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

Zplyňování borové dřevní štěpky s parovzduchovou směsí ve fluidním loži

DOCTORAL THESIS

DOKTORSKÁ PRÁCE

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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 °C $\frac{S}{B} = 0.67 \left(\frac{kg\ steam}{kg\ biomass}\right)$,$\frac{S}{A} = 0.57 \left(\frac{kg\ steam}{kg\ air}\right)$, 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 ℃ .

Keywords

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

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 .

Klíčová slova

Pára , vzduchu, zplyňování, biomasa, fluidní lože, dehet, poměr páry a biomasy, ekvivalentní poměr.

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Čestné Prohlášení

Prohlašuji, že jsem disertacní práci "Zplyňování borové dřevní štěpky s parovzduchovou směsí ve fluidním loži" vypracoval samostatne. Vycházel jsem pouze ze svých vedomostí a znalostí,literatury ocitované na konci dokumentu a odborných konzultací.

Brně dne 15. 9. 2014 Ing.Najdat Salami

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CONTENTS

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 [3].

Renewable energy sources are alternative sources because, most of industrialized countries do not depend on them as their main energy source. Instead, they rely on non-renewable sources such as fossil fuels or nuclear power. Because the energy crisis during the 1970s, decrease supplies of fossil fuels and their associated problems such as greenhouse gas emissions, high operating costs, local pollution and hazards associated with nuclear power, therefore using of renewable energy sources has grown. Renewable energy technologies are receiving increasing attention from governments, industry, and consumers. [3].

Renewable energies are clean, inexhaustible, and it can be used in the same place as they are produced, it has additional advantage, that it is free. The current global concern about climate change, with its imperative to decouple economic growth from an increase in carbon dioxide emissions, makes investing in renewable energy sources particularly timely and strategic. Renewables supply an exemplary result for economic growth and environmental sustainability [6]. Recently there has been renewed interest in the biomass as a renewable energy source worldwide. Using biomass could be the solving to the energy problems, which made its more imminent by the recent crisis that have further threatened our oil supply [3].

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].

2. 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).

3. Historical Perspective

Gasification technologies have been commercially used for the last century for the production fuels and chemicals. Current view about power generation and refinery industries support has advanced stages of the technology and will continue to be applied toward the synthesis of syngas, with an increasing number of applications in power generation, fuels, and basic chemicals manufacturing [1].

The history of gasification back to seventeenth century as the first conception of idea which has passed through several phases of development.

In 1669Thomas Shirley conducted crude experiments with carbonated hydrogen but the earliest practical production of synthetic gas (syngas) is reported to have taken place in 1792 when Murdoch, a Scottish engineer, pyrolyzed coal in an iron retort and then used the product, coal gas, to light his home [1].

In 1812, was developed first gas producer which used oil as fuel. In 1816, the first coal gasification company in the USA, Baltimore Gas Company, was established based on the same technology to light the streets of the city of Baltimore [1]. In 1840 the First commercially used gasifier was done in France [2].

In the 1850s, the gas producer was invented, and the water - gas process was discovered in Europe. In the gas producer, coal and coke were completely converted to gas by reacting coal with air and steam continuously in a downdraft moving bed at atmospheric pressure. The gas obtained in this method, called producer gas, had low heating value (3500–6000 KJ/m^3) To increase the heating value of the gas product, a cyclic steam - air process was developed in 1873. This process produced water gas, composed mainly of carbon monoxide and hydrogen, which had a higher heat value (12000–13000 KJ/m^3). Compared with the producer gas [11].

In early 1900s, biomass gasification processes were used to making synthetic gases for production of fuels, chemicals, and hydrogen. In the industry, the exist of pure O_2 led to the development of some of the important fully continuous oxygen - based processes for the production of syngas in coal gasification. The Winkler fluidized - bed process (1926), the Lurgi moving - bed pressurized gasification process (1931), and the Koppers –Totzek entrained - flow process (1940s). During World War II, over 1 million air-blown gasifiers had been constructed to produce synthetic gas from wood and charcoal to power vehicles and to generate steam and electricity [1].

After World War II, the discovery of large quantities of low-cost natural gas with heating values of about 37 MJ/m^3 led to lose of glory and importance of gasification technology [2].

The attention in gasification technologies was renewed throughout the 1960s and 1970s when controversial projections referred that natural gas reserves would be ended and demand would exceed reserves by the 1980s and 1990s. The oil embargo of 1973 created awareness for the need to determine alternative sources of fuel. Much of the works focused on coal hydrogasification. Throughout the 1980s, researchers and industry had been recognized some of the environmental advantages of gasification technology [14]. Figure 1 shows the power generation from overall gasification (including coal and biomass) from 1970 to 2004[2].

The technology of biomass air gasification have a practical application and has been developed actively for industrial applications [8]. This technology produces a gas with a low heating value (4–6) and an 8–14 vol. % . Biomass oxygen air gasification is one effective method to produce medium heating value (MHV) gas, but it needs a large cost for oxygen production equipment and this disadvantage prevent its popularization[8]. More experimental studies reported in the literature (Delgado et al., 1996; Aznar et al., 1998; Gil et al., 1999; Rapagna et al.,2000; Mathieu and Dubuisson,2002; Lv PM et al.,2004) show that fluidized-bed, steam-gasification processes (with or without O2 added) are able to produce a MHV (10–16) gas with a 30–60 vol.% content[16]. However, this technology (steam as agent gasification) needs that the temperature of steam be over 700 °C, which requires additional cost for steam generator of good performance [9]. Under this background, the technology of biomass air gasification with low temperature steam was prepared from the economic view [16].

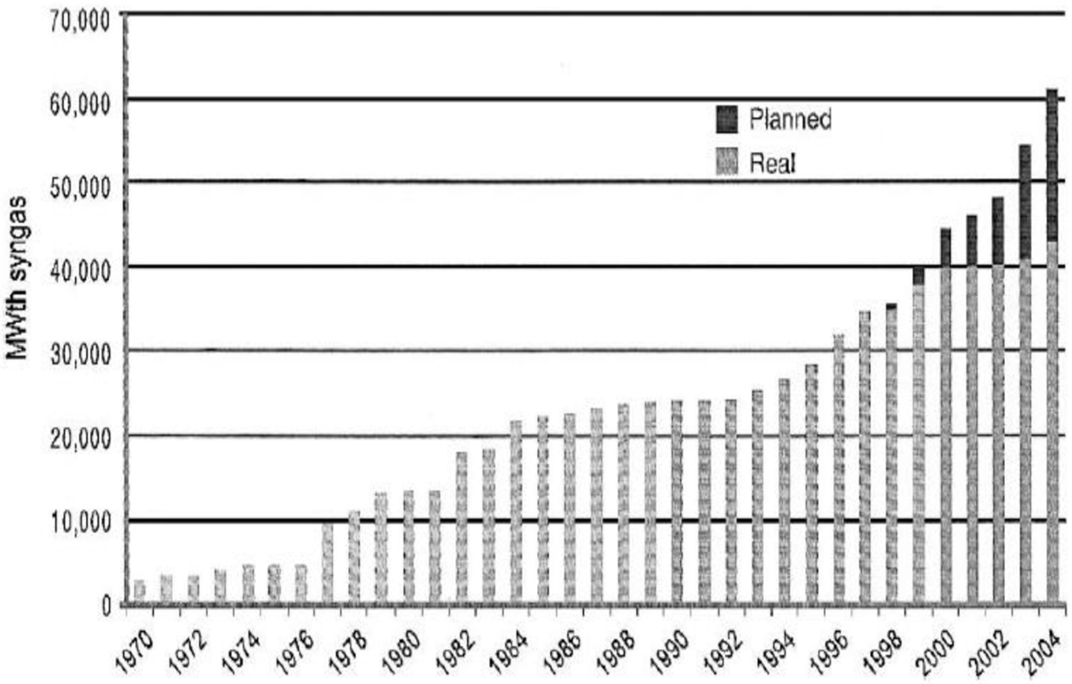


Figure 1:Worldwide power generation from gasification [2]

4. Biomass as a Fuel

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 [40]. he opportunities for developing improved and modern biomass energy technologies, which offer substantial advantages in terms of increase quality of energy services and reduction in negative health and environmental impacts. Also the sustainable harvesting of biomass resources is essential for ensuring the continued availability of this important energy source particularly. Biomass, in ecology, is the mass of living biological organisms in a given ecosystem at a given time. Biomass can mean species biomass, which is the mass of one or more species, or to community biomass, which is the mass of all species in the community. It can include microorganisms, plants or animals [3].

Much of the current using of biomass in the developed world is heavily subsidised to make it possible for the resource to compete with much cheaper fossil fuels. Woody biomass wastes and residues are used on commercial wood processing and paper manufacturing sites to produce heat and electricity for on site use; however, if biomass is going to make a major contribution to the world's energy mix then dedicated energy crops are the only answer[3]. By 2010 large quantities of high yielding energy crops could compete economically with coal in some areas of the USA. There are no large scale trials being undertaken to substantiate these claims but these will be required to obtain the necessary investment[43]. Gasification is a one of technology for utilization thermo chemical convert renewable energy sources (RES) into more significant fuels. The RES utilizing is trend of world power industry in this time. Gasification with air is a conversion of organic matter into low-energy gas, which after some modification is suitable for use in boilers, combustion engines or turbines [42].

4.1 Assessment of the Suitability of Various Types of Biomass as Gasifier fuel

- Charcoal:

It burns slowly and does not produce any smoke, good quality charcoal does not contain any tar, so it is suitable for all kinds of gasifiers. Good gasifier charcoal is low in mineral material and does not crumble easily [11]. Compared to other biomass fuels, charcoal is costly. Important disadvantage is that during conversion of wood into charcoal, more than 50% of energy is lost. This is not suitable factor for those developing countries which suffer in energy crisis [44].

- Wood:

The experiment has shown that most types of wood and some agricultural residues can provide first class gasification charcoal[3]. Most wood species have ash contents below two percent and next to charcoal, wood is suitable fuel for fluidized bed gasifiers[54]. As fuel contains high volatile matter, updraft systems produce a tar containing gas suitable for direct burning [11].

- Sawdust

Gasification of sawdust caused the problems of excessive tar production, undesirable pressure drop and lack of bunker flow [44]. Most currently available downdraft gasifiers is not suitable for sawdust[55]. Fluidized bed gasifiers can be accommodated small sawdust particles and produce quality gas. For use in engines, a fairly elaborate clean-up system is necessary [11].

- Agricultural Residues

Agricultural residues are mainly biomass materials which are from agriculture. It includes cotton stalks, wheat and rice straw, coconut shells, maize and jowar cobs jute sticks, rice husks etc. Many developing countries have a large variety of agricultural waste in ample quantities [3]. Coconut shells and maize cobs have been chosen for fixed bed gasifiers and they unlikely causes any problems. Most cereal straws contains ash content above 10% and will be slagging problem in downdraft gasifier. Rice husk with ash contents above 20% is difficult to gasify [11].

5. Gasification Principles

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 [12].

Biomass is organic carbonaceous material, which consist of carbon, hydrogen, and oxygen atoms though in a dizzying variety of molecule forms. The target of gasification process is to destroy this wide variety of forms into the simple gases of hydrogen and carbon monoxide[60]. Both hydrogen and carbon monoxide are Combustible gases [2]. Carbon monoxide as a fuel gas actually has very good combustion characteristics [1].

Carbon monoxide and hydrogen have about the same volumetric energy density . They are very clean burning as they only take on one oxygen atom, in one simple step, to reach at the suitable end stages of combustion, CO_2 and H_2O [1]

Gasification technologies differ in many aspects but depend on these engineering factors [1]:

1. Gasification reactor atmosphere (level of oxygen or air content).
2. Reactor design.
3. Internal and external heating.
4. Operating temperature.

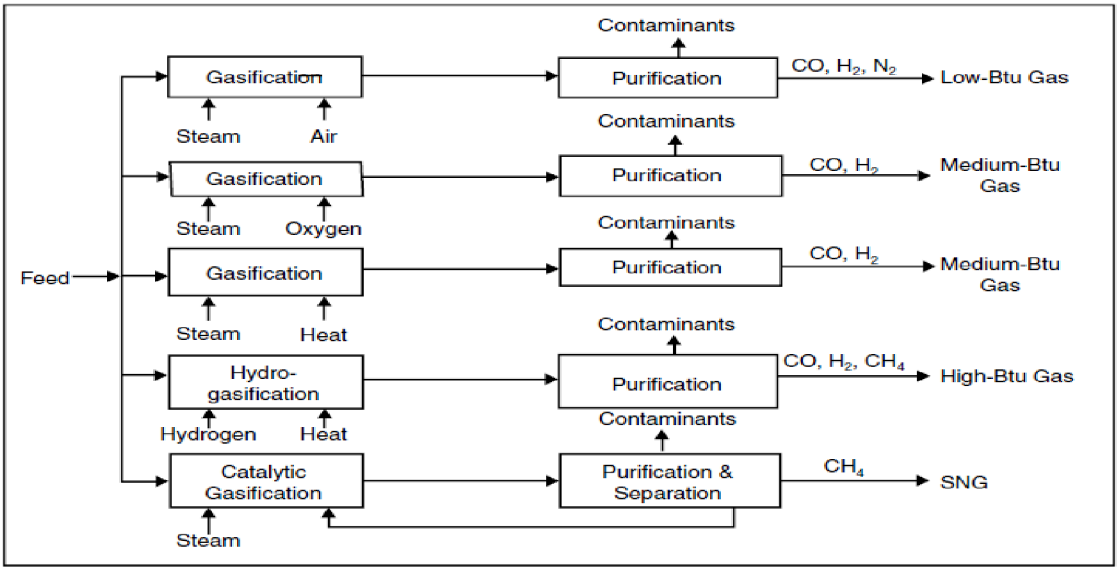


Figure 2 :Gasification methods [1]

5.1 Processes of Gasification

Gasification is consisting of four thermal processes. Drying, Pyrolysis, Combustion and Reduction Figure 3. All processes naturally show in the flame you can see burning off a match, in spite of the mix in a way that make them invisible to eyes not yet initiated into the mysteries of gasification[56]. Gasification is the technology to pull apart and isolate these separate processes. Figure 4 shows the four processes of gasifying a carbonaceous material [12].

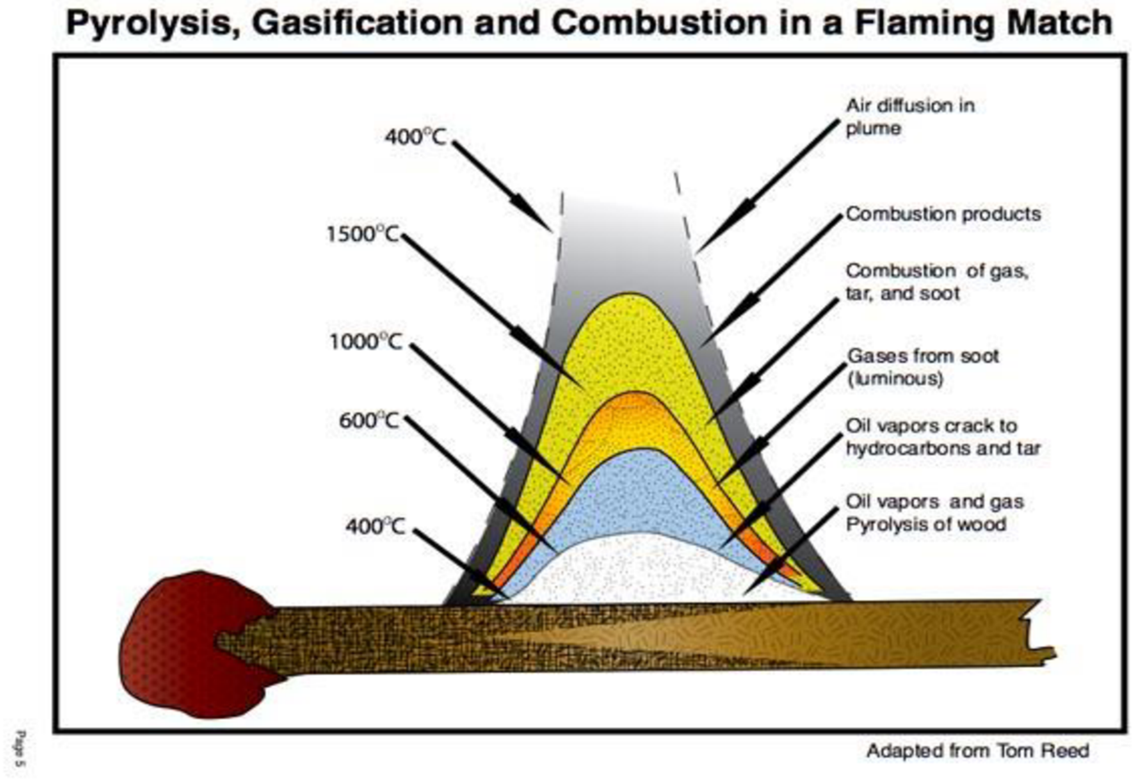


Figure 3 : Pyrolysis, Gasification and combustion in flaming Match [12]

5.1.1 Drying

Drying removes the moisture in the biomass before it enters to pyrolysis stage. All the moisture will be removed from the biomass before any above 100 °C processes occur [5]. The water in the biomass will get vaporized out of the fuel at some point in the higher temperature processes[59]. High moisture content fuel, and mistaken handling of the moisture internally, is one of the most common reasons for failure to produce clean gas [12].

