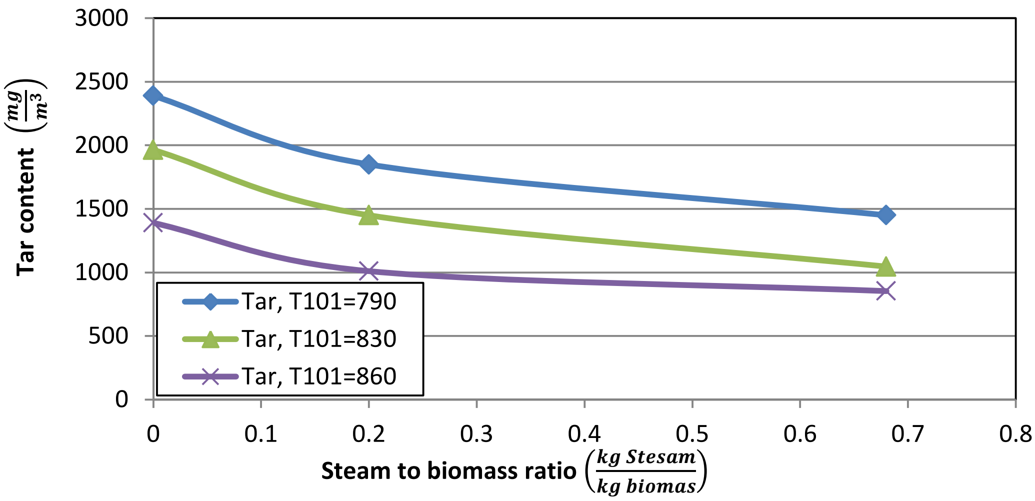

Figure 17 : The effect of $\frac{S}{B}$ and T101 on tar content

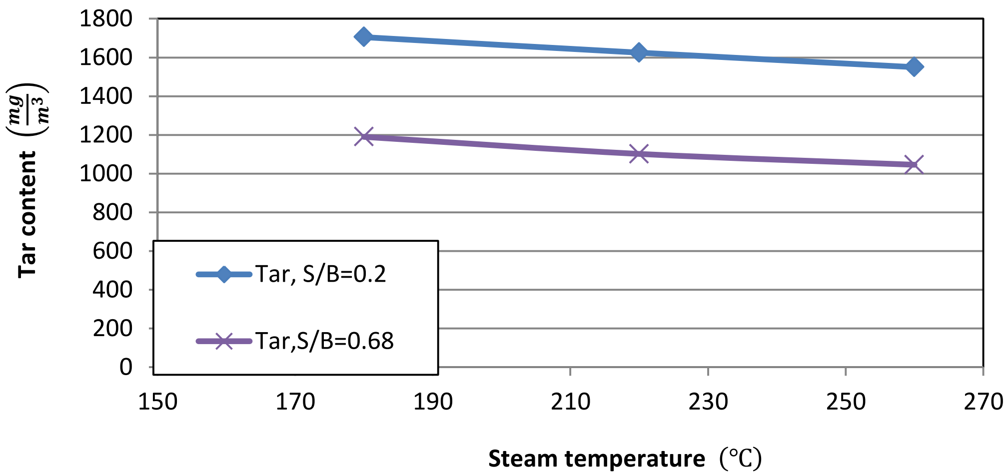

Figure 18 : The effect of $Tf1$ on tar content

4.6 The Evaluation of Experiments and Discuss the Results

4.6.1 The Effect of Reactor Temperature T101

Figures 3 to 11, shows, that the effect of reactor temperature on the gas quality. Reactor temperature is one effective parameters on biomass gasification process. In the present work, reactor temperature was varied from 780 to 861 (℃) in 20 (℃) increments, temperature of steam was$Tf1 = 260$ ℃.

- The effect of reactor temperature T101 on hydrogen content in produced gas :

Figure 3 shows, that the effect of reactor temperature on hydrogen content, it can be seen that hydrogen content of the produced gas increases with increasing of reactor temperature, where hydrogen concentration have been increased to about 20 % , This is 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 endothermic reactions (15) and (16) will be enhanced with increase of temperature which leads to increase of hydrogen concentration.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \ - 206\ KJ \ldots\ldots\ldots 15$$
$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 - 165\ KJ \ldots\ldots 16$$

- The water–gas reaction Equation 4 will be more activity reaction by high temperature [5]. But this equation produces hydrogen and carbon monoxide at the same molar rate, they have the same molar concentration at balance state [5].

- Cracking of the heavier hydrocarbons as (tar, ethane, ethane and methane),by high temperature and produce elemental hydrogen [19].