Moist feedstock + Heat → Dry feedstock + H_2O………..1

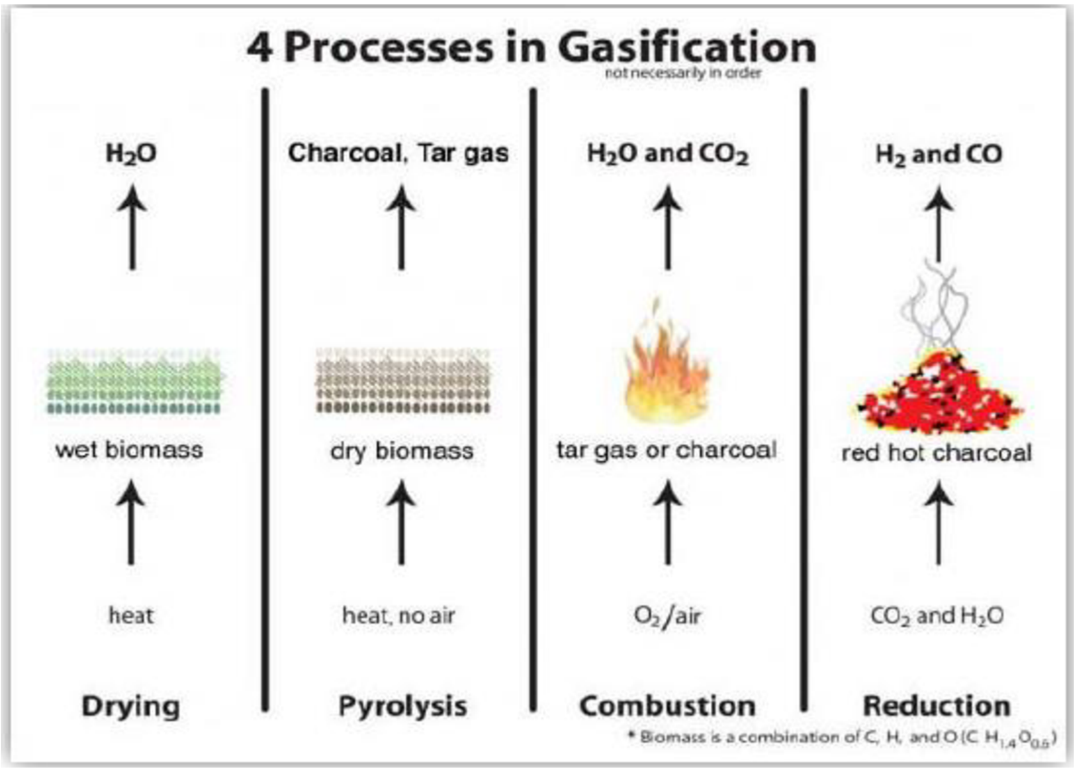


Figure 4 : ***Processes of Gasification [12]***

5.1.2 Pyrolysis or Devolatilization

Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures without oxygen [58]. It encloses the simultaneous change of chemical composition and physical series of complex physical and chemical processes take place during the devolatilization or pyrolysis processes, which begin slowly at less than 350 °C, accelerating to rate above 700 °C[12]. The composition of the developed products is a function of the temperature, pressure, and gas composition during devolatilization[13] . The biomass destroys into a combination of solids, liquids and gasses. The solids that remain it is charcoal. The gasses and liquids that are released are tar. The gas produced in pyrolysis has heating value is low about (3.5 to $9\left(\frac{MJ}{m^3}\right)$).Pyrolysis generally produces the following products:

1. Light gases such as H_2, CO, CO_2, H_2O, CH_4
2. Tar
3. inorganic molecules
4. Char, a solid residue mainly containing carbon.

The pyrolysis product components depends on many factors including the temperature and rate of heating. The tar and gas content of coal pyrolysis product increases with temperature up to 900 to 1000 °C [31]. Pyrolysis is the application of heat to biomass in the without of air/oxygen. The volatiles in the biomass are "evaporated" off as tars, and the fixed carbon-to-carbon chains remains known as charcoal[5].

5.1.3 Reduction

Reduction is the process removing of oxygen atoms off hydrocarbon molecules which is completely combusted, so as to conversion the molecules to forms that can burn again. Reduction is the direct reverse process of combustion[12]. Combustion is the reaction of an HC molecule with oxygen to produce heat. However reduction is the stripping of oxygen from an HC molecule by adding heat [5]. Combustion and reduction are equal and opposite reactions. In most combustion environments, they are both operating at the same time, in some form of dynamic equilibrium, with repeated movement back and forth between the two both cases [11].

Reduction in a gasifier is done when carbon dioxide (CO_2) or water vapor (H_2O) pass across a bed of red hot char (C) [12]. The hot char is highly reactive with oxygen, and this removes the oxygen off the gases. Through this process, CO_2 is reduced to CO. And H_2O is reduced to H_2 and CO. Combustion products become combustible gases [11].

5.1.4 Combustion

The combustion of char is the most important chemical reactions happen in the gasifier, giving all the thermal energy required for the endothermic reactions [59]. Oxygen supplied to the gasifier reacts with the combustible material present, which leads to formation of carbon dioxide and water vapor, which reduction subsequently with the char produced from pyrolysis stage [11].

The combustion reaction is the oxidation of char in fuel to produce carbon dioxide

$$C + O_2 \rightarrow CO_2 + 393.77\, KJ/mol \quad carbon \qquad \ldots\ldots\ldots\ldots\ldots 2$$

The other combustion reaction is the oxidation of hydrogen in fuel to produce water vapor [11]:

$$H_2 + \frac{1}{2} O_2 = H_2O + 742\, KJ/mol \quad H_2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

5.1.5 Gasification

Gasification includes a series of endothermic reactions supported by the heat produced from the combustion reaction described above. Gasification Production includes combustible gases such as hydrogen, carbon monoxide, and methane through a many of reactions. The following are four major gasification reactions [5]:

I. Water–gas reaction

II. Boudouard reaction
III. Shift conversion
IV. Methanation

Brief descriptions of these reactions are given below[5].

I. Water–Gas Reaction

Water–gas reaction is the partial oxidation of carbon by steam, which come from a set of different sources (fuel moisture, steam as gasification medium..etc). Steam reacts with the hot carbon due to the heterogeneous water–gas reaction [5]:

$$C + H_2O \rightarrow CO + H_2 - 131.38\,Kj/mol \quad carbon \qquad \ldots\ldots\ldots\ldots 4$$

In some gasifiers, steam is supplied as the gasification medium with or without air

II. Boudouard Reaction

It is reaction between the carbon dioxide present in the gasifier with char to produce carbon monoxide according to the following endothermic reaction, which is known as the Boudouard reaction [5]:

$$C + CO_2 \rightarrow 2CO - 172.58\,Kj/mol \quad carbon \qquad \ldots\ldots\ldots\ldots 5$$

III. Shift Conversion

The heating value of hydrogen is higher than of carbon monoxide. So, the reduction of steam by carbon monoxide to produce hydrogen is a highly desirable reaction [1].

$$CO + H_2O \rightarrow H_2 + CO_2 + 41.58\,Kj/mol \qquad \ldots\ldots\ldots\ldots 6$$

This reaction called water–gas shift, results in an increase in the ratio of hydrogen to carbon monoxide in the gas, and is help in the making of synthesis gas [5].

IV. Methanation

Methane could also form in the gasifier through the following overall reaction[5]:

$$C + 2H_2 \rightarrow CH_4 + 74.90\,Kj/mol \quad carbon \qquad \ldots\ldots\ldots\ldots 7$$

This reaction can be increased by nickel-based catalysts at 1100 °C and 6 to 8 bar [11].

5.2 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 [27]

	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.

From Table 1 it can be seen, that the oxygen or air, which supply into reactor ,is used in reactions (1) through (3) to produce the needful heat to dry the solid fuel, destroy chemical bonds, and increase the reactor temperature to drive gasification reactions [38]. Reactions (4) and (5), are endothermic reactions, and enhance by high temperatures and low pressures. Reaction (6), the Boudouard reaction,is endothermic but combustion reaction (1) Faster ,at the same temperature without of a catalyst [1]. Reaction (7), hydro-gasification, is very slow at low pressure. Reaction (14), the water-gas shift reaction, it is very important reaction to produce hydrogen . Reaction (9), the methane reaction, is very slowly at low temperatures without catalysts. Methane formation is slow relative to reactions (4) and (5) unless stimulated [1].

5.3 Composition of the Product Gas

The composition of the gas produced from a gasification depends on a number of parameters such as[1]:

1. Fuel
2. Gasifying medium
3. Pressure
4. Temperature
5. Moisture content of the fuels
6. Mode of bringing the reactants into contact inside the gasifier, etc.

The gas produced by air gasification technology, has small low heating value, it is about (3.5-4.2) $\left(\frac{MJ}{m^3}\right)$ depending mainly on the type of fuel [45].

Generally , used of steam with or without air as gasifying agent will produce rich gas with low heating value (5-12) $\left(\frac{MJ}{m^3}\right)$ and the increase in the concentration of hydrogen in the gas produced[51].

Syngas content: The main combustible gas are, $(CO, H_2, and\ CH_4)$,nitrogen, carbon dioxide , water vapor entrained soot, ash, a in addition to organic (tars) and inorganic (H_2S, HCl, NH_3), impurities and particulates[53] .Syngas contains about 2 -10 $\left(\frac{g}{m^3}\right)$ tar, that enhance the heating value of gas , if the gas temperature does not drop below the dew point of the tar compounds remain in the gas phase, which is useful for the operation of the equipment. Usually the composition of the gas produced is in the following ranges table 2 [5].

Table 2: the composition of the gas produced[5]

hydrogen	8-25%
carbon monoxide	10-30 %
carbon-dioxide	2-16%
methane	0-5%
nitrogen	45-60 %

6. Types of Gasifiers

There are many gasifies have been built and operated using a wide variety of configurations including [2]:

1. Updraft
2. downdraft
3. Cross-draught
4. fluidized beds where fluidized or entrained solids serve as the bed material
5. Others including moving grate beds and molten salt reactors.

Most of these gasifiers can be designed for work at either ambient conditions or high pressure conditions up to approximately 20 atm .The most common of this gasifies which are listed above, downdraft, updraft and CFB gasifies are. Commercially, about 75% of the gasifiers are downdraft gasifiers, 20% fluidized bed, 2.5% updraft, and 2.5% of the other types. Table 3 shows Advantages and disadvantages of various gasifiers[5].

6.1 Updraft Gasifier

The gasification medium and the produced gas flow during the gasification reactor in the opposite direction to the fuel supply from Figure 5.a, it could be seen ,that if the reactor is fed from above, the gasification media (air, oxygen, steam) enters the reactor in the bottom of reactor[11]. The updraft gasifier is more popular for using when the required of gasification is heating only (below 10 MW) because its high thermal efficiency and ability to handle fuel with wide variation in size and moisture content up to 50% [19]. The tar content is high in the gas from this gasifier because the gas formed is not forced to pass during the high temperature zone. The gas was exited from this gasifier was with low temperature [11].

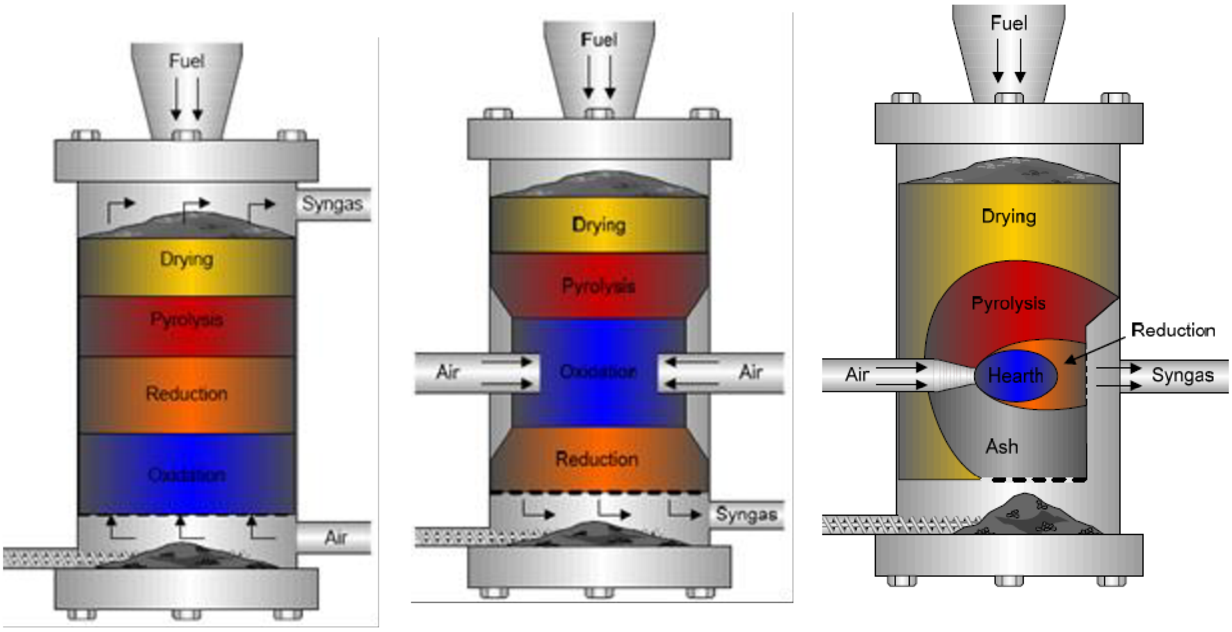
Because of high tar content in the produced gas, a subsequent tar cleaning system is required [4].

6.2 Downdraft Gasifier

In a downdraft gasifier, the fuel and gasifying medium both move in the same direction Figure 5.b. The gases have to pass during the high-temperature zone, therefore amount of tar is significantly lower than that in an updraft gasifier[4]. But the particulate content is higher for downdraft gasifier and the thermal efficiency is lower, where gas produced lose an appreciable amount of energy when passing during the high temperature zone in the gasifier [11].

6.3 Cross-draft Gasifier

Cross draft gasifiers, it could be seen from Figure 5c, that they are suitable for gasification of charcoal. Charcoal gasification in very high temperatures (1500 °C and higher) may be causes problems in the combustion zone. Advantages of this system is very small scale at which it can be operated in installations below 10 kW (shaft power) can under certain conditions be economically feasible. Disadvantage of cross-draft gasifiers is their minimal tar converting ability and this lead to need for high quality [4].



a) Updraft Gasifier b) Downdraft Gasifie c) Cross-draught Gasifier

Figure 5 : Types of gasifier with a fixed bed [4]

Table 3 : Advantages and dis advantages of various Gasifies [5]

Gasifier Type	Advantage	Disadvantages
Updraft	• Small pressure drop. • Good thermal efficiency. • Little tendency towards slag formation.	• Great sensitivity to tar and moisture content of fuel. • Relatively long time required for start up. • Poor reaction capability with heavy gas load.
Downdraft	• Flexible adaptation of gas production to load. • Low sensitivity to charcoal dust and tar content of fuel.	• Design tends to be tall. • Not feasible for very small particle size of fuel.
Cross-draft	• Short design height. • Very fast response time to load. • Flexible gas production.	• Very high sensitivity to slag formation. • High pressure drop.

6.4 Fluidized Gasifier

Fluidized bed reactors include a bed, which consist of small particles of inorganic material (small diameter ceramic beads, sand and gravel), which a gasifying medium can be air or steam. The bed is fluidized by blowing hot oxidant up from the bottom (individual particles are raised by aerodynamic drag, and become suspended or entrained on the gas stream at velocities for which the drag force becomes equal to or exceeds the gravitational force or weight) at this time, fluidized bed behaves much like a liquid. When the bed became hot enough, biomass is injected either into the bed or up the surface (bubbling beds) and can begin to combust or gasifier depending according to the amount of oxygen available. Fluidized bed gasifier provides higher yield than those with a fixed bed [2]. Fluidization increases mass and heat transfer from the fuel, and increasing heating value of the output and higher efficiency so it suitable for low-rank coal and biomass gasification. They are two types of fluidized bed gasifiers: bubbling and circulating. Bubbling fluidized bed reactors it can be seen in figure 6 have relatively slow velocity media gasifying (air, oxygen, and steam) flow and therefore have lower particle entrainment in the produced gas [4]. The bed material congregates in the lower dense bed zone because the freeboard section over the bed has a larger diameter and lower gas velocity. The gas velocity in the freeboard zone is too low to continue to suspend bed particles, which fall again into the bed zone. The design is simple but has lower capacity and maybe less uniform reactor temperature distribution than circulating fluidized beds. The circulating fluidized bed is could be seen in figure 7.Although it uses higher gas velocities but it offers higher conversion rates and efficiencies. The reactor diameter remains constant, which keeps bed and fuel particles suspended. The bed material goes up with the gas and it is carried over to a cyclone, which separates most of the particles from the gas which are re-injected into the bottom part of the bed [5].

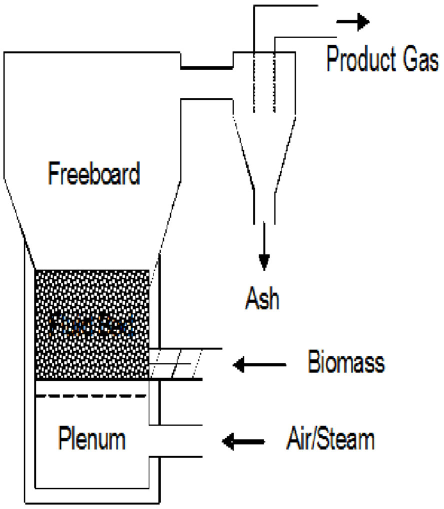


Figure 6: Bubbling bed reactor [5]

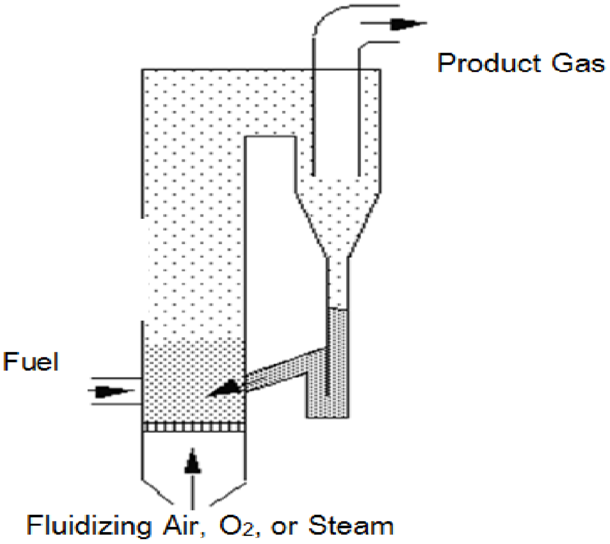


Figure 7: Circulating fluidized bed reactor [5]

7. Effect of Various Parameters in Gasification Process

Syngas composition varies widely, which is a mixture of carbon monoxide, methane, hydrogen, nitrogen, carbon dioxide, etc. The effects of major parameters on the quality of syngas are discussed in the sections below [5].

7.1 Equivalence Ratio

Equivalence ratio (ER),the ratio between the amount of oxygen content in the gasifying medium(air ,oxygen steam ...) and the amount of oxygen, which it is required to complete stoichiometric combustion[8]. Equivalence ratio (ER) is The most effective parameter in gasification process and has considerable effect on syngas composition, where it strongly impacts the gas composition (including tar content) and its heating value[11] . Increase in ER increases the reactor temperature, but decrease ER will increases char formation inside the gasifier [2].