- The effect of reactor temperature T101 on carbon monoxide content in produced gas :

Figures 4 shows, that the effect of reactor temperature on carbon monoxide content, it can be observed that carbon monoxide content of the produced gas, increases with increases of reactor temperature, where carbon monoxide concentration have been increased to about 17 % due to :

- The Boudouard reaction Equation 6, it can be seen that this reaction will be improved by high temperature, so high temperature enhances carbon monoxide formation [5].
- The water–gas reaction Equation 4, will be more activity by high temperature , as mentioned previously .
- Cracking of the heavier hydrocarbons as (tar, ethane, ethane and methane) at high temperature and produce carbon and hydrogen, where part of carbon converts carbon monoxide [19].
- As mentioned previously, that Equation 15 which will be improved by increasing temperature and that leads to increase in carbon monoxide content.

- The effect of reactor temperature T101 on methane content in produced gas :

Figure 5 shows, that the effect of reactor temperature on methane content, it can be seen, that methane content of the product gas decreases with increasing reactor temperature, this is due to:

- The methane formation reaction Equation 7, is improved by low temperature therefore decrease methane by increasing temperature [5].
- Cracking of the methane at high temperature [15].
- Equation 15 and 16 will be more activity by increasing temperature according to Le Chatelier's principle.

- The effect of reactor temperature T101 on carbon dioxide content in produced gas :

  Figure 6 shows, that the effect of reactor temperature on carbon dioxide content, it can be seen that carbon dioxide content of the product gas decreases with increasing of reactor temperature, this due to :

  - By high temperature the Boudouard reaction Equation 6, will be more activity so the carbon dioxide decreasing and carbon monoxide increasing [5].

- The effect of reactor temperature T101 on Low heating value of gas produced :

  Figure 7 shows, that the effect of reactor temperature on low heating value of produced gas ,it can be seen that low heating value increases with increasing reactor temperature till reaches maximum value then decreases with 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 heating value are 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.

- The effect of reactor temperature T101 on carbon conversion efficiency η_c :

  Figures 9 shows, that the effect of reactor temperature on carbon conversion efficiency ,it can be seen, that carbon conversion efficiency increases with increasing reactor temperature and because of, by high temperature the Boudouard reaction Equation 6 and the water–gas reaction Equation 4, will be more activity therefore conversion of carbon increases with high temperature .

- The effect of reactor temperature T101 on gasifier efficiency η_{geff} :
  Figure 10 shows, that the effect of reactor temperature on gasifier efficiency η_{geff} ,it can be seen that gasifier efficiency increases with increasing reactor temperature in the beginning till reaches maximum value then decreases by increasing temperature this because, that from Equitation 25 the gasifier efficiency η_{geff} depend on high heating value of combustible gases (CO, H_2, C_xH_y) by increasing temperature increases combustible gases (CO, H_2) , but the heavier hydrocarbons as (tar, ethane, ethane and methane), which have high heating value are cracked at high temperature and produce carbon and hydrogen, that conversion to combustible gases and non-combustible gas therefore gasifier efficiency η_{geff} decreases at high temperature.
- The effect of reactor temperature T101 on gas yield :
  Figure 8 shows, that the effect of reactor temperature on gas yield ,it can be seen that gas yield increases with increases reactor temperature this due to that ,the carbon conversion efficiency increases with increasing temperature reactor.

By depending on the results of the experiment and discussing, the best temperature of the reactor T101, which achieve best low heating value and best gas composition is 830 ℃ ,where $H_2 = 19.7\ \%$, $CO = 16.8\ \%$ and $LHV = 5.53\ \left(\frac{MJ}{m^3}\right)$.

4.6.2 The Effect of Steam to Biomass Ratio

Figures 3 to 10 show, that the effect of steam to biomass ratio $\frac{S}{B}$ on the quality of gas. In these tests, steam flow rate was varied from 0 to 20 $\left(\frac{kg}{h}\right)$,also steam to biomass ratio varied from 0 to 0.85 $\left(\frac{kg_{steam}}{kg_{biomass}}\right)$

- The effect of steam to biomass ratio $\frac{S}{B}$ on hydrogen content in produced gas :
  From Figure 3, it can be seen that the concentration of hydrogen, significantly increases by the increasing of steam to biomass ratio until it reaches to the highest value ,then begins to decrease gradually, this highest value called the best steam to biomass ratio which achieved the maximum of hydrogen concentration in produced gas, it can be seen from figure 3, that best steam to biomass ratio increases by reactor temperature T101 , it can be represented by the figure 24 .

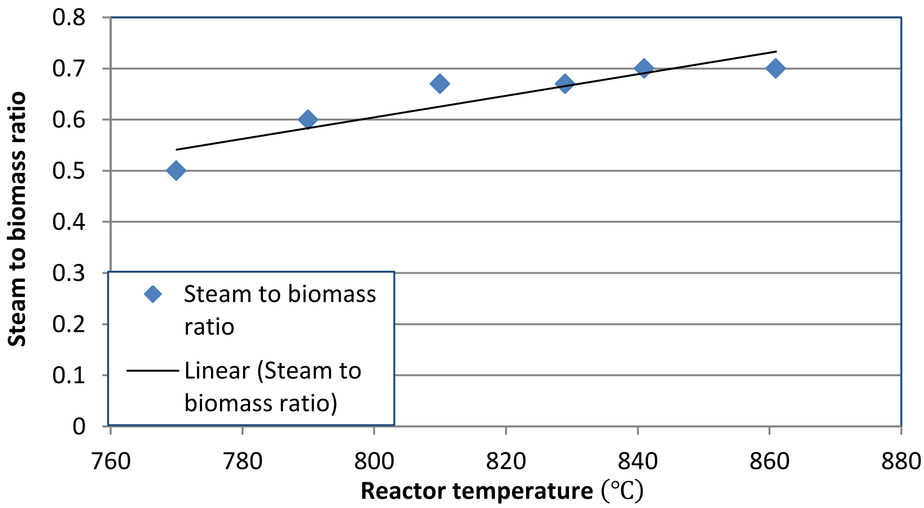

Figure 19: The effect of T101 on the best of steam to biomass ratio $\frac{S}{B}$

From the Figure 18, it can see that the relationship between the best ratio of steam to biomass $\frac{S}{B}$ and the temperature of the reactor T101 is given by this approximate equation:

$$\frac{S}{B} = 0.0025T101 - 1.4 \quad ......17$$

From Equation 17 , it can be calculated value of the best ratio of steam to biomass which achieves maximum concentration of hydrogen for any reactor temperatures (T101> 600 ℃) ,but this for our experimental conditions in biofluid 100.

The behavior of hydrogen concentration with steam to biomass ratio 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 to carbon monoxide in the gas [5].
- Equations 15 and 16 will be improved with steam and reactor temperature so it produces more amount of hydrogen by steam and reactor temperature ,therefore the best ratio of steam to biomass which achieved maximum hydrogen concentration ,will increasing by temperature .
- The excessive increase of steam at steam temperature 260 ℃ (according to our experiments) leads to a reduction reaction temperature, so it leads to decreasing in hydrogen during the experiment after a certain value of steam to biomass ratio (as mentioned previously).

- The effect of steam to biomass ratio $\frac{S}{B}$ on monoxide carbon content in produced gas:

  Figure 4 shows, that the effect of steam to biomass ratio on carbon monoxide content, it can be seen , that carbon monoxide content of the product gas decreases with increasing of steam to biomass ratio due to:

  - As discussed above that the water–gas shift reaction, Equation 14, will be more activate with steam, therefore concentration of carbon monoxide will be decreased.

- The effect of steam to biomass ratio $\frac{S}{B}$ on methane and carbon dioxide content in produced gas:

  Figure 5 shows, that the effect of steam to biomass on methane content, that methane content of the product gas increases with increasing of steam to biomass ratio. Figure 6, shows that the effect of steam to biomass ratio on carbon dioxide content, it can be seen that carbon dioxide content increases with increasing of reactor temperature this due to:

  - Water gas shift reaction, Equation 6, lead to increases carbon dioxide by steam.

- The effect of steam to biomass ratio $\frac{S}{B}$ on Low heating value of gas produced :

  Figure 7 shows , that the effect of steam to biomass ratio on low heating value of produced gas ,it can be seen that low heating value increases with increasing steam to biomass ratio $\frac{S}{B}$ till reaches maximum value then decreases with increasing $\frac{S}{B}$. The increasing of LHV due to increasing hydrogen and methane concentration at the beginning , then decreasing LHV with decreasing hydrogen and carbon monoxide concentration according to the results of experiments.

- The effect of steam to biomass ratio $\frac{S}{B}$ on carbon conversion efficiency :

  Figure 9, shows, that the effect of steam to biomass ratio on carbon conversion efficiency ,it can be seen that carbon conversion efficiency increases with increasing $\frac{S}{B}$ till reachs maximum value, then began decreasing by steam to biomass ratio, this is due to: By increasing steam to biomass ratio the water gas reaction Equation 4 will be more active with steam so increasing char conversion . But the excessive increase of steam lead to a reduction reaction temperature, so

Boudouard reaction Equation 6, will be less activate, so decreasing in char conversion by steam to biomass ratio .