It has been calculated the value of Equivalence ratio (ER) by the following equation [11]:

$$ER = \frac{\text{weight oxygen (air)}/\text{weight dry biomass}}{\text{stoichiometric oxygen (air)}/\text{biomass ratio}} \quad \ldots\ldots .8$$

If values of equivalence ratio near to zero the process will be close to pyrolysis conditions, but if values equal or greater than one the process will be close to combustion conditions[11]. Figure 8 is shown the effect of ER on the syngas composition [8]. the best value of ER for the downdraft gasifier with using furniture wood and wood chips as fuel was around 0.25–0.35 to conversion maximum of char amount and then are those typically used in large scale commercial plants[13] .The best value of equivalence ratio is different according to the biomass types due to the amount of oxygen exist in the biomass and the ash content .The best optimal value for the fluidized bed gasifier was about 0.2-0.3 by using wood pine gasification and air as medium of gasification [49] .Tar concentration decreases with increase ER because increase ER enhance reactor temperature so increases reaction rates of the chemical products also high ER increase additional oxygen for cracking of tar into lower hydrocarbons CO_2 and H_2O [2].

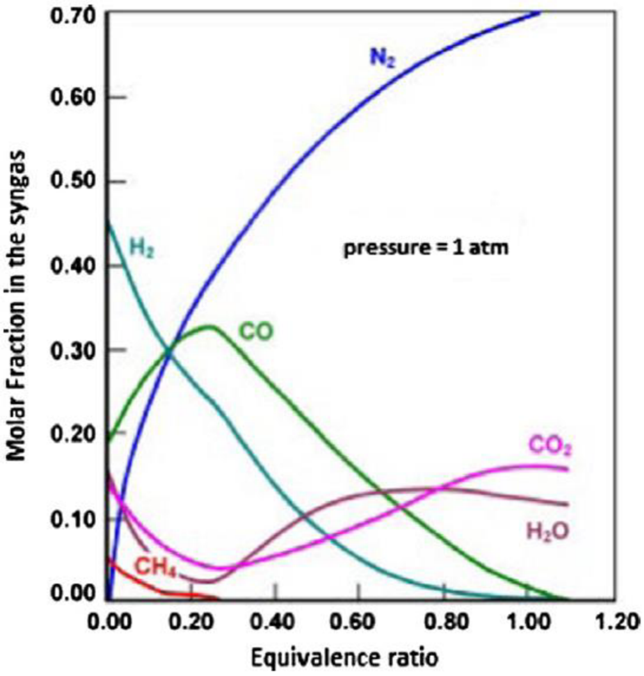


Figure 8 : Syngas composition at the chemical equilibrium as a function of equivalence ratio, for the gasification of wood at 1 atm (redrawn from Kaupp and Goss, 1981) [13].

7.2 Temperature and Pressure

The temperature and the pressure of the gasifier has the greatest effect on the product composition. In fluidized bed gasifier ,which the HHV of the produced gas increased by 10% for an increase in the temperature from 700 to 800 °C [5].

The temperature along the reactor can be also determined the state of bottom ash (the possibility to obtain a vitrified slag)[52]. Increase in temperature reduces the tar content as well as decreases char inside the gasifier and cracks tar , temperatures are often reported to be around 1000-1100.C with some dependency on gasifier design, CO_2 concentration increases with increasing pressures and decreases sharply with increasing temperatures[5].

It can be noted from Figures 9 a,b , 10 a,b and 11 a,b that [5] :

- The production of hydrogen and carbon monoxide increase with rising temperature and low pressure within the reactor. Maximum concentration of H_2 and CO can be obtained at atmospheric pressure and temperature range of 800 to 1000 °C.
- Concentration of methane in the product gas increases with low temperature and high pressure.

Therefore, reactor temperature and pressure can be determined the concentration of product, CH_4 , H_2 and CO. [1].

According to this results,It can be fund,that to produce high carbon monoxide content gas, the gasifier should be designed to work at a high temperature and low pressure [5].

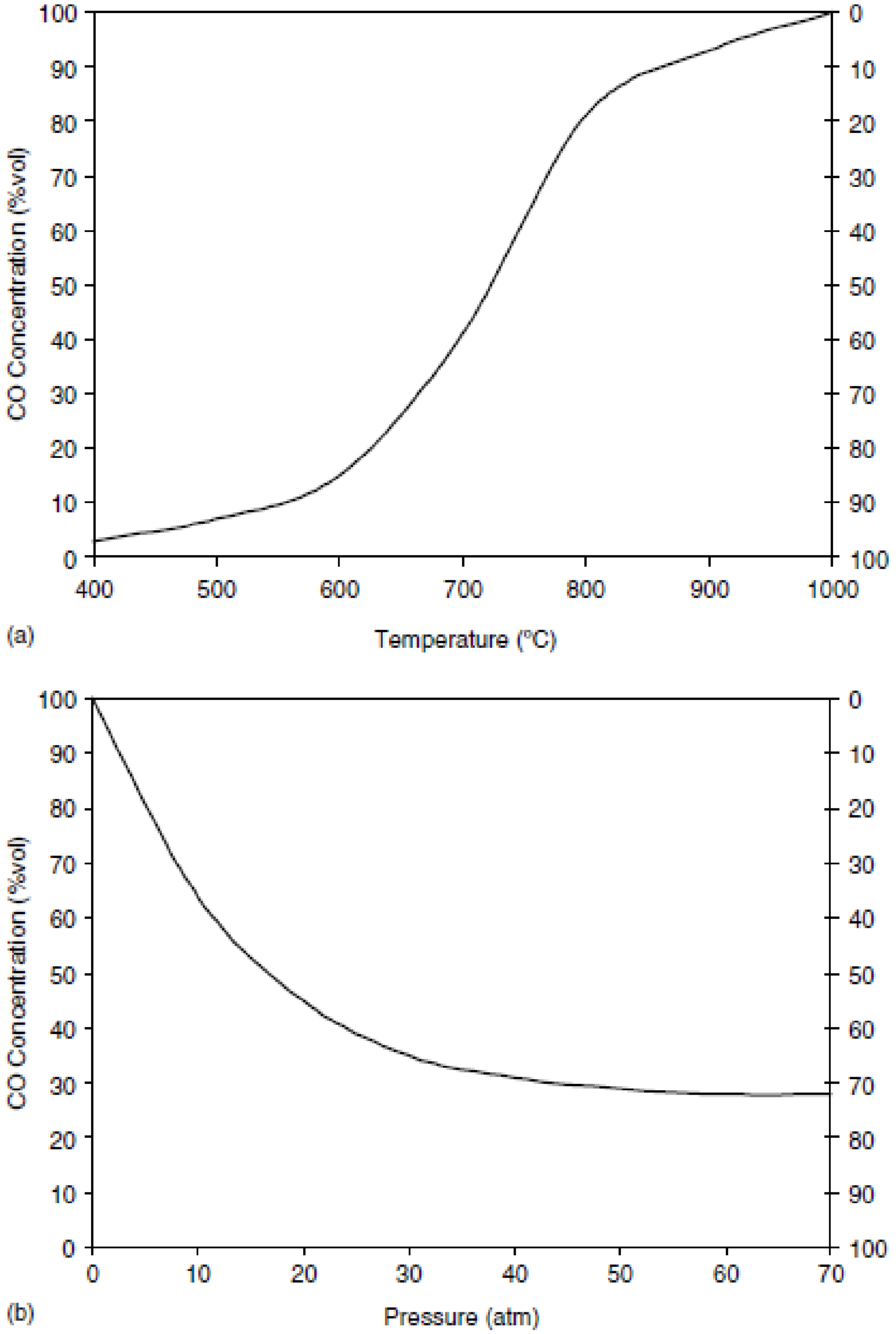


Figure 9: Boudouar reaction equilibrium: difference of CO and CO_2 for gasification of carbon with oxygen (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800 °C [5].

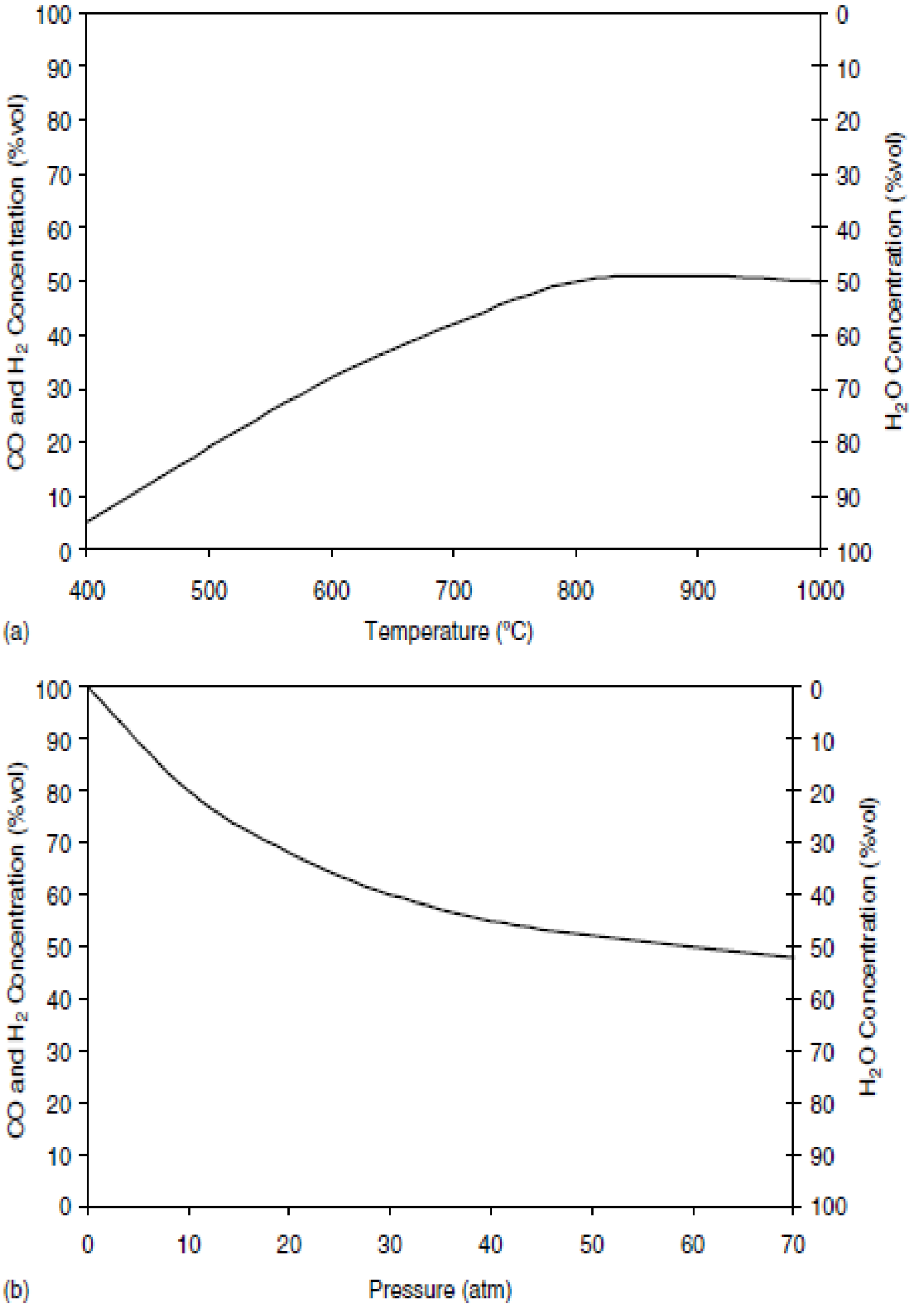


Figure 10 : Water–gas reaction equilibrium: difference of CO, H_2 and H_2O (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800 °C[5].

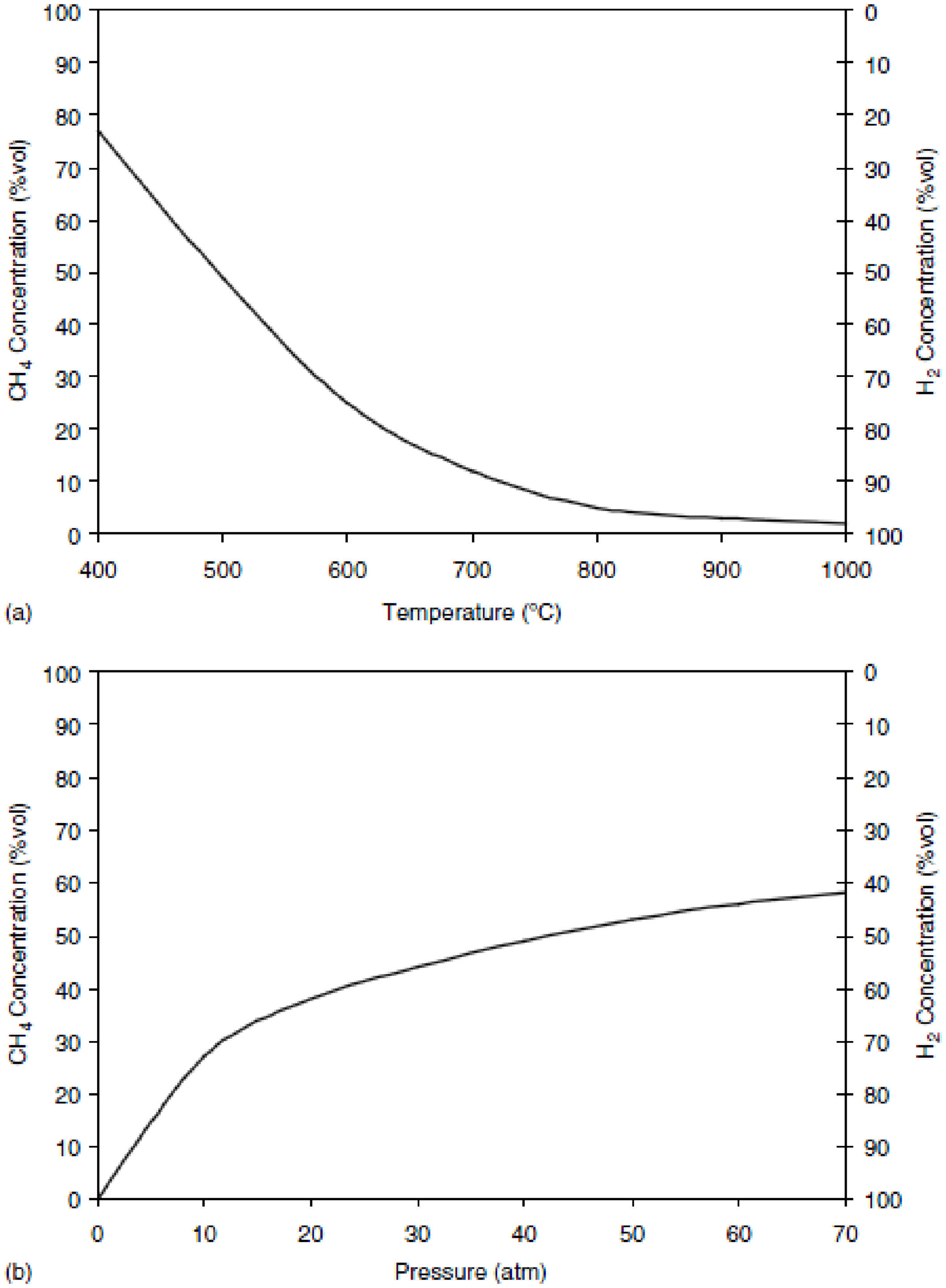


Figure 11 : Difference of CH_4 and H_2 at equilibrium (a) with temperature at a pressure of 1.0 atm, and (b) with pressure at a temperature of 800 °C[5].

7.3 Carbon Conversion Efficiency η_c

Carbon conversion efficiency (η_C) is the ratio between the carbon content in produced gas to the carbon content in fuel [7].

It can be calculated (η_C) by this equation[7] :

$$\eta_C = \frac{wight\ carbon\ in\ gas\ produced}{wight\ carbon\ in\ fuel} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Carbon conversion efficiency shows the amount of unconverted fuel, that has to be treated with other technique or get rid of it , it gives a measure of chemical efficiency of the gasification process [2]. Carbon conversion efficiency also effects on gas yield rate [22].

7.4 Gasification Medium

Gasification of biomass can be classified according to the gasifying medium like(air, steam, oxygen, air/steam,..etc)[2]. Gasifying medium provides necessary oxygen amount for the gasification process, therefore it is significantly affects the quality of the product gas [23].

7.4.1 Air Gasification

Using of air as a gasifying agent is not complex way ,however the produced gas is with little heating value and little amount of hydrogen and high amount of nitrogen[22].The produced gas by this method is suitable for boiler and engine applications but not for use that require its transportation through pipelines [24]. Air gasification is used widely by compare to oxygen and steam ,because its economical and operational advantages. However this technology produces a gas with a low heating value 3.5-6 ($\frac{\mathrm{MJ}}{\mathrm{Nm^3}}$) and an 8–11 (vol.%) H_2 content only [16].

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

7.4.2 Steam Gasification

Steam gasification needs an external heat source, if it is used alone as gasifying agent [16]. 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 [20]. Steam will react with carbon monoxide to produce hydrogen and carbon dioxide it is called the water–gas shift reaction equation (6). However the excessive increase of steam provided, will be lowered the gas quality [18].

Steam gasification produces gas with higher heating value compared with the air gasification [18]. Hoveland et al. (1982) studied corn grain-dust gasification in fluidized bed gasifier by using steam as a fluidizing medium at the reactor temperature 760 °C it was produced gas yield 0.73 $\left(\frac{m^3}{kg}\right)$ and the gas heating value 11.5$(\frac{\mathrm{MJ}}{\mathrm{Nm^3}})$ [8].

Extensive experimental studies reported in the 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 heating value about 10 $(\frac{\mathrm{MJ}}{\mathrm{Nm^3}})$ and hydrogen content about a 30 (vol.%). However, this technology needs ,that the temperature of steam be over 700 °C, which requires additional cost for steam generator [7].

7.4.3 Oxygen Gasification

Oxygen gasification is one of effective way to improve syngas quality which produce gas with heating value approximately 12$(\frac{\mathrm{MJ}}{\mathrm{Nm^3}})$, and product gas without nitrogen, this gas can be economically transported in pipeline network systems and therefore, be used for process heat [16] .In this case, an oxygen plant or a nearby source of oxygen is needed, which it raise the capital cost which it need for the plant and this disadvantage impedes its popularization [2].

7.4.4 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 [11].

7.5 Effect of Steam to Biomass Ratio

The Steam to biomass ratio is ratio between the steam feed rate to the air feed rate [5]:

$$\frac{S}{B} = \frac{m_S}{m_A} \ (\frac{kg\ steam}{kg\ biomass}) \ldots\ldots\ldots..10$$

Where :

m_s: Steam feed rate flow $\left(\frac{kg}{h}\right)$

m_A: Air feed rate flow $\left(\frac{kg}{h}\right)$

The introduction of steam greatly improved gas yield, LHV and carbon conversion efficiency but excessive increase in the $\frac{S}{B}$ will lower gas quality which can be explained by that excessive quantity of low temperature steam lowered reaction temperature and then caused gas quality to degrade [7].

In this present work, it has been studied the effect of steam to biomass ratio on gas quality and it has been chosen the best value of $\frac{S}{B}$ which achieve the best quality.

8. The Effect of Biomass Characteristics Related to Gasification

Every type of biomass has specific properties, which determines its behavior as a fuel in gasification plants. The most important characteristics for gasification are [11]:

- moisture content
- ash content and ash composition
- elemental composition
- heating value
- bulk density and morphology
- volatile matter content
- other fuel related contaminants like N, S, CI, alkalies, heavy metals, etc.

8.1 Moisture Content

Biomass contains intrinsically moisture by its nature, and extrinsically moisture where is absorbed from the surrounding atmosphere .The moisture content of biomass is different widely according to their types, starting from below 5% for anthracite to about 40% for low-rank sub-bituminous coal and lignite.during gasification,moisture content in the biomass, enhance CO_2 concentration by the water-shift reaction (Eq.6),which consumes CO and produces H_2 [5].

Excessive moisture content of the feed biomass lowers the temperature reaction Thus, the decrease in temperature leads to increased CO_2 so it reduction in heating value of syngas . Therefore, an maximum limit of moisture content is defined for satisfactory gasification.In a typical fixed bed this maximum limit is about 35% for coal, and about 25% for wood but in fluidized bed gasifier, normally need moisture content of the biomass to be lowered to 5 to 10%. Natural drying is cheap but needs long times. Artificial drying is more expensive but also more effective [11].

It has been used pine wood as experimental fuel in this present work, which has about 11% moisture.

8.2 Particle Size

The size of biomass particle has impact on produced gas component and yield [7]. The smaller particles produced moreCH_4,CO and C_2H_4 and less CO_2 than the larger ones. This because of that the gas yields, gas LHV and carbon conversion efficiency have been improved with decrease of biomass particle size [7]. Fine grained fuel causes flow problems in the bunker section of the gasifier and unwanted pressure drop over the reduction zone and a high dust content in the gas. large particle sizes cause problems of gas channeling in updraft gasifiers .Usually, feed size less than 51 mm and 6 mm is recommended for fixed bed and fluidized bed, respectively [2].

8.3 Ash Content

Ash is the inorganic or mineral content of the biomass, which remains after complete combustion. The amount of ash varies widely according to type of biomass (0.1%for wood up to 15% for some agricultural products)[2]. The design of the reactor affects on the ash removal system. Ashes can make different problems particularly in up or downdraft gasifiers. Slagging or clinker formation in the reactor, occured by melting and collection of ashes, . worst case is the possibility of air-channeling which can make great explosion, especially in updraft gasifiers[43].

8.4 Elemental Composition

The elemental composition of the fuel is important for the heating value and the emission levels in almost all applications [10]. The nitrogen and sulfur compounds are generally small in biomass gasification because of the low nitrogen and sulfur content in biomass [43].

8.5 Heating Value

The heating value is determined by the combustible elemental composition. On a dry and ash free basis, most biomass species have a heating value of about 19 $\left(\frac{MJ}{kg}\right)$. The higher heating value (HHV) is the maximum amount of energy that can be obtained from combustion the fuel and this HHV is necessary to calculate the gasifier efficiency [11].

To calculate HHV regarding the composition of burnable part it can be used this equation (institute of gas technology 1990) This equation is suitable for biomass combustion [9]

$$HHV_h = 341 \cdot C_h + 1322 \cdot H_h + 68.5 S_h - 120 \cdot (O_h - N_h) \qquad \text{...........(12)}$$

Where :

C_h ,H_h,S_h,O_h,N_h : content of carbon ,hydrogen ,sulphur ,oxygen and nitrogen content of biomass

8.6 Bulk Density and Morphology

Bulk density is the weight per one meter cubic of biomass. It differs according to various types of biomass. Bulk density the heating value, determines the energy density of the biomass. Fuels with high bulk density are useful because they have high energy for volumetric value. Biomass with low bulk density is expensive to handle, transport and store. The bulk density is important for the operation of the biomass as a fuel because of Low bulk density fuels sometimes lead to unwanted flow under gravity, as result, low gas heating values and ultimately in combustion of the char in the reduction area. Average of bulk densities of wood, charcoal and peat are given in Table 4 [11].

Table 4: ***: Average bulk densities [11]:***

Fuel	Bulk density (kg/m³)
Wood	300 - 550
Charcoal	200 - 300
Peat	300 - 400

8.7 Volatile Matter Content

The amount of volatiles in the biomass effect on the tar production content in gas produced [44]. For biomass materials the volatile matter content varies between 50 and 80%. In practice the only biomass fuel that does not require special care is good and high quality charcoal [11].

8.8 Feedstock Preparation Requirements

They are many processes to pretreat different types of biomass when they are using as a gasifier fuel [43]. Fuel demands for different gasifier types are presented in Table 5.

However, the most important Treatment technologies are drying, sizing and densification and with other Treatment technologies like screening and sifting, which are importance to very specific materials like heavy contaminated (sand, paper, plastic, non-ferro and ferro metals, etc.) . Harvesting is necessary when an energy crops are the fuel [43].

Table 5: ***fuel*** **requirements** ***versus gasifier design [11]***

Gasifier type	downdraft	updraft	open-core	cross-draft
Size (mm)	20-100	5-100	10 -100	<1
Moisture content (% w.b.)	<1520	<50	<40	<15
Ash content (% d.b.)	<5	<15	<20	<20
Morphology	Uniform	Almost uniform	Uniform	Uniform
Bulk density (kg/m3)	>500	>400	>100	>400
Ash melting point (°C)	>1250	>1000	>1000	>1250

9 Gas Cleaning

The syngas contains the desired combustible components,$(CO, H_2 \; and \; CH_4)$ and undesired components like entrained soot, ash, organic (tars) and inorganic(H_2S, HCl, NH_3), impurities and particulates [5]. The organic impurities consist of low molecular weight hydrocarbons and high molecular weight polynuclear aromatic hydrocarbons. The lower molecular weight hydrocarbons enable to use as fuel in gas turbine or engine applications, but they are unwanted products in fuel cell applications and methanol synthesis. The higher molecular weight hydrocarbons are called tar. The gas requires to be cleaned to remove the contaminants. Tar causes difficulties in using syngas in engines. Thus, depending on the application, type of gasifier, and contaminants in the fuel, a certain level of gas conditioning (cleaning/cooling) is required [31]

9.1 Sulfur and Other Chemical Contaminant Removal

In a gasifier, nearly the all sulfur in the biomass is converted to (H_2S) , which should be effectively removed to keep the sulfur content of the gas in acceptable limits. In the fluidized bed gasifiers, can be used limestone into the gasifier to catch most of the (H_2S) produced. The limestone $(CaCO_3)$ calcines is converted to calcium sulfide(CaO) upon reaction with the (H_2S) inside the gasifier.

$$CaCO_3 \rightarrow CaO + CO_2 \text{....................................} 12$$

$$CaO + H_2S \rightarrow CaS + H_2O \text{ ....} 13$$

Residual (H_2S) is normally removed in an external desulfurization system [5].

9.2 Tar Removal

Tar, which is produced during gasification, is a major problem. It is a mixture of chemical compounds, which condense on metal surfaces at room temperature [24]. The heating value of tar is about 20,000 to 40,000 $\left(\frac{kJ}{kg}\right)$. Tars may be considered as hydrocarbons, which have molecular weights higher than where of benzene [32]. Tar sampling protocols are being developed to help for uniform ways of tar collection; however, these methods are not yet widely used [28]. Tar removal, destruction or conversion, is one of the biggest technical challenges for commercial advanced gasification technologies [31]. Tars are big problem in biomass gasification systems for following reasons [27]:

- Tars can condense at low gas temperature in exit pipes and on particulate filters and thus cause closing and blocking filters.
- Tears have different effect on other downstream processes.
- Tars can block fuel pipes and injectors in internal combustion engines.

- When the product gas is combusted in a gas turbine ,luminous combustion and erosion from soot formation can happened in pressurized combined cycle systems.
- The product gas required to be compressed before its combustion in a gas turbine and tars maybe condense in the compressor or in the transfer pipes when the product gas cools.

Primary tars,is formed when molecular bonds break by heat and it is the large molecules which can react to form secondary tars by further reactions at the same temperature but tertiary tars at higher temperatures .The pathway of tar formation can be described in the figure 12 , referring the temperature at which each tar occurs [5].

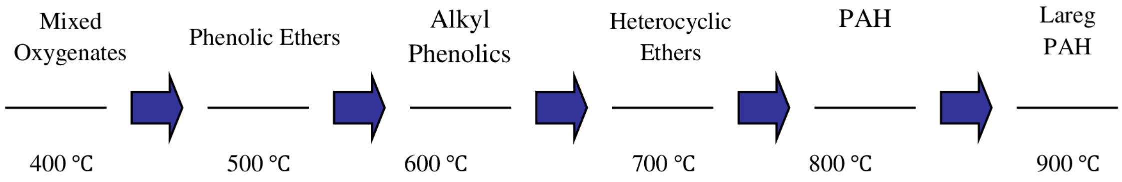


Figure 12 :Tar formation Scheme [5]

The maximum limit of tar concentration in syngas depending on its end usage [2]. The value of tolerable limit of tar concentration in syngas is 50-500 $\left(\frac{mg}{m^3}\right)$, less than 0.5$\left(\frac{mg}{m^3}\right)$ and less than 5 $\left(\frac{mg}{m^3}\right)$ for compressors, internal combustion engines, methanol synthesis and gas turbines, respectively [5]. The nature of tar varies due to gasifier design. Downdraft gasifiers produce tertiary tar, but tar from updraft gasifiers majority contain primary tar according to lower ability of tar cracking in the gasifier. Syngas from fluidized bed gasifiers contain mixture of secondary and tertiary tar [31]. Tar content in a downdraft gasifier is usually about 0.01- 6$\left(\frac{mg}{m^3}\right)$, but updraft and fluidized bed gasifiers usually about 50 $\left(\frac{mg}{m^3}\right)$ and 6-12 $\left(\frac{mg}{m^3}\right)$ in average, respectively [27]. With increase in reactor temperature, tar content in the gas produced decreases according to thermal cracking. By increasing in temperature from about 700 °C to 820 °C, tar content decreasing from 15 to 0.54 $\left(\frac{mg}{m^3}\right)$in a circulating fluidized bed. Increase in equivalence ratio also decreases tar content but lead to a higher concentration of CO_2, which is an unwanted product [2].

9.2.1 Removal Options

It can be removed tar from the product gas by chemical and physical ways. Chemical ways cracking the tar, to smaller molecules. Physical ways only remove the tar yielding from syngas. Most of devices are able for tar conversion and removal, most of them are mainly for particle removal [5].The following table shows the several of chemical and physical methods to remove tar [5]:

(Chemical Methods)	(Physical Methods)
• Catalytic destruction • Thermal destruction • Plasma reactors (Pyroarc, Corona, Glidarc) • Use of catalytic bed materials	• Cyclone • Filters (baffle, fabric, ceramic, granular beds) • Electrostatic precipitators • Scrubbers

The tar content in produced gas does not condense if the gas temperature is above 400 (°C) Therefore, in applications of direct burning, gas does not need to remove tar [31]. Catalytic destruction of tar which is the best way for tar cracking , they are two forms of catalysts nonmetallic and metallic:

a) Non Metallic Oxides: Calcined dolomite has been proven that it destroys tar. These catalysts has advantages are relatively cheap and it save the heating value of the tar by converting it to other combustible gases , but The efficiency of tar conversion will be enhanced when dolomites are worked at high temperatures (900°C) with steam[2]. Calcined dolomites are not very robust and quickly increasing in fluidized bed reactors[31] .It has also proven, that tar conversion activity by olivine like that of calcined dolomite. Olivine is a much more robust material than calcined dolomite and it has been used as a primary catalyst to decrease production tar in fluidized bed biomass gasifiers [5].
b) Commercial Nickel Reforming Catalysts: Commercial Nickel steam reforming catalysts have been widely applied to remove tar in biomass gasification[6] .They have high efficacy for tar cracked with the added benefits of completely reforming methane and reaction of water-gas shift are more activity[31]. Some studies have also shown that nickel catalyzes the reverse ammonia reaction thus decreases the amount of ammonium in gasification product gas [5].

9.3 Particulate Removal

The particulate in the produced gas have been removed mainly by cyclones, which located next to the gasifier [6]. More removing take place in hot dry filters also this, located downstream of the cyclone or in water washing system after the gas is cooled in a heat recovery system. Water washing system removes the particulate matter as slurry, and also removes some of the other contaminants [5].

10 Description of the experimental apparatus and equipment

10.1 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.

The experimental set-up, shown in Figure 13, it consists of six main parts: 1) atmospheric fluidized bed reactor 2) biomass feeding section, 3) steam, air providing and preheating section, 4) gas metering, cleaning and sampling section, 5) temperature control section, 6) gas offline analysis section.

This system can work in a gasification mode or a combustion mode. The gasification mode is worked with a stationary fluid layer. The fuel is transferred from a feeder tank (at the Figure 13 no. 1) by a screw feeder fitted with a frequency converter fed to the reactor (no. 2). The primary air is compressed by pump and fed to the reactor passing through a fan grate. The secondary and tertiary air enters the reactor along its height. Flue dust and particulate are separated from the syngas produced in a cyclone. The reactor ash is get rid of into a storage vessel. To enable observing the effect of air before heating, an electric heater is took place behind the blow pump. A water sprinkling column was used to clean the syngas in the first years of operation. A hot catalytic filter (no. 3) was put behind the gasifier in 2004. This system can be worked in both gasifying and combustion modes. Fluidized bed gasifier start working as combustion mode to steady state. Process temperature control by changing the fuel to air ratio, with control of temperature range within the 750°C to 900 $(°C)$. The value of average heating of the produced gas, the content of solid particles and the content of tars depending on fuel used and operating conditions. Fuel comes from storage tank to be fed to the gasifier in batches by worm conveyor [41].

A mixture of air and steam was used as the gasification agent. Air was supplied by a compressor and it can be heated to $200(°C)$ in a preheater. The steam has been produced in electric boiler with temperature about $150(°C)$, and then it has been heated to 450 $(°C)$ by Subsequent heater. The partial oxidation of fuel and maintaining the fluidized bed has been done by the primary air .Also, air can be supplied at two other levels as secondary air and tertiary air [42]. Simplified diagram of the experimental facility is shown in Figure 14.

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 13 : Atmospheric fluidized bed gasifier Biofluid 100

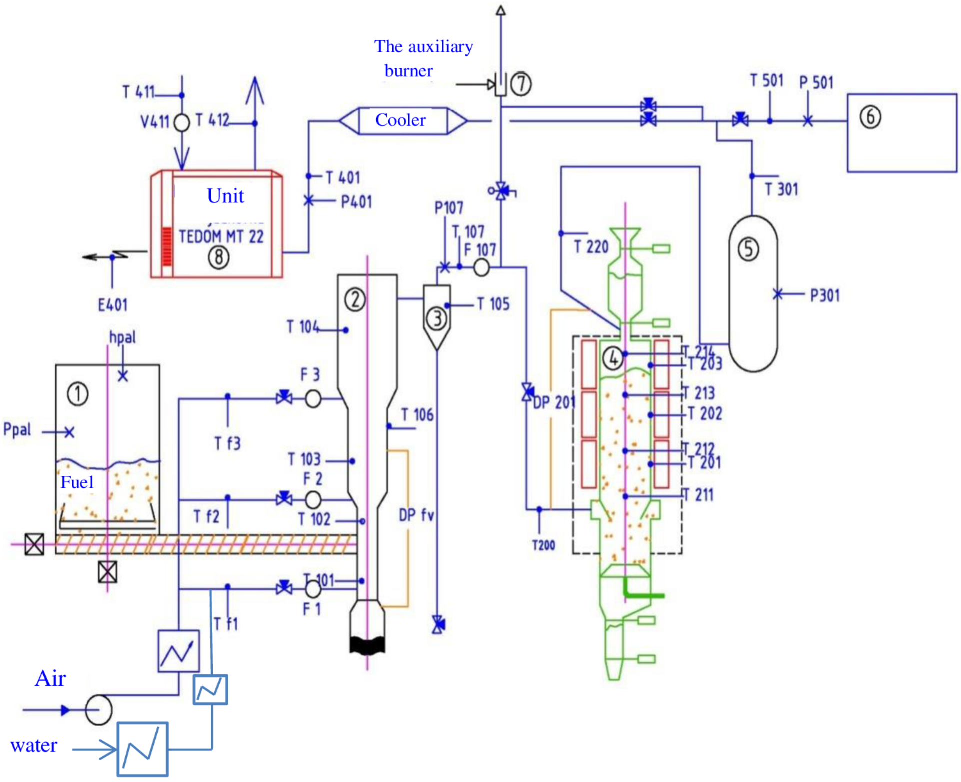


Figure 14 : Simplified layout of the gasifier connections

10.2 Steam Generator

Steam has been generated by electrical steam boiler Figure 15 with temperature about 150 (℃) and pressure about 4 (bar), then it has been heated to 450 (℃) by Subsequent heater. Steam stream with primary air stream in the inlet of the reactor so the temperature Tf1 is the temperature of steam air mixture in the inlet of reactor.

Electric steam boiler BM 25, which used in experiments is a small steam source used mainly in small enterprises, wine plants, laboratories, etc , Operating parameters:

- Performance: up to 27 kg of steam / hour.
- Power supply: 400V/50Hz - Other voltages on request.
- Capacity generators boiler - 25 liters.
- It possible to set a heating element 6-9 - 12 - 15 -18(kW).
- Optional possibility of dividing into two independent heaters.
- Max. operating pressure is 4 (bar).