- The effect of steam to biomass ratio on gasifier efficiency η_{geff} :

  Figure 10,shows, that the effect of $\frac{S}{B}$ on gasifier efficiency η_{geff} ,it can be seen that gasifier efficiency increases by increasing steam to biomass ratio in the beginning till reaches maximum value, then decreases by increasing steam to biomass ratio ,that is because by increasing steam to biomass ratio ,increases combustible gases (CH_4, H_2) ,so gasifier efficiency η_{geff} increases, but by the excessive increasing of steam , the gasifier efficiency decreased by decreasing each of hydrogen and carbon monoxide .

- The effect of steam to biomass ratio on gas yield :

  Figure 8 shows the effect of steam to biomass ratio on gas yield ,it can be seen ,that gas yield increases with increasing steam to biomass ratio, but it decreases by the excessive increasing of steam this is due mainly to the carbon conversion efficiency behavior with steam during the gasification.

By depending on the results of the experiment and discussion, it has been found, that the best steam to bio mass ratio, which achieved the best of low heating value, carbon conversion efficiency, gasifier efficiency, and gas yield increases with increasing reactor temperature, it is the same ratio which achieve the best hydrogen content , so it can be calculated from the Equitation 28,and for reactor temperature $T101 = 830$ °C was $\frac{S}{B} = 0.67$ $\left(\frac{kg\ steam}{kg\ biomass}\right)$.

4.6.3 The Effect of Steam Temperature $Tf1$:

Figures 11 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. In the present work, Steam temperature was varied from 180 to 261 (°C) in 20 (°C) increments, reactor temperature was $T101 = 830$°C, ER about 0.29, B about 23$\left(\frac{kg}{h}\right)$, F1 about 21$\left(\frac{m^3}{h}\right)$, steam rate was 15.4 kg/h also steam to biomass ratio was 0,67 $\left(\frac{kg_{steam}}{kg_{biomass}}\right)$.

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 15 and 16 ,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, while the concentration of methane and carbon dioxide decrease with rising steam temperature Figure 11, 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 .

By depending on results discussion, it can be seen, that the best value of steam temperature is the higher value, it can be.

4.6.4 The Effect of Equivalence Ratio ER :

Equivalence ratio ER was varied from 0.26 to 0.32 through changing the air flow rate by holding the other conditions constant reactor temperature was T101=830°C, B = 23 $\left(\frac{kg}{h}\right)$, steam rate was varied from 0 to 20 $\left(\frac{kg}{h}\right)$ also steam to biomass ratio varied from 0 to 0.85 $\left(\frac{kg_{steam}}{kg_{biomass}}\right)$.

As it is evident from the Figure 12, that hydrogen content changed little in the range of ER, while gas yield at the beginning increased, then decreased as it is shown in Table 4.

ER is the oxygen amount, which provided into the reactor, therefore its impacts on the reaction temperature [7]. Higher ER led to higher gasification temperature which can improve the product quality to a certain extent, also higher ER improve oxidation reaction and led to decrease quality .Therefore the gas quality is influenced by the two contradictory factors of ER[44].

Table 4 and Figure 12, show that the process could be divided into two stages to be investigated. In the first stage ER varied from 0.26 to 0.29, and in the second stage ER varied from 0.29 to 0.32. In the first stage, the positive effect of ER, has important function, so the gas yield increased from 30.97 to 35.89 $\left(\frac{m^3}{h}\right)$ and low heating value LHV increased from 5.1 to 5.52 $\left(\frac{MJ}{.m^3}\right)$, for the best value of steam to biomass ratio, as it is shown in Table 4.

When ER > 0.29, this lead to decreasing enough oxygen, therefore partial combustion reaction was more likely to occur, than complete combustion reaction. It is obvious from equations below, that partial combustion reaction converts 1 mole carbon more than combustion reaction. Therefore carbon conversion efficiency increased at the first stage ER (0.26 to 0.29). Because the reactor temperature increases with ER.

Partial combustion reaction: $2C + O_2 \to 2CO$

Combustion reaction : $C + O_2 \to CO_2$

When ER > 0.29, the oxidation reactions of combustible product gases are enhanced because the increasing in oxygen amount, this lead to lowered LHV and gas yield, and also decreases concentration of (CO and CH_4), but increases CO_2 concentration in this stage.

According to this discussion, it can be found above, that it is not useful use too small or too large ER in biomass air steam gasification. So the best value of ER, differ due to different operating conditions. In this present work, the best value of ER was about 0.29 under the experimental conditions.

4.6.5 The Effect of Steam to Air Ratio:

Steam to air ratio was varied from 0 to 0.72 $\left(\frac{\mathrm{kg_{steam}}}{\mathrm{kg_{air}}}\right)$ through changing the steam flow rate from 0 to 20 $\left(\frac{kg}{h}\right)$, steam to biomass ratio varied from 0 to 0.85 $\left(\frac{\mathrm{kg_{steam}}}{\mathrm{kg_{biomass}}}\right)$, by holding the other conditions constant ,reactor temperature was T101=830℃, B = 23$\left(\frac{kg}{h}\right)$ The tests results is cleared in Figures 13 to 16.

The impact of the ratio of steam to air $\frac{S}{B}$ on the gasification processes is similar to the impact of the ratio of steam to biomass. By supplying steam, each of water–gas shift reaction, Equation 14, and Equations 15 and 16, will be improved, Therefore it can be seen from Figure 13, that hydrogen and carbon dioxide are increased, but carbon monoxide is decreased by steam, and each of low heating value Figure 14, gas yield Figure 15, carbon conversion efficiency and gasifier efficiency Figure 15, have been increased.

But the excessive increase of steam at steam temperature 261 ℃ (according to experiments) leads to lower reaction temperature, and this leads to lower concentration of hydrogen in the gas produced during the experiment after the certain value of steam to air ratio about 0.57 , this explain, that decreasing each of low heating value, gas yield, carbon conversion efficiency and gasifier efficiency , after the certain value of steam to air ratio. In this present work, the best value of $\frac{S}{A}$ was about 0.57 $\left(\frac{\text{kg}_{\text{steam}}}{\text{kg}_{\text{air}}}\right)$ at our experiment conditions.

4.6.6 The Effect of $T101$, $\frac{S}{B}$ and $Tf1$ on Tar Content

Steam converts high molecular weight hydrocarbons of tar into smaller gas products including H_2,CH_4, CO and CO_2 [24].Also cracking of the heavier hydrocarbons as (tar, ethane, ethane and methane) will be done by high temperature and produce carbon and hydrogen, part of carbon converts to carbon monoxide[23].Therefore Tar content will be decreased by increasing each of reactor temperature T101 and steam to biomass ratio.

Figurer17 shows, that tar content decreases by increases T101 and $\frac{S}{B}$,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 $\frac{S}{B} = 0.67 \left(\frac{\text{kg}_{\text{steam}}}{\text{kg}_{\text{biomass}}}\right)$ in the same range of increasing temperature.

From Figure 18 show that tar content decreases with increasing $Tf1$ because high steam temperature will be improved reaction temperature.

4.7 Comparison between the Properties of Produced Gas by Using Steam /air and Air as Agent

It have been found from the results of the experiments and discussion , that the parameters, which achieved the best quality of produced gas at the experimental conditions, are $T101 = 830°\text{C}, \frac{S}{B} = 0.68$ and $ER = 0.29$. $Tf1$ is the highest possible temperature ,for our experiment is about 261 °C.

it has been compared between properties of gas ,which produced by using steam and air as gasifying agent at the best parameters ,which it has been mentioned above and properties of gas , which produced by using air as gasifying agent at same reactor temperature and equivalence ratio, Figure 20 shows This comparison .It is clearly that gas quality has been improved by using mixture steam and air ,where H_2 increased from 10.3 to 19.67 % , CH_4 from 2 to 3.5 % also LHV from 3.9 to 5.55 $\left(\frac{MJ}{m^3}\right)$ and tar content decreased from 1970 to 1050 $\left(\frac{mg}{m^3}\right)$

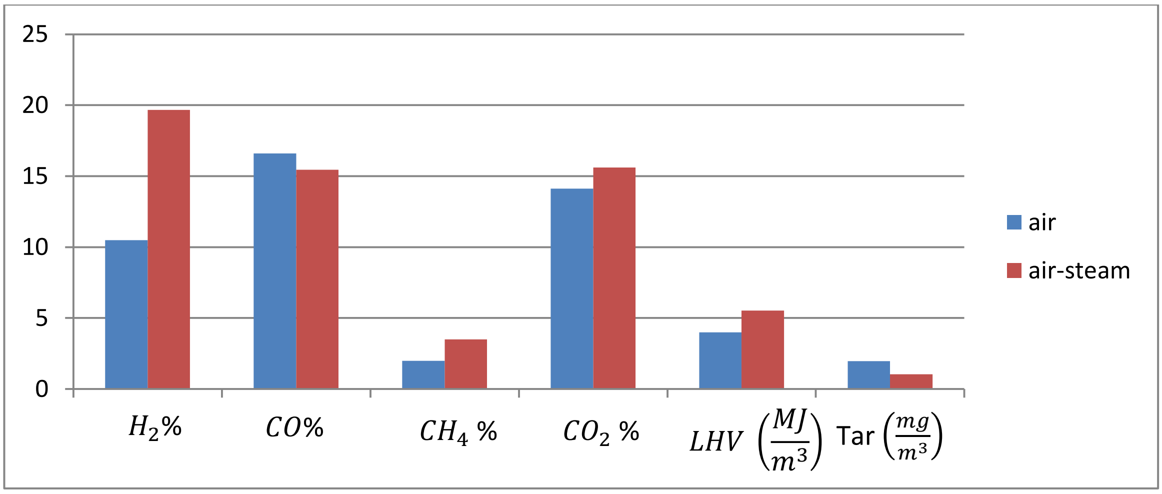

Figure 20: Comparison between the properties of produced gas by using steam /air and air as gasifying agent at the best parameters

Conclusion

The using of steam and air mixture as gasifying agent for gasification of pine wood chips in fluidized bed gasifier have been studied in this present work .