Figure 15: electrical steam generator

10.3 Fuel Material

The solid biomass do not need to complex technological treatments [49]. It had been harvested biomass and dried and cut and shredded it into a suitable size for easy transport. To control of the combustion and gasification process, according to the surface small reactions will be less suitable in large pieces of biomass, that means it is better having the smallest particle of fuel, not so small as to be carried away from the fluidized bed [15]. The pine wood chips are obtained from a local timber mill were used as the feedstock. The analysis of the feedstock was reported in Table 6, the analyses of the feedstock by RWTUV Praha, Spol.sr.o. Laboratories and test Olomoucka 7/9 656 66 Brno [48]

Table 6 : The analyses of the feedstock by RWTUV Praha, Spol.sr.o. Laboratories and test Olomoucka 7/9 656 66 Brno [48]

Specified	Sample in delivered stat	Water-free sample	Sample in flammable matter
Coarse water %	2.46	-	-
Residual water %	8.54	-	-
Total water %	11.00	-	-
Ashes %	0.47	0.53	-
Flammable material %	88.53	99.47	100.00
Combustion heat at HHV at 25°C $\left(\frac{kJ}{kg}\right)$	17893	20105	20212
Caloric value LHV at 25 °C $\left(\frac{kJ}{kg}\right)$	16426	18760	18860
Volatile matter %	74.06	83.21	83.65
Non-Volatile matter %	14.47	16.26	16.35
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	-

10.4 The Connection of Sensors and Measuring Units

In the experimental unit Biofluid 100 has been installed many of important sensors for actual operation and control, and to monitor and track the status of technology during the experiments .The sensors are connected to the measuring system, EMS 99, which measures and records of values.

The values are introduced directly and regularly by measuring system, where sensors are installed on system. For this purpose, it is used the individual measuring unit MJ type EMS-932.

10.4.1 Connecting the Measuring Unit

The measuring units are connected to the network then to the control computer, where this computer on the network likes master, it controls all technological processes of gasification unit. Communication units are equipped with a communication address, which is set by passages. For simplicity of units corresponding address,it has designated MJ. To run the external sensors units ,it equipped with an auxiliary voltage source ± 15 [V] with a current load of about l00 [mA].If the sensors require higher power, it can possible to connect the power supply terminal units with a voltage of 24 [V]. Measuring units are integrated 32 different input channels and 8 outputs. Basic Measurement of quantities in the voltage ranges 4, which correspond to the calibration of conversion constants. (Sensors are connected to the measuring unit MJ2).

10.4.2 The Measuring Unit MJ1

Measuring units MJ1 is located inside the hall C3-part heavy laboratories of the Energy Institute. Measuring unit is not yet connected with any sensor. The unit is ready for the possibility of further expansion of the measuring system in laboratory.

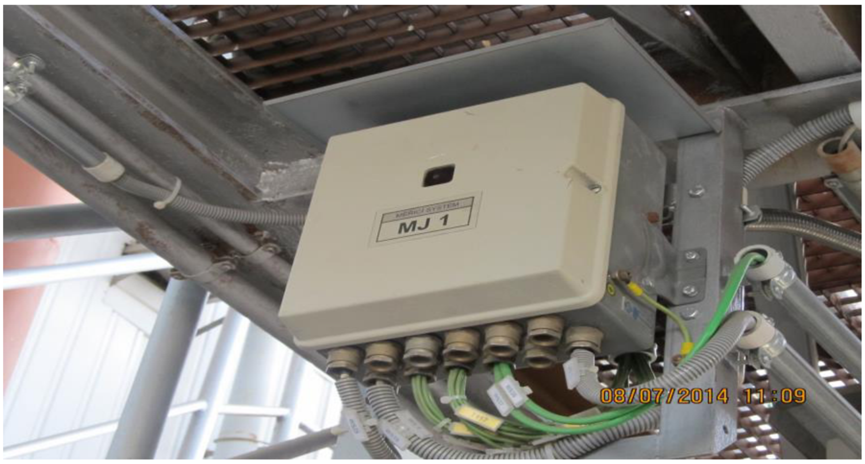


Figure 16: Measuring units MJ1 in laboratory (outdoor installation)

10.4.3 The Measuring Unit MJ2

The measurement unit MJ2 is located outside near the gasification reactor. It receives measurements from sensors ,which is installed on the gasification unit and gas filters.

Figure 17: Measuring units MJ2 in laboratory (outdoor installation)

10.4.4 Measuring Unit MJ3

The measurement unit is located inside of laboratory near the control switchboard technology. It measures hydrogen content in produced gas, it is online measurement. (Note: Name HI-201, output 0-20 [mA] on channel 21).

Figure 18 :Connecting the measuring units MJ3 (used only for measurement hydrogen content in the produced gas -online measurement)

10.4.5 The Measuring Unit MJ4

The measurement unit MJ4 is located inside the heavy laboratory of the Energy Institute in the room. It is connected to sensors for measuring performance and balance characteristics of gasification system.

This unit MJ4 is measuring and recording the following quantities :

- The pressure of gas at the inlet of the gasification system.
- The temperature of gas at the inlet of the gasification system.
- The gas flow rate which coming to the gasification system.
- The flow rate of cooling water.
- The temperature of the cooling water at the inlet and outlet of the gasification system.
- The temperature of flue gas at the outlet from the gasification system.

10.5 Temperature Measurement

Temperature sensors are used to measure the temperature inside the reactor and the gas temperature in the gasification unit. As described above.

On the equipment, rods are installed, which are thermocouple type K,where from : T 101 toT104 are temperatures in the gasifier, T105 is temperature inside the cyclone, Tf1 is temperature of the incoming primary air (the temperature of the mixture of incoming primary air and steam), T107 is gas temperature at jacket outlet.

Figure 19 : Location of one of the rod thermocouple (type K)

10.6 Measurement of pressure (differential pressure)

Pressure sensors and pressure difference is used to measure pressure and pressure drop inside the reactor in gasification unit. In the sensor body are integrated converters for the current loop. Sensors are located on the measuring panel MP1 and cables are routed to the Enclosure SK1.Power is carried from the source GU4.

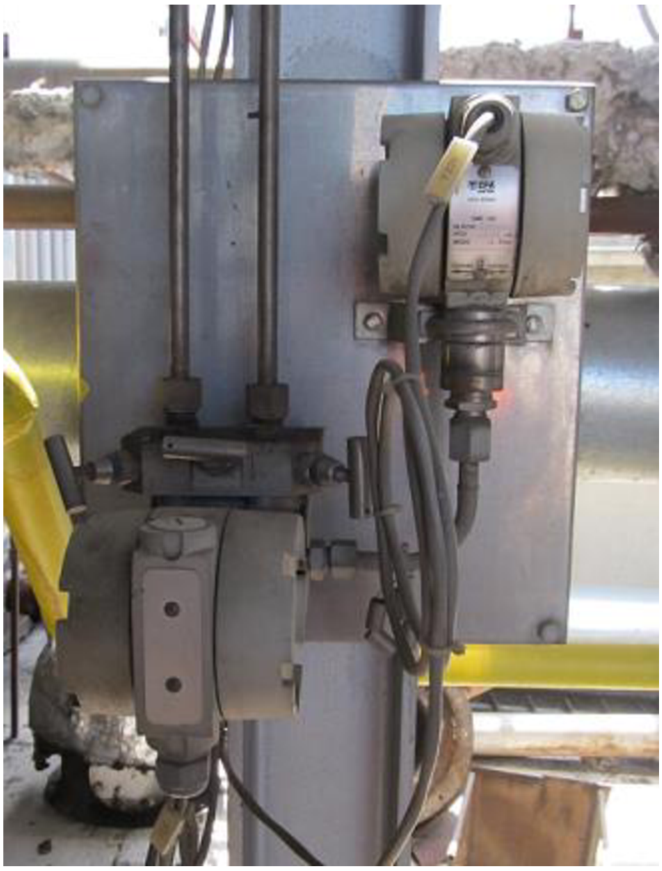


Figure 20 : Sensor of pressure loss in fluidized bed gasification reactor.

Note: For information about measurement and control system obtained from technical reports delivered in implementing equipment company ENRGOVÝZKUM spol sro.

11. Experimental Work

The principles and mechanisms of experimental measurements were described in the previous parts (chapter 10.).

The following part of the work is devoted to measure and evaluate of measured data. Samples of produced gas mixture and tar compounds are taken in the case of suitable operating mode and the stability of the gasification process.

According to the complexity of the gasifier and its operation condition, the experience was a time-consuming. Experimental measurements on Biofluid always require the cooperation of several people, especially when samples of gas and tar are taken.

11.1 Feeding Fuel Test

Most of the fuels behave differently even with basic mechanical operations such as transporting the fuel to the fluidized bed gasification reactor by using a screw conveyor. By using different types of fuels, screw conveyor transports at the same speed, different amount of fuel material. From this perspective, it is advantageous to measure the amount of transported fuel dependence on the frequency of the feed screw for a particular type of fuel. Experiment has been done to determine the flow rate of the fuel, which used in the experiments (pine wood chips) in unit Biofluid 100. Figure 21 shows the relation between the frequency and the amount of transported fuel per hour, It can be observed that every $1Hz$ is equal to 3.25 $(\frac{kg\ biomass}{h})$.

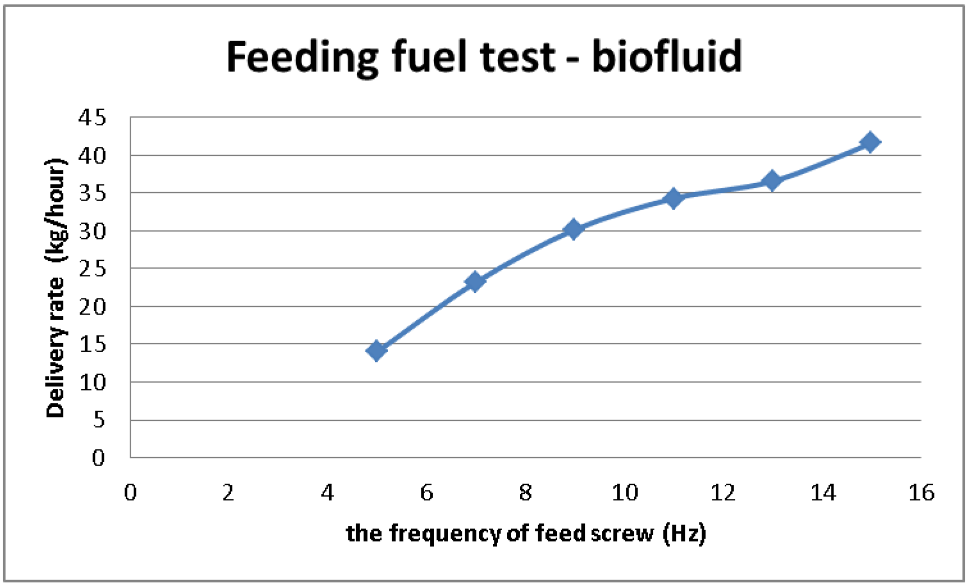


Figure 21: Showing the result of feeding trials for fuel used in experimental gasification

11.2 Methods of Measurement at Experimental Unit Biofluid 100

To determine the composition of the produced gas is used both on-line and off-line analysis [42].

11.2.1 On-line Measurement

Online measurement of the produced gas composition has advantage that it provides current information about the current process of gasification. Knowledge of the current composition of the produced gas is granted the ability to control and monitor of the current process of gasification during the experiment.

By using device INFRALYT 5000,it has been carried on-line to measure the content of produced gas[49]. The displayed data have only minimal delay by comparing to the current state. The maximum delayed length of value is two minutes[50]. The delay due to the time it takes to cross the samples of produced gas through pipelines from the point of collection to the analyzer and the actual processing of the gas analyzer[51].

The results of the online analysis of samples from INFRALYT 5000, it has been processed and saved on computer. This device measures the carbon dioxide CO_2, carbon monoxide CO, mixture of hydrocarbons $HC$and the remaining oxygen O_2. There is a sensor to measurement of hydrogen content in the product gas, which is connected to the measurement and control system.

the collected samples gas have been passed through tube in a relatively cool environment, so the temperature of gas sample has been cooled when passing through the tubing to the gas analyzer, at the ambient temperature 20°C, this leads to condensation tar on the walls of the pipes, therefore it is often a blockage tubes of supplying gas to the analyzer during the experiment.

The produced gas contains a large amount of tar compounds, which could damage a gas analyzer; therefore it must get rid of tar content of gas before analysis. Gas is cleaned by lowering the temperature to a lower temperature than the temperature of the dew point of the tar compounds. Lowering of collected gas sample temperature is realized by use two flasks with acetone chilled to about $(-20°\mathrm{C})$. The passing gas was cooled by chilled acetone and also acts as a solvent which dissolves and captures undesirable tar. Here is the problems that condensing moisture which contained in the produced gas , freezes in the flask, thereby hindering gas flow to the gas analyzer.

.

Figure 22 : Device INFRALYT 5000 for on-line evaluation of the basic components of produced gas

11.2.2 Off-line Measurement

To describe the quality of the produced gas is necessary to know its composition exactly. The On-line measurement have been determined the content of some components of the product gas, but they are often inaccurate measurements, and cannot be relied upon to evaluate the state of the gas .It is partial information to control the experience better. At the same time, samples are taken of the produced gas, by glass flask as it shown in Figure 23.

Flask must be filled by water before the sampling and must be placed in a vertical position during taking the sample. The upper tap is connected to teflon tube , where gas must flow through it already, then the first upper tap is opened and then is opened tap bottom, as a result, the water come out from bottom tap , thus it creates a vacuum, and therefore the gas is sucked into the bottle through the upper tap ,after all water in the flask flow away , in first , it must closed the bottom tap of flask, thus creating a slight overpressure,after the top tap have been closed ,this prevents contamination of the gas sample by air .Then have to send gas samples, that have been taken in glass flasks to the lab for analysis and accurately identify the components of the gas. Figure 24 shows the sampling of gas.

Figure 23: Bottles for gas sampling

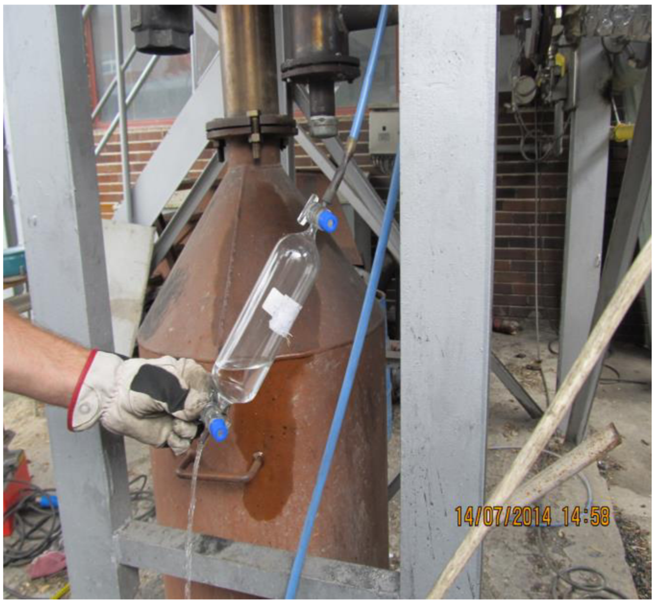


Figure 24: The gas sampling

11.3 Sampling Tars

The content of tar in produced gas generally be within the domain 1 - 5 $\left(\frac{gr}{m^3}\right)$, this is depending on used fuel, operating conditions and gasification agents. Experiments will be done to quantify the tar concentration in syngas. Figure 25 shows the schematic diagram of the experimental set-up used to measure tar concentration in a syngas, which is produced from the gasification of wood chips in a fluidized bed gasifier. A standard sampling line was used for tar collection. It is described in more detail in the Tar Protocol [28]. For our purposes it had been used three absorption flasks with acetone (150 ml). The first and second was in water with salt at temperature -20 °C, the third flask was cooled in a bath by ethanol at temperature - 40 °C. The second and third flask filled with glass beads with a diameter of 5 [mm], then it have to send tar samples to the lab .Tar analysis were done in the chemical Laboratory in Prague [28].

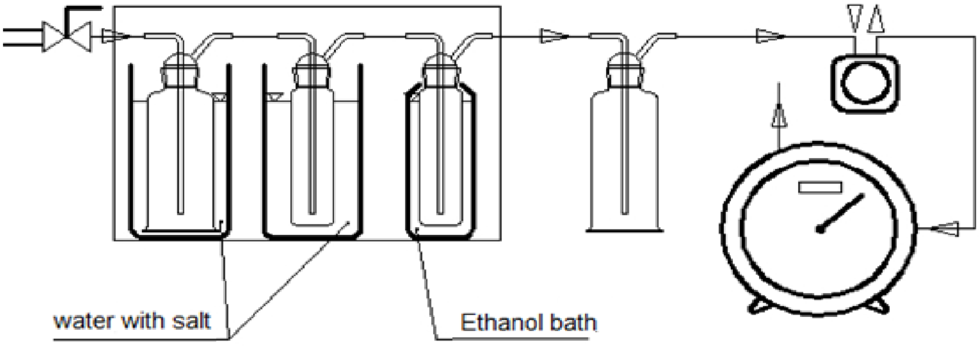


Figure 25 : schematic diagram of the experimental set-up used to measure tar content in a syngas

11.4 During the Gasification

The following chapter describes the stages of the experiment of the pine wood chips gasification by using two gasification agents (air, air-steam mixture),where have been focused on the description of processes of gasification and the operating parameters of the system gasification for both agent.

During the experiment the sampling of the gas product has been done, to know the components of the produced gas, and others samples were taken to measure the gas content of the tar. It has been selected sampling method in order to obtain the required information. Before taking a sample of tar and after, the sample of the gas have been taken in the glass sample flask. Analysis of the gas sample was carried out by gas chromatography at the Technical University in Brno, and tar samples were conducted at Technical University in Prague.

11.4.1 During of the Experiment

Experiment often has been lasted two days,the first day has been devoted to the preparation and cleaning of the experimental equipment. It has been cleaning gasification reactor, emptied the ashes from the bottom of the reactor ,emptied ash from the cyclone, cleaning the leaky pipe under the cyclone and outlet pipes. It was also needed to prepare glassware for sampling tar and gas.

To reach to the operating temperature of gasification reactor ,the reactor must be ignited around 7:00 o'clock to around noon to start the sampling. Heating is not only a reactor , that will warm up relatively quickly, but also the outlet pipe of produced gas, which is located behind the cyclone, where is separator of solid particles ,and orifice of gas flow ,which is the place where the tar samples are taking . To prevent unwanted condensation of tar in this section of biofluid , the pipe outlet must be warmed to a temperature of at least 200 °C [12]. Unwanted condensation of tar compounds in the pipe reduces the amount of tar trapped in the collection line, so the obtained data from a sample of tar and may not correspond to reality, and this increases the measurement error.

At the beginning, the gasification reactor was operated in the combustion mode. When the temperature in the primary zone reached 700 ° C , it has been added the amount of fuel fed to the reactor , which ensure the transition to the gasification systém. It has been feed a small amount of tertiary air ,about $3-6\ \left(\frac{m^3}{h}\right)$,in the upper part of the reactor to speed up the warming , this allowed the partial combustion to occur, and causes the increasing output gas temperature. To reach the required temperature of the reactor usually requires about 3 hours, this depends mainly on the quality of used biofuel. After connecting the measurement devices and stabilize of the gasification process can be started gas and tar sampling at the operational parameters.

Experiments were repeated multiple times with varios success. Often unable of the operation parameters of reactor stabilize ,so that they cant be sampled.

11.4.2 Describtion of Experiment

The purpose of the measurement was to compare the properties of the produced gas $(H_2, CO, CO_2, CH_4, C_2H_6, LHV)$ and tar content by using each of the agents (air and air-steam mixture). Attempts have been done to ignited the reactor from 7:30 o'clock , with the flow of primary air was about 10 $\left(\frac{m^3}{h}\right)$m3/hour at about 70 ℃ . Fails to stabilize the temperature in the primary zone of the reactor, the device had to be shut down a few times and started again (about 8:50 o'clock to 9:30 o'clock), It must be cleaning up the fluidized layer to improve the operation of the equipment.

At 10:00 o'clock : gasification mode have been started , Biomass feed flow had been added about B =23 $\left(\frac{kg}{h}\right)$.To achieve stability of gasifier it must raise the reactor temperature to the required temperature for gasification (it must be more than 800℃) , so it must be increased the flow of primary air to 20 $\left(\frac{m^3}{h}\right)$, and tertiary air supply was turned on for better warming of downstream pipeline routes F3 =6.5 $\left(\frac{m^3}{h}\right)$

At 11:08 o'clock : stability was achieved, where reactor temperatore was about $T101 = 829$℃ (look to the figure 26) , so tertiary air had been turend off and started measurement .

At 11:30 o'clock :gas sample (gas1) has been taken and tar sampling has been started (tar1) .

At 11:49 o'clock : tar sampling has been finished and gas sample (gas2) has been taken also.

at 12:00 o'clock : steam has been feed to the reactor, where it has been mixed with the air at the inlet of the reactor, the steam flow was about 17 $\left(\frac{kg}{h}\right)$.

At 12:59 o'clock : gas sample (gas3) has been taken and tar sampling has been started (tar2)

At 12:59 o'clock : tar sampling has been finished and gas sample (gas4)has been taken also.

At 13:06 o'clock : steam flow has been reduced from 17 to 13:52 $\left(\frac{kg}{h}\right)$.

At 14:00 o'clock : gas sample (gas5) has been taken and tar sample(tar3) has been started .

At 14:22 o'clock : tar sampling has been finished and gas sample (gas6)has been taken also.

At 14:29 o'clock : steam flow was reduced from 13:52 to 11:77 $\left(\frac{kg}{h}\right)$

At 15:00 o'clock : gas sample (gas7) has been taken and tar sample(tar4) has been started .

At 15:23 o'clock : tar sampling has been finished and gas sample (gas8)has been taken also.

At 15:35 o'clock : the experiment had been finished.

Note : T107 is the temperature of the outlet produced gas at the outlet of gasifier ,it must be more than 200 °C when sampling tar .

The gradual increase of pressure in the reactor shown in figure 27, there was a pipe clogging by mixtures of tar compounds and dust in produced gas. After increased the temperature of reactor to improve the gasification process, the clogging of pipes decreased because the hot gas, it is clear that after add steam pressure was increased

Feeding the reactor by fuel plays an important role in stabilizing the temperature in the primary zone of the reactor .transporting the fuel to the fluidized bed gasification reactor by using a screw conveyor. The amount of fuel transported dependence on the frequency of the feed screw (see paragraph 11.1).

As shown in the Figure 26, reactor has been reached to stabilized with a little interfere. Control frequencies of the fuel feed screw to achieve stabilized temperature in the primary zone of the reactor then when need to change to another gasification temperature.

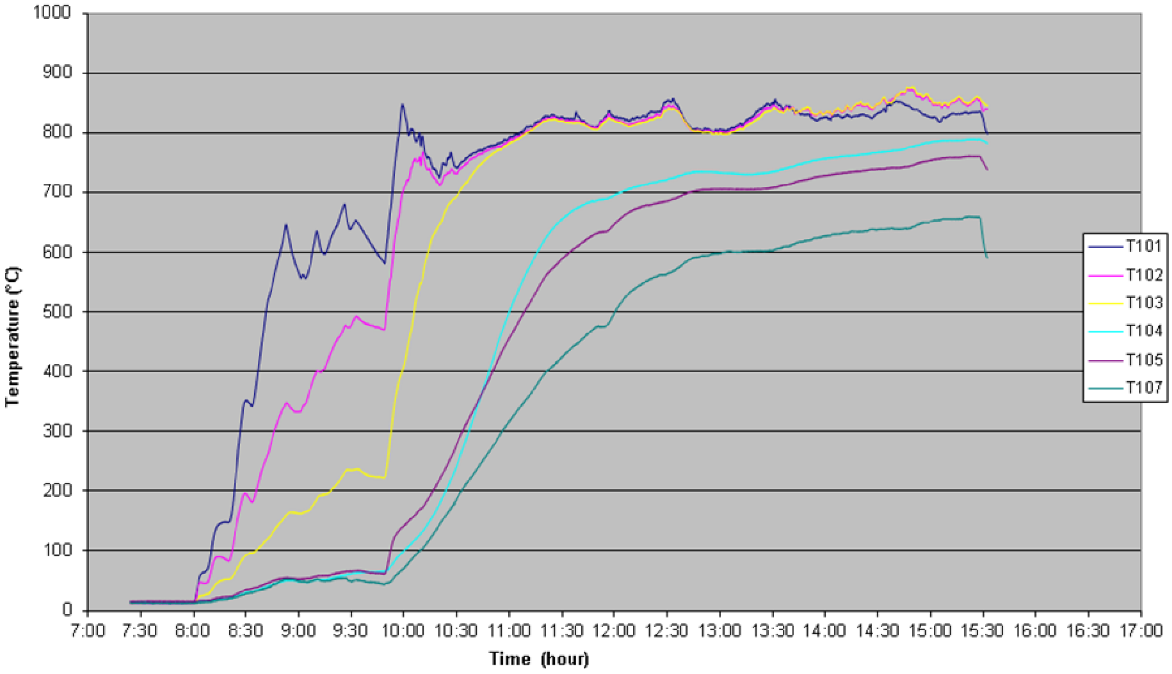


Figure 26.: Temperatures in the reactor

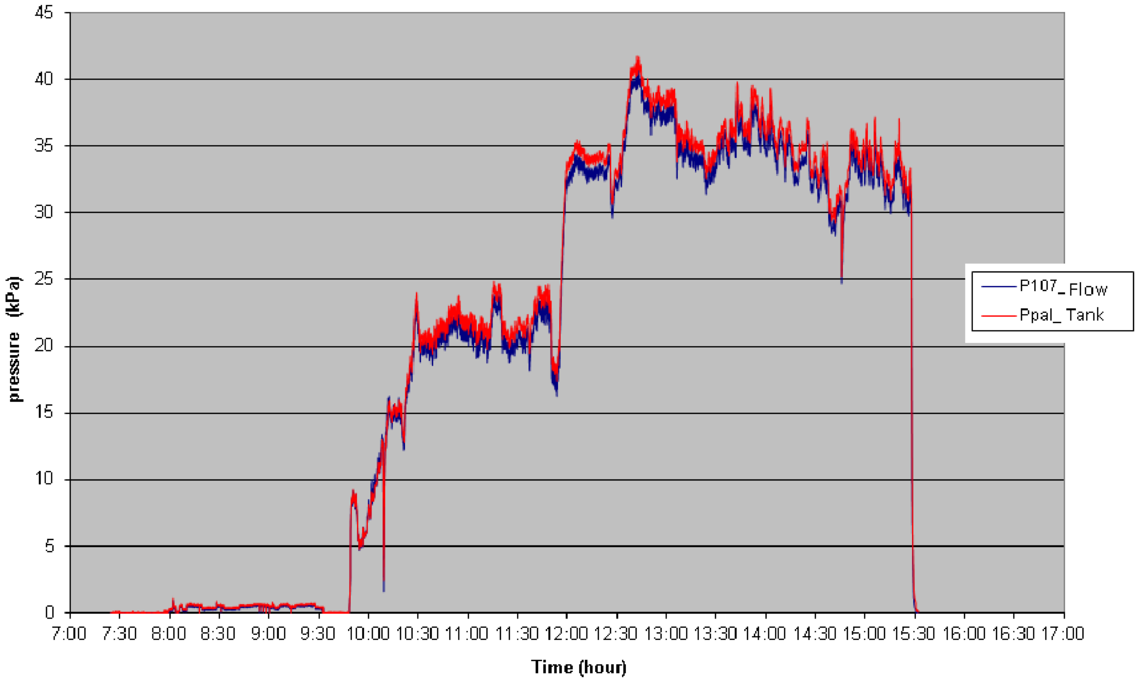


Figure 27 : The overpressure at the outlet of the gasifier (PI07) a positive pressure in the fuel tank (Ppal)

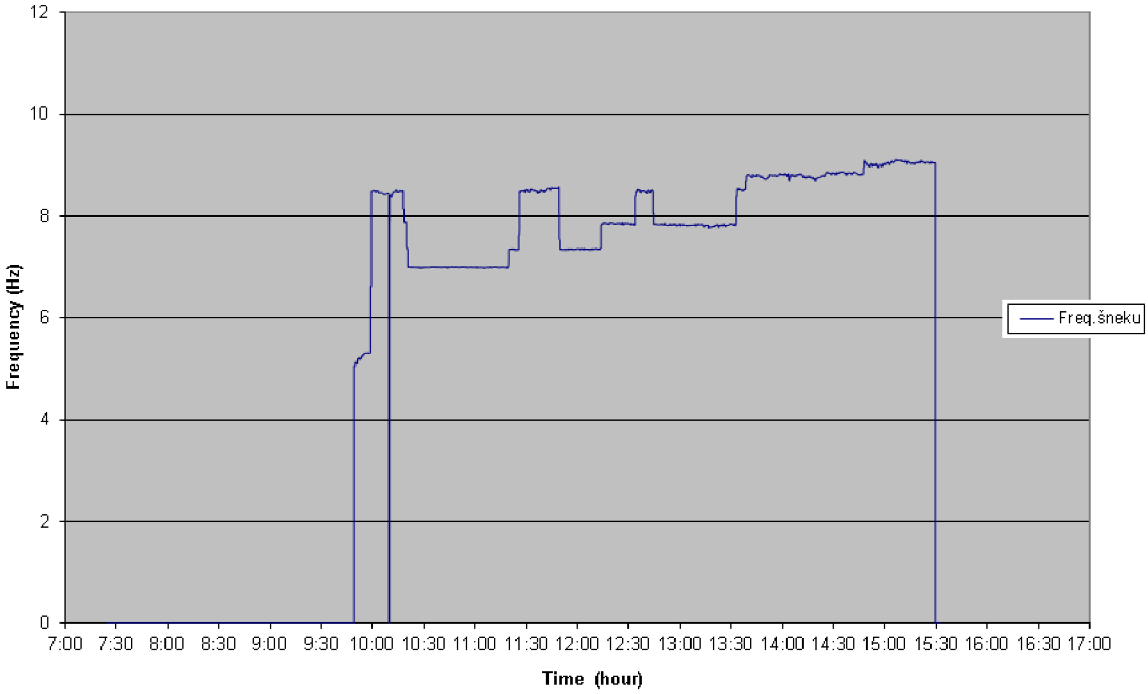


Figure 28 : Frequency of the feed screw during the experiment

Figure 29 and Figure 30 ,show the change in values of each steam to biomass ratio $\frac{S}{B}$ $(\frac{\text{kg steam}}{\text{kg biomass}})$ and steam to air ratio $\frac{S}{A}$ $\left(\frac{\text{kg steam}}{\text{kg air}}\right)$, during the experiment , respectively

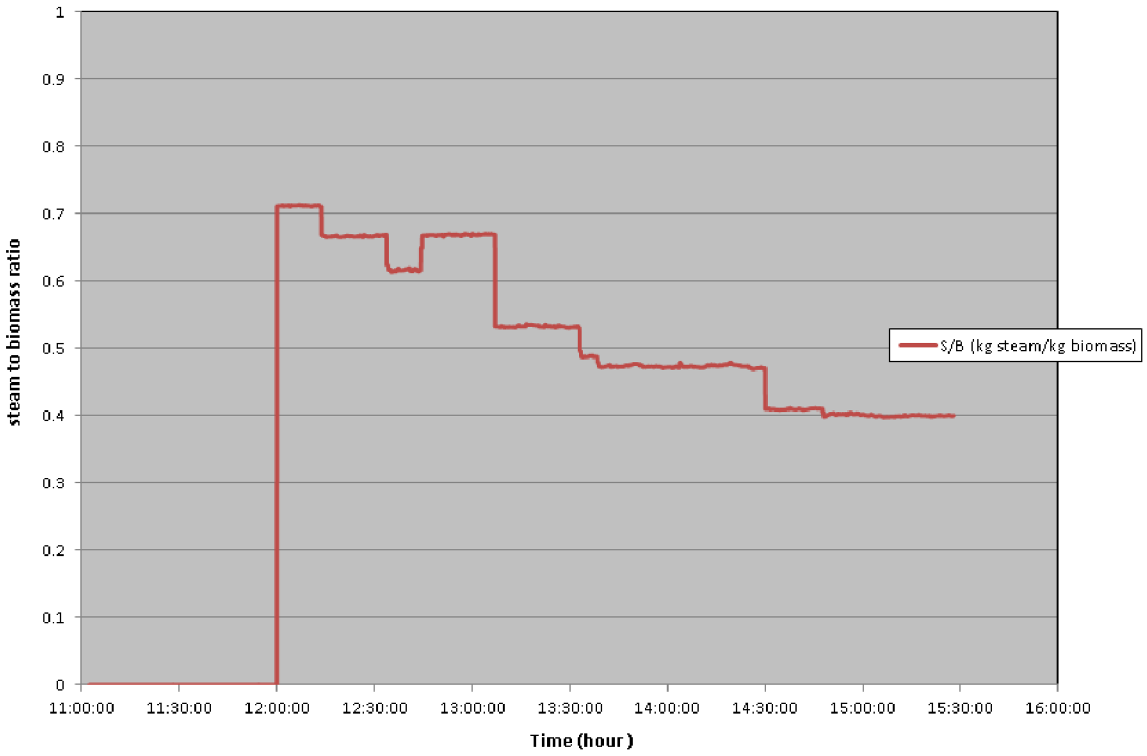


Figure 29:Steam to Biomass ratio during the expirment

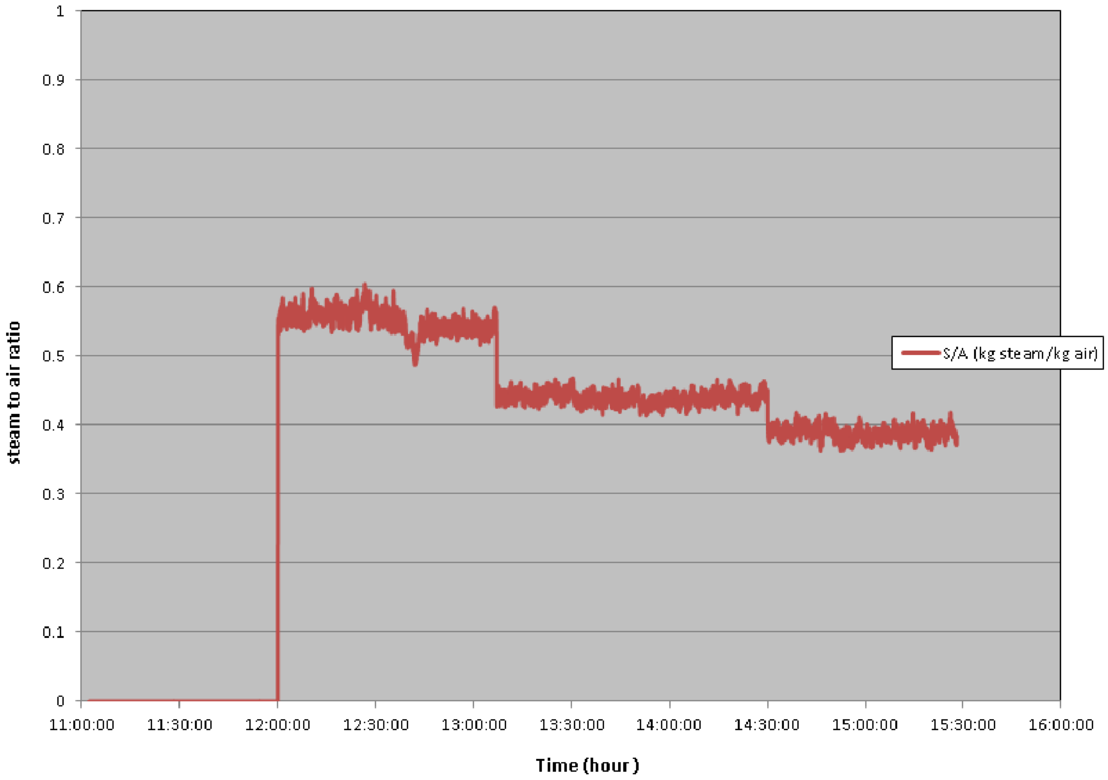


Figure 30: Steam to air ratio during the expirment

The following figures, show the evolution of the concentration of the basic components of produced gas . The collected gas line has been connected to the measurement units (INFRALYT 5000 , measuring units MJ3 , and Computer of control and driving) . It has been recorded the results of the analysis of gas samples intraday(every two seconds). This measurments called online . The aim of this measurement is controling and monitoring the gasification process to achieve the stabilization of the gasification process.

Note: more particular values of gas composition have been detected by analyzing of gas samples, which has been taken into the glass flasks during the experiment (offline measurement).