A series of experiments have been done in fluidized bed gasifier called Biofluid 100, where exists in lab of the Institute of Power Engineering, Brno University of Technology, to choose the best parameters each of reactor temperature $T101$, steam to biomass ratio $\frac{S}{B}$, temperature of steam $Tf1$, equivalence ratio ER and steam to air ratio $\frac{S}{A}$,which achieved the best quality of produced gas .

In order to accomplish this task ,it has been divided the experimental work into three stages .In the first stage has been studied the effect of both the temperature of the reactor T101 and the ratio of steam to biomass on components of gas $(O_2, N_2, H_2, CO, CO_2, CH_4, C_2H_6)$,tar content , low heating value LHV of the produced gas, gas yield ,carbon conversion efficiency and gasifier efficiency, by holding the other conditions , which were carefully selected on the basis of previous studies .In this stage it has been selected the best reactor temperature and the best ratio of steam to biomass, that achieve the best quality of the gas .

The second stage has been depended on the results of the first stage. The aim of this stage is studying the effect of steam temperature $Tf1$ on quality of the gas product at different values of steam to biomass ratio $\frac{S}{B}$. In this stage it has been selected the best steam temperature.

The third stage has been depended on the results of the first and second stage (the best of reactor temperature and steam temperature),the aim of this stage is to define the best value of equivalence ratio ,that achieves the best gas quality with a gradual increase of the ratio of steam to biomass.

At each stage of the experimental work, gas and tar samples have been taken after achieving thermal stability in the region of the reactor. It has been sampling tar depending on the protocol.

The task of on-line measuring was monitoring and controling the gasification processes only.

The analysis of the gas samples have been carried out in Mechanical Engineering Faculty at the Brno Technical University (BUT), by using the HP 6890 chromatograph fitted with the TCD and FID detectors, to determine the basic components of the sample gas $(O_2, N_2, H_2, CO, CO_2, CH_4, C_2H_6)$.

The analysis of tar samples have been carried out in The Institute of Chemical Technology, Prague (ICT).

Gas yield , carbon conversion efficiency and gasifier efficiency ,have been calculated for every gas sample and have been discussed for every stage alone .

Temperatures have been measured inside the reactor and its inlet and outlet during the experiment.

Fluidized bed pressure difference, outlet gas pressure,tank pressure,they have measured during the expermint .

The primary air flow rate $F1$,has been measured at the inlet of the reactor.

The biomass flow B has been calculated by depending on the frequency of the feed screw $1Hz = 3.25\ \left(\frac{kg}{h}\right)$.

Data measurements have been recorded directly in the computer data every two seconds, and they have been used to evaluate the results of experiments after taking the arithmetic average .

The experimental results have been reported in the present work and have been discussed carefully.

The results of experimental work can be illustrated by the following points:

1. The increasing in reactor temperature $T101$ lead to increase in hydrogen, carbon monoxide, gas yield and carbon conversion efficiency, and decrease in methane and carbon dioxide. Low heating value and gasifier efficiency, at the first increase with $T101$, until reach to temperature 829 ℃, they start decreasing by increasing $T101$.
2. 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, carbon conversion efficiency and gasifier efficiency ,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 ,carbon conversion efficiency and gasifier efficiency).
3. 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 conditions ($Tf1$=261 ℃ and ER =28) , it was $\frac{\mathrm{S}}{\mathrm{B}} = 0.67(\frac{\text{kg steam}}{\text{kg biomass}})$ at $T101$ =829℃ .
4. Whenever steam temperature was higher whenever the gas produced was more quality, where increases the concentration of gas combustible ($\mathrm{H_2}, \mathrm{CO}$) and thus increases each of$\left(\mathrm{LHV}, \mathrm{V_{gas}}, \eta_\mathrm{C} \text{ and } \eta_\mathrm{geff}\right)$, but the increase steam temperature will increase the economic cost of the product gas, which must take into account when gas production widely.
5. The effect of equivalence ratio has been studied with increasing $\frac{S}{B}$, it has found, that the best value of equivalence ratio was around 0.29 ,which achieved the best quality of produced gas , and when ER > 0.29 ,the combustible gases decreased, so it led to lower the quality of gas.
6. The effect of steam to air ratio has been studied in the present work ,it has been found, that quality of gas increased by increasing of $\frac{S}{A}$, but the excessive increase in the provided steam lead to the reduction of the reaction temperature and this cause decreasing each of $\left(H_2, \mathrm{LHV}, \mathrm{V_{gas}}, \eta_\mathrm{C} \text{ and } \eta_\mathrm{geff}\right)$ .It has been found that the best value of steam to air was $\frac{S}{A} = 0.57\left(\frac{\mathrm{kg_{steam}}}{\mathrm{kg_{air}}}\right)$ at $T101 = 830℃, Tf1 = 261℃$ and $ER = 29$.
7. Tar content decreases by increasing each of $T101$ and $\frac{S}{A}$,where tar content decreased from 2390 to 1390 $\left(\frac{\mathrm{mg}}{\mathrm{m^3}}\right)$ by increasing temperature from 770 to 861℃ when used air only , but tar content decreased from 1450 to 853 $\left(\frac{\mathrm{mg}}{\mathrm{m^3}}\right)$ by using steam and air mixture at $\frac{S}{B} = 0.67$ $\left(\frac{\mathrm{kg_{steam}}}{\mathrm{kg_{biomass}}}\right)$ for same range of temperature However tar content decreased weakly by increasing $Tf1$.
8. Method of tar removing by steam has been verified effectiveness, it converts tar into combustible gases ,this lead to increase the heating value of gas.
9. 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, are $T101 = 830℃, \frac{S}{B} = 0.68$ and $ER = 0.29$. $Tf1$ i is the highest possible temperature for our experiment is about 261 ℃., where H_2 increased from 10.3 to 19.67 % , CH_4 from 2 to 3.5 % , LHV from 3.9 to 5.55 $\left(\frac{MJ}{m^3}\right)$ and tar content decreased from 1970 to 1050 $\left(\frac{mg}{m^3}\right)$ at the best parametrs.

An article has been published, focused on the effect of using of gasifying agents in fluidized bed on the gas quality.

Another article has been published ,focused on discussion of the experimental results of using steam air mixture for gasification of pine wood chips in fluidized bed gasifier.

Another article has been published, focused on definition the best parameters which achieve best gas quality for steam –air gasification of pine wood chips in fluidized bed gasifier.

Currently an article to be published, about using of steam to improve the quality of gas

But the search did not discuss the costs of this process. This is necessary to assess the economic feasibility, and this will pave the way for more research in the future and at the same time to find cheap methods to produce high quality gas.

Search did not discuss the ways of gas cleaning and tar removal ,but it opened the road for many research in this field in the future.

Experiments have been carried for pine wood chips as biofuel therefore, it have to refer to importance of using other types of biofuel.

Modeling of this study is possible because of very successful results, that have been obtained and the simplicity of both the design and conduct experiments.

The utilization of steam-air for pine wood chips gasification process to produce syngas suitable for the implementation of plants of energy generation, and this will pave the way for many jobs and contributes to maintaining a clean environment.

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Abstract

This work has been studied the impact of using of air-steam as gasification agent in fluidized bed gasifier on produced gas properties (Carbon monoxide, Hydrogen,tar content and low heating value .

This study has been based on the experiments which have been done in fluidized bed gasifier called Biofluid 100, where exists in lab of the Institute of Power Engineering, Brno University of Technology, by using air-steam as agent of gasifier and pine wood chips as the feedstock.

The aim of this thesis is to determine the best operating parameters of system air- steam gasification in biofloud 100 which achive the best gas quality.

To accomplish this task , many experiments have been performed to studied the effect of reactor temperature $(T101)$, steam to biomass ratio $(\frac{S}{B})$, steam to air ratio $(\frac{S}{A})$, temperature of provided steam $(Tf1)$ and equivalence ratio (ER)on produced gas composition , low heating value(LHV),gas yield ,carbon conversion efficiency and gasifier efficiency.

The results of experiments have been shown , that the increase the temperature of reactor $(T101)$ lead to increase hydrogen content , carbon monoxide content ,low heating value,gas yield , carbon conversion efficiency ,gasifier efficiency and reduce the tar content, but too high reactor temperature lowered low heating value of gas.

By providing steam,the gas quality $(H_2, LHV and\ tar\ content)$ has been imroved ,however excessive steam has been lowered gasification temperature and thus reduced gas quality. The ratio of steam to biomass, which achieve the best gas quality has been increased by reactor temperature.

It has been found, that whenever steam temperature $(Tf1)$ was higher , whenever the gas produced more quality, but the increase of steam temperature will increase the economic cost of the product gas,which must take into account when gas production widely.