From Figure 31, it can be observed , that concentration of hydrogen in the product gas increases by using mixture of steam and air as a gasifying agent, this seems clearly through period from 12:00 o'clock to 15:30 o'clock.The concentration of hydrogen has been reduced with reduced flow steam rate , where in the period from 12:00 o'clock to 13:06 o'clock, hydrogen content was about (16.5-18.5 %), the flow of steam about $17\left(\frac{\text{kg steam}}{\text{h}}\right)$ and steam to biomass ratio of about $\frac{\text{S}}{\text{B}} = 0.67(\frac{\text{kg steam}}{\text{kg biomass}})$, and in period from 13:06 o'clock to 14:29 o'clock, hydrogen content was about (14.5-15.5 %.), where the flow of steam is reduced from 17 to about $13{:}52\left(\frac{\text{kg steam}}{\text{kg biomass}}\right)$ and steam to biomass ratio was about 0.5 , also from 14:29 o'clock to 15:25 o'clock, where the flow of steam is reduced from 13.52 to about 11.77 $\left(\frac{\text{kg steam}}{\text{h}}\right)$and steam to fuel ratio of about S/B = 0.4 , the hydrogen content was about (13-14 5 %).

Note: These values are not accurate , because of the problems, that have been mentioned in paragraph 13.4, but these values are important for the control and monitor of the experiment.

From figure 32 ,it can be observed, that the concentration of carbon monoxide in the product gas has been reduced by using mixture of steam and air as a gasifying agent this seems clearly through period from 12:00 o'clock to 13:30 o'clock.

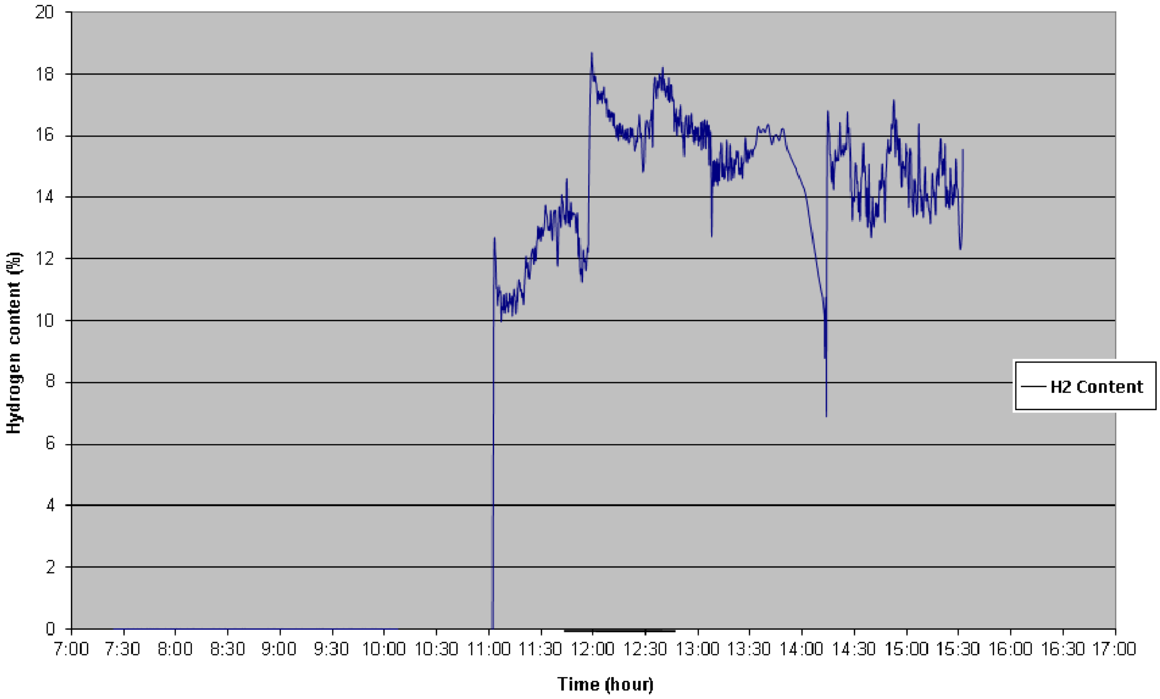


Figure 31: The hydrogen content during the experiment

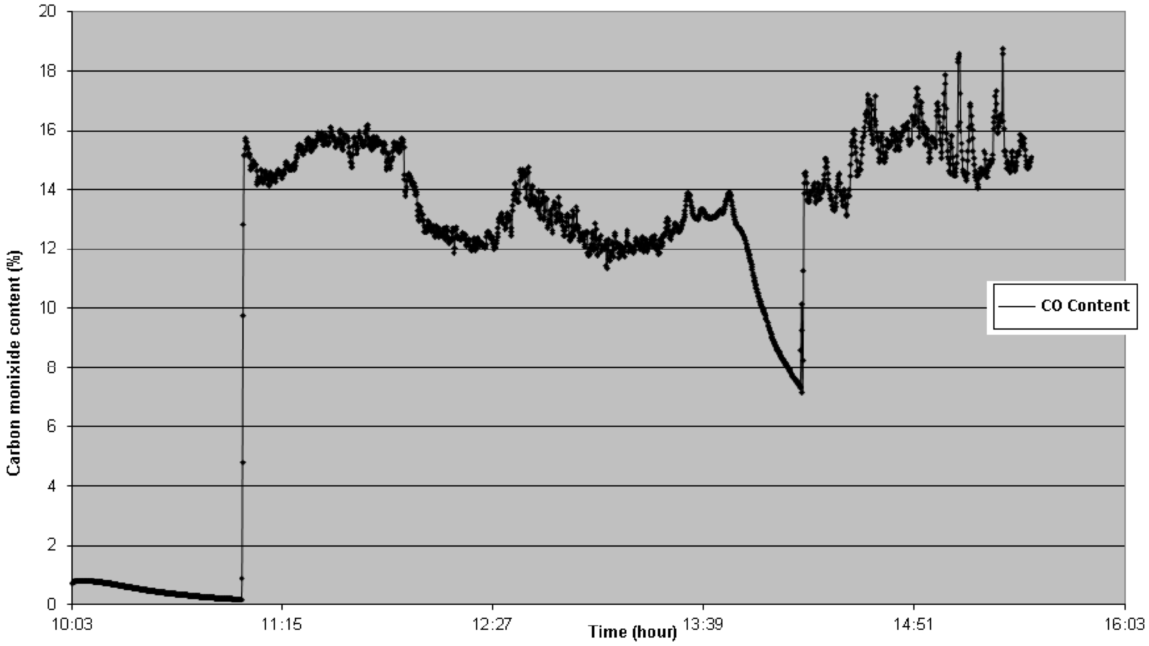


Figure 32:The concentration of Carbon monixide during the experiment

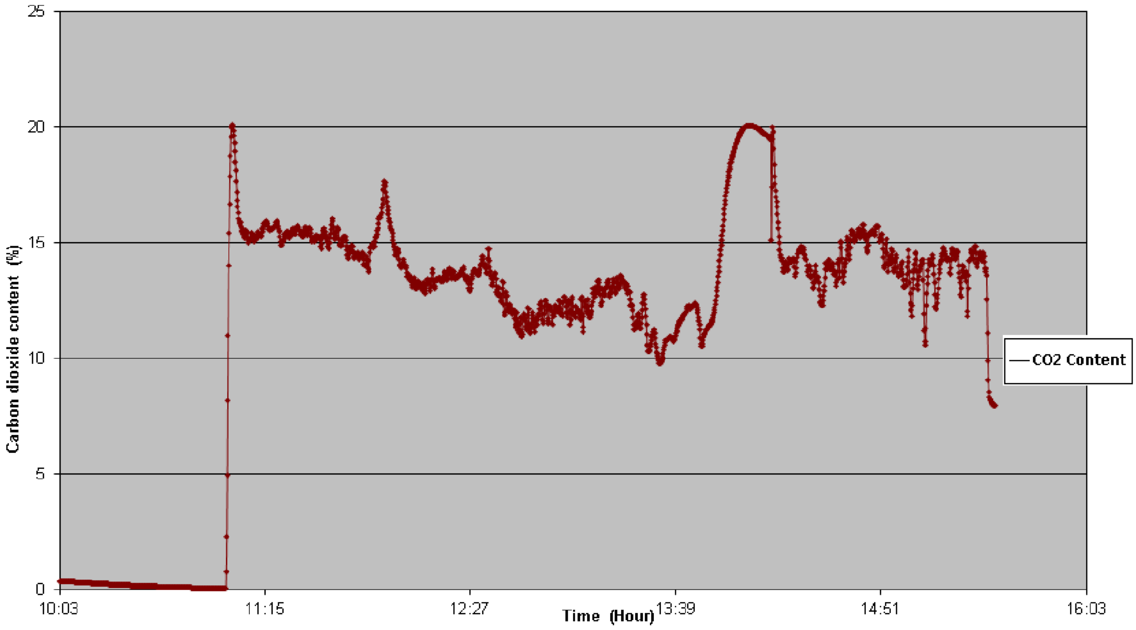


Figure 33: The concentration of Carbon dioxide during the experiment.

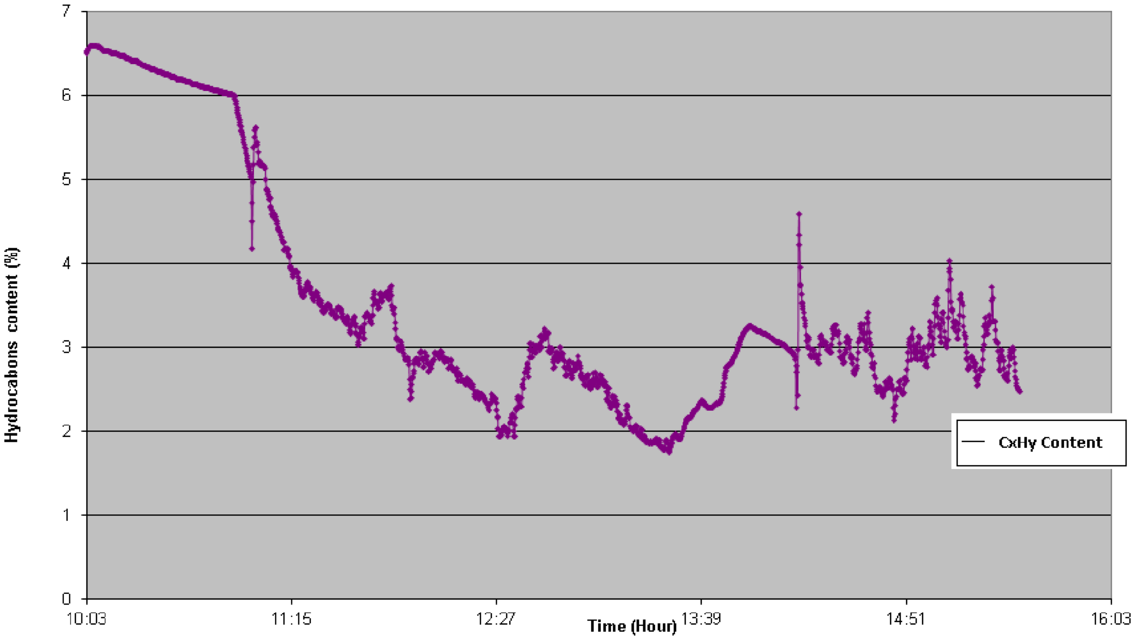


Figure 34 : The concentration of Hydrocarbons during the experiment

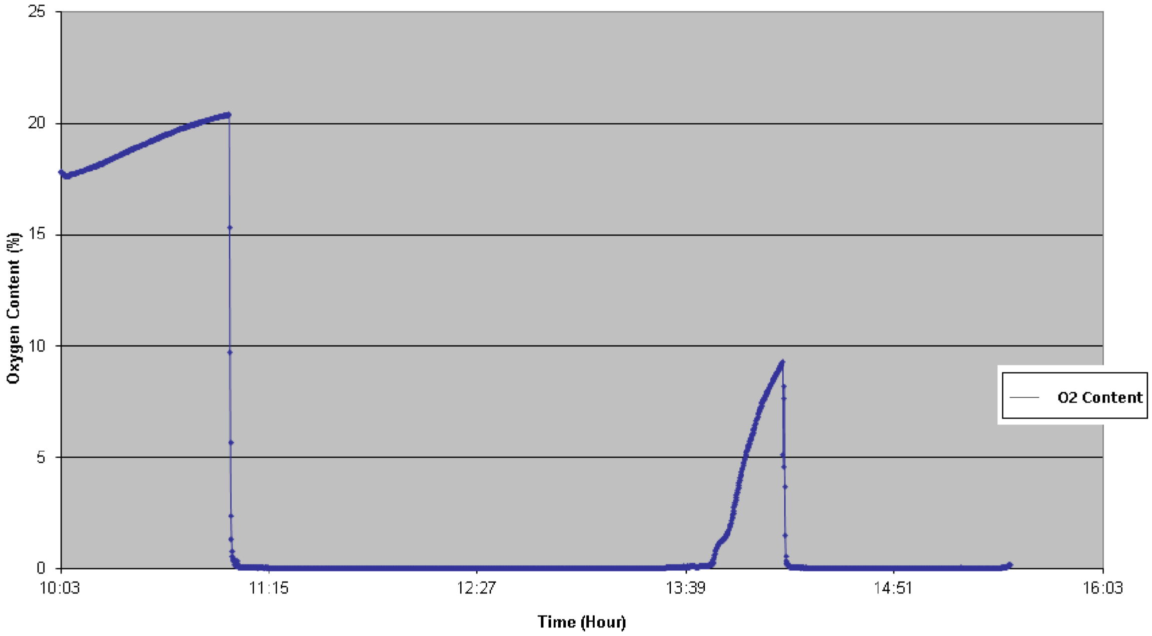


Figure 35 :The concentration of Oxygen during the experiment

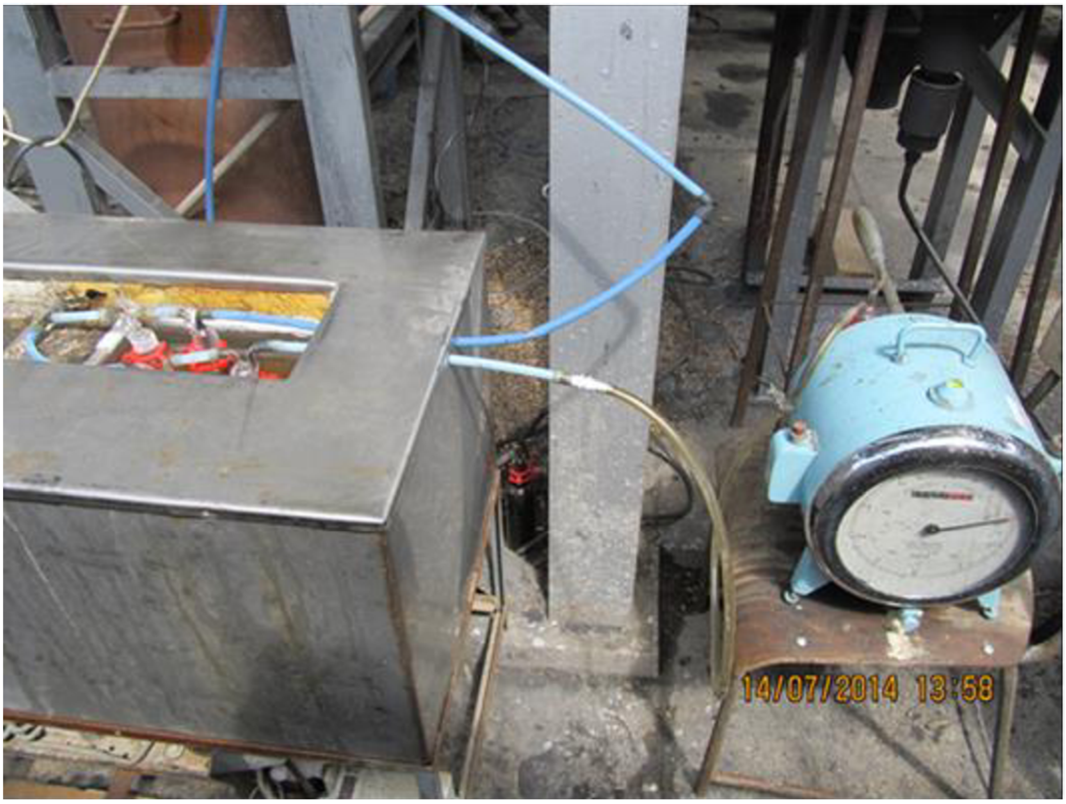


Figure 36 : The experimental equipments which used to measure tar content in a produced gas.

Figure 37 : The samples of tar which had been collected during the experiment

11.5 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.

11.5.1 Analysis of Gas Samples

As mentioned above, the analysis of the gas samples, which have been collected in glass flask, they have been carried in Mechanical Engineering Faculty at the Brno Technical University (BUT).It has been used HP 6890 chromatograph fitted with TCD and FID detectors. The concentration of basic components of the sample gas $(H_2, CO, CH_4, CO_2, O_2, N_2)$ have been determined by using TCD detector. the concentration of Mixtures of lighter hydrocarbons have been determined by FID detection. For both channels have been used helium as carrier gas[49].

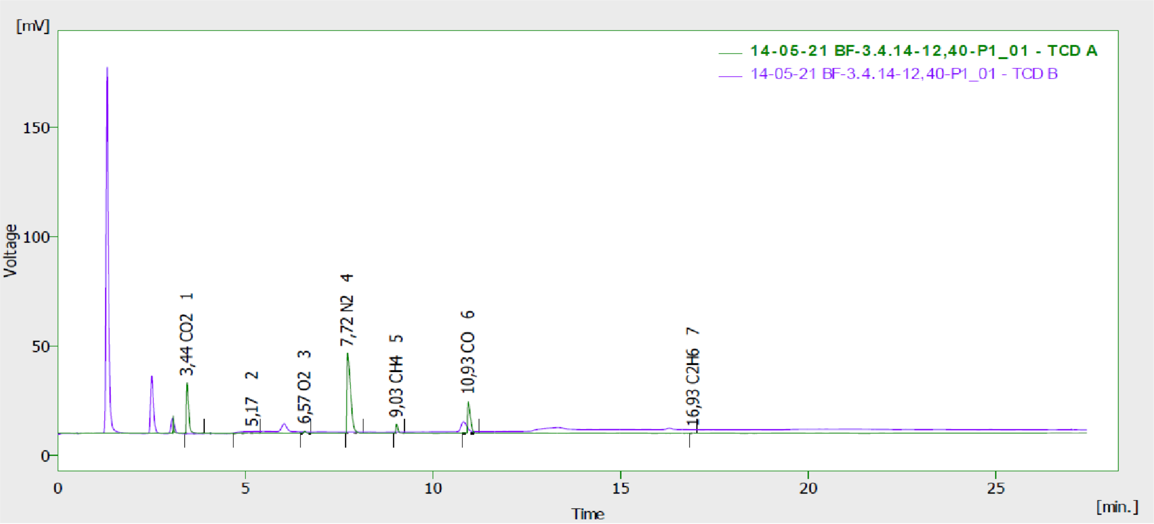


Figure 38 : Diagram of output sample of a gas by using chromatograph HP 6890, with a HP 5973 mass spectrometer for analysis of samples of gas composition

11.5.2 Analysis of Tar Sample

Before the analysis, the samples adjusted by filtration on a paper filter for the fine filtration. Weight of collected dust has been measured and used for calculation of dust in the gas, the values obtained are indicative only, it is possible to observe during the sampling. After filtration, the transportation flask flushed with 20-25 (ml) of pure acetone, which was also purged with the filter dust. It was measured the total volume of the solution obtained and its parts $1(ml)$ was analyzed by gas chromatography with mass detector [49].