The effect of equivalence ratio (ER) has been studied with increase $\frac{S}{B}$, it has been found that the best value of equivalence ratio was around 0.29 which achieved the best quality of produced gas , where when ER > 0.29 the combustible gases content have been decreased so it led to lower the gas quality .

Tar content decreases by increasing each of reactor temperature $(T101)$ and steam to biomass ratio .

According to the results of the experiments and discussion, it has been found, that by using the mixture of steam and air ,the gas quality will be improved ,and the parameters, which will achieve the best quality of the produced gas at experimental conditions are: $T101$ =829 ℃ $\frac{S}{B} = 0.67\left(\frac{kg\ steam}{kg\ biomass}\right)$,$\frac{S}{A} = 0.57\left(\frac{kg\ steam}{kg\ air}\right)$, ER= 0.29 and $Tf1$ is the highest possible temperature, where hydrogen increased from 10.48 to 19,68 % and Low heating value from 3.99 to 5.52$\left(\frac{MJ}{m^3}\right)$ and tar decreased from 1964 to 1046 $\left(\frac{mg}{m^3}\right)$ by increasing $\frac{S}{B}$ from 0 to 0.67 at T101=829 ℃ .

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Abstract

Tato práce studovala vliv použití vzduchu a páry jako zplynovacího činidla ve zkapalňovacím generátoru plynu na vlastnosti vyprodukovaného plynu (oxid uhelnatý, vodík, obsah dehtu a nízká výhřevnost).

Tato studie byla založena na experimentech které byly provedeny ve fluidním generátoru plynu Biofluid 100 v laboratoři Energetického ústavu technologické univerzity Brno s použitím páry jako zplynovacího činidla a borovicového dřeva jako výchozí suroviny.

Cílem této dizertační práce je stanovit nejlepší provozní parametry systému při užití vodní páry a vzduchu ve zplynovacím zařízení biofluid 100, při kterých se dosáhne nejvyšší kvality plynu.

K dosažení tohoto cíle bylo provedeno mnoho experimentů studujících účinky teploty reaktoru$(T101)$, poměru páry a biomasy $(\frac{S}{B})$ poměru páry a vzduchu $(\frac{S}{A})$, teploty dodávané páry $(Tf1)$, ekvivalentního poměru ER,ve složení vyprodukovaném plynu, výhřevnost, výtěžnost plynu, efektivnost přeměny uhlíku a účinnost zplynovače.

Výsledky experimentů ukázaly, že zvýšení teploty reaktoru vede ke zvýšení obsahu vodíku a oxidu uhelnatého, výhřevnosti, výtěžnosti plynu, efektivnosti přeměny uhlíku, efektivnosti zplynovače a ke snížení obsahu dehtu. Příliš vysoká teplota reaktoru ale snižuje výhřevnost plynu.

Dodáváním páry se zvýšila kvalita plynu, vyšší H_2, LHV a nižší obsah dehtu. Přesto ale nadměrné množství páry snižuje zplyňovací teplotu a tím i kvalitu plynu. Poměr páry a biomasy při kterém se dosáhne nejlepší kvality plynu se zvýší s teplotou reaktoru.

Bylo zjištěno, že kdykoli byla teplota páry $(Tf1)$ vyšší, byl plyn více kvalitní, ale zvyšování teploty páry také zvyšuje ekonomické náklady na vyprodukovaný plyn což se při masové produkci plynu musí brát v úvahu.

Efekt ekvivalentního poměru ER, byl studován postupným zvyšováním, bylo zjištěno, že nejlepší ekvivalentní poměr pro dosažení nejvyšší kvality plynu byl kolem 0.29, při ER > 0.29 byl obsah hořlavého plynu snížen a to vedlo ke snížení kvality plynu.

Obsah dehtu se snižuje jak zvýšením teploty reaktoru tak poměrem páry k biomase. Podle výsledků experimentů a diskuze, bylo zjištěno, že při použití směsi páry a vzduchu se kvalita plynu zvýší, parametry pro dosažení nejvyšší kvality vyprodukovaného plynu při experimentálních podmínkách jsou: $T101$ =829 °C $\frac{S}{B} = 0.67 \left(\frac{kg\ steam}{kg\ biomass}\right)$,$\frac{S}{A} = 0.67 \left(\frac{kg\ steam}{kg\ air}\right)$, ER= 0.29 and a $Tf1$ je nejvyšší možná teplota,při které se vodík zvýší z 10.48 na 19,68% a výhřevnost z 3.99 na 5.52$\left(\frac{MJ}{m^3}\right)$ a obsah dehtu z 1964$\left(\frac{mg}{m^3}\right)$ na 1046$\left(\frac{mg}{m^3}\right)$ zvýšením z 0 na 0.67 při T101=829 °C .