For the analysis of the composition and content of tar substances used gas chromatograph HP 6890 with mass spectrometer HP 5973 from Agilent (USA). Sample injection will perform an autosampler HTA 300A (Italy). It was injected sample of 1 [µg], the temperature of the spraying chamber was 280 °C. For identification of unknown components and qualitative analysis of a mixture of standard polyaromatic hydrocarbons (PAH) [50]. Unknown compounds were identified based on comparison of retention times of the standard, compliance mass spectra identified substances database (NIST 98) and comparing the calculated retention index with published values. For the quantitative determination method was used absolute calibration using the external standard. As the standard solution was used 16 PAHu with concentration about 200[µg/ml]. Processing and evaluation of the resulting chromatographic recording was performed using ChemStation Software[49].

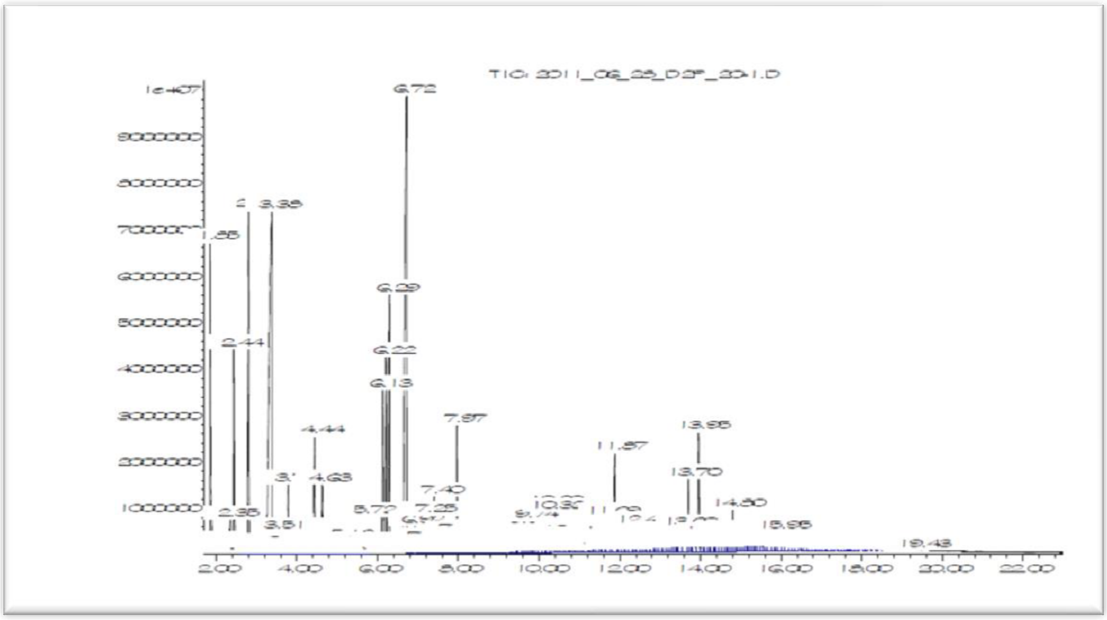


Figure 39 :Sample output diagram of a gas chromatograph HP 6890 with HP 5973 mass spectrometer for analysis of the composition of tar compounds

12 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 .

In order to accomplish this task, it has been divided the experimental work into three primary stages:

I. Determination the best of reactor temperature T101 and steam to biomass ratio $\frac{S}{B}$.
II. Determination the best of steam temperature Tf1 at the best reactor temperature T101.
III. Determination the best of reactor equivalence ratio at the best T101 and the best Tf1.

Three stages have been carried out at the variable values of steam to biomass ratio.

Gas and tar samples have been taken during the experiment in different condition according to the aim of this work.

12.1 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 (℃) in 20 (℃) 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 (℃), 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(℃), 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 40 to 55.

Table 7: Results of the analysis of some gas samples

T101 = 829 (°C), Tf1 = 260 (°C), ER=0.29									
$\frac{S}{B}$	H_2	CO	CH_4	CO_2	C_2H_6	O_2	N_2	Others	total
0	10.48	16.60	1.98	14.11	0.09	0.054	56.41	0.25	100
0.23	14.16	16.61	2.50	14.24	0.17	0.071	51.75	0.46	100
0.4	16.33	16.33	2.99	14.60	0.20	0.083	49.15	0.30	100
0.50	17.46	15.99	3.22	14.80	0.23	0.059	46.65	1.57	100
0.6	18.97	15.77	3.45	15.36	0.25	0.005	46.00	0.16	100
0.67	19.67	15.46	3.49	15.59	0.30	0.05	44.60	0.80	100
0.7	19.54	15.09	3.55	15.89	0.29	0.004	45.28	0.33	100
0.75	18.29	14.81	3.56	16.02	0.25	0.045	46.80	0.21	100
0.85	17.89	14.51	3.58	16.10	0.23	0.045	47.35	0.27	100

Where : Others are included the Argon(A_r) and hydrocarbons which cannot be calculated in the lab ,but its content in the gas samples.

Note : 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 $\left(\frac{MJ}{m^3}\right)$ has been calculated by this flowing quation [7]:

$$LHV = (30\,CO + 25.7H_2 + 85.4CH_4 + 151.3\,C_nH_m).4.2/1000 \ldots\ldots 14$$

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

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

$$V_{gas} = \frac{0.79}{N_2}.F_1 \ldots\ldots\ldots\ldots 15$$

$$M_{gas} = \frac{0.769\,.\,A+N_f}{28\,N_2} \ldots\ldots\ldots\ldots 16$$

Where: Air contains 76.9% nitrogen by mass and 79 % by volume.

N_f (%): Content of nitrogen in biofuel feed.

N_2 (%): Content of nitrogen in produced gas.

$A\left(\frac{kg_{air}}{kg_{biomass}}\right)$: Air supply rate.

Air supply rate has been calculated by this equation[49] :

$$A = \frac{F1/\rho_{air}}{B} \text{ ....17}$$

Where :

$F1\left(\frac{m^3}{h}\right)$: primary air flow rate ,it has been measured during the experiment .

$B\left(\frac{kg}{h}\right)$: Biomass flow rate . it has been measured during the experiment..

$\rho_{air}\left(\frac{kg}{m^3}\right)$: Specific weight of air it has been calculated by the equation of state[6]:

$$P.V = mRT \text{.............18}$$

$$\rho_{air} = \frac{m}{V} = \frac{P}{RT} \text{...........19}$$

$T\ (K)$: The temperature of inlet air before mixing with steam .

$R\left(\frac{J}{kg.K}\right)$: Ideal air constant, it is about 287 $\left(\frac{J}{kg.K}\right)$ for air.

$P\ (Pa)$: The air pressure, It has been considered equal to the gas pressure at the outlet of gasifier P107,

$$P = P107 + P_{atm} \text{.......20}$$

Where :
$P_{atm}(Pa)$: Atmospheric pressure

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

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

$$\eta_c = \frac{(CO+CO_2+CH_4+2\ .\ C_2H_2).M_{gas}\ X\ 12}{C}\ X100 \text{......21}$$

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 6 .

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

$$\eta_{geff} = \frac{\sum HHV_{gas}}{HHV_{biomass}}\ X100 \text{..........22}$$

Where :

$HHV_{biomass}\left(\frac{MJ}{kg_{biomass}}\right)$: High heating value of biomass it has been taken from table 6 .

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

$$\sum HHV_{gas} = HHV_{CO} + HHV_{CO_2} + HHV_{CH_4} + HHV_{C_2H_6} \ldots\ldots 23$$

The heats of combustion for different gas constituents are [5] :

$HHV_{\dot{C}o} = 282.99\left(\frac{MJ}{kg\ mol}\right), HHV_{\dot{H}_2} = 285.84\left(\frac{MJ}{kg\ mol}\right),$
$HHV^{\cdot}{}_{CH_4} = 890.36\left(\frac{MJ}{kg\ mol}\right)$

And $HHV^{\cdot}{}_{C_2H_6} = 1559.7\left(\frac{MJ}{kg\ mol}\right)$:

By using this values, it can be computed the heat of combustion of the gas.

$$HHV_{Co} = CO\ .M_{gas}.\,282.99 \quad \left(\frac{MJ}{kg\ \ biomass}\right)$$

$$HHV_{H_2} = H_2\,.M_{gas}\,.\ 285.84 \quad \left(\frac{MJ}{kg\ \ biomass}\right)$$

$$HHV_{CH_4} = CH_4\,.\ M_{gas}\,.890.36 \quad \left(\frac{MJ}{kg\ \ biomass}\right)$$

- Calculate of equivalence ratio ER , which has been calculated by this flowing equation[5]:

$$ER = \frac{A}{A_{min}} \ldots\ldots\ldots 24$$

Where :

A $\left(\frac{kg\ air}{kg\ biomass}\right)$: air flow rate.

$A_{min}\left(\frac{kg\ air}{kg\ biomass}\right)$: stoichiometric air which has been calculated by[49] :

$$A_{min} = \left[\left(\frac{22.39}{12.01}C + \frac{22.39}{4.032}H - \frac{22.39}{32}O\right).\frac{100}{21}\right].1.016 \ldots\ldots\ldots\ldots\ldots\ldots 25$$

Where : C ,H ,O (%) are the content in the ultimate analysis of biomass (table 6)

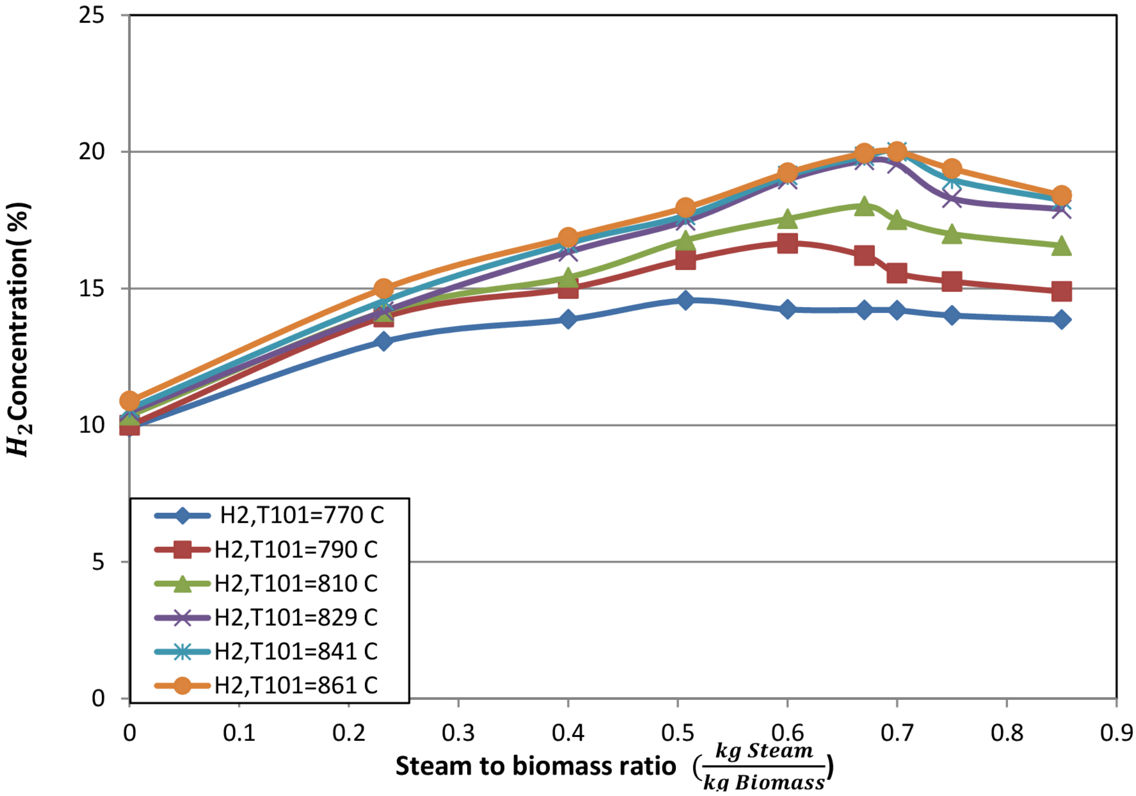


Figure 40 : The effect of $\frac{S}{B}$ and T101 on hydrogen content in produced gas

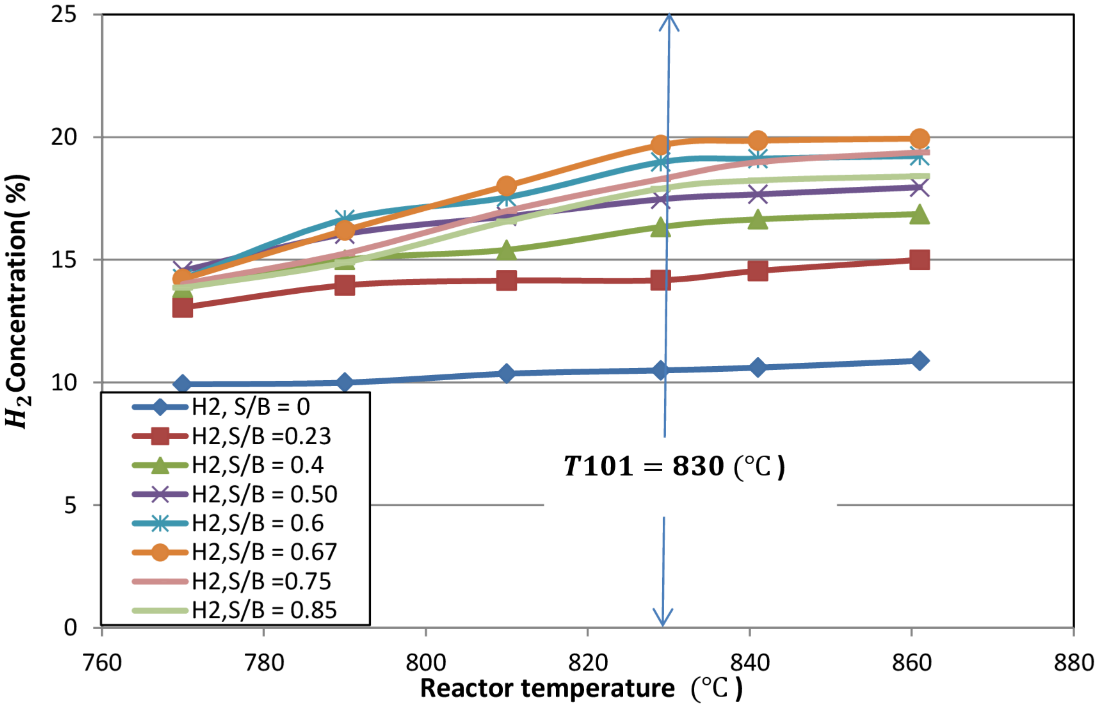


Figure 41 : The effect of $\frac{S}{B}$ and T101 on hydrogen content in produced gas

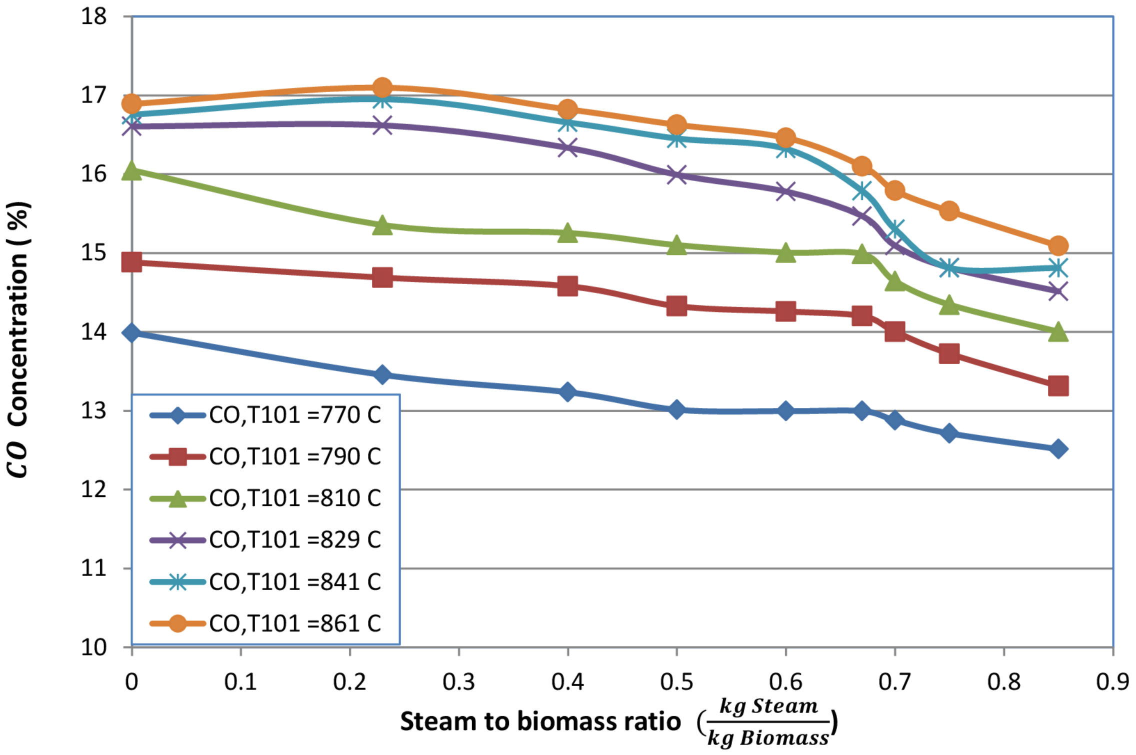


Figure 42 : The effect of $\frac{S}{B}$ and T101 on Carbon monoxide content in produced gas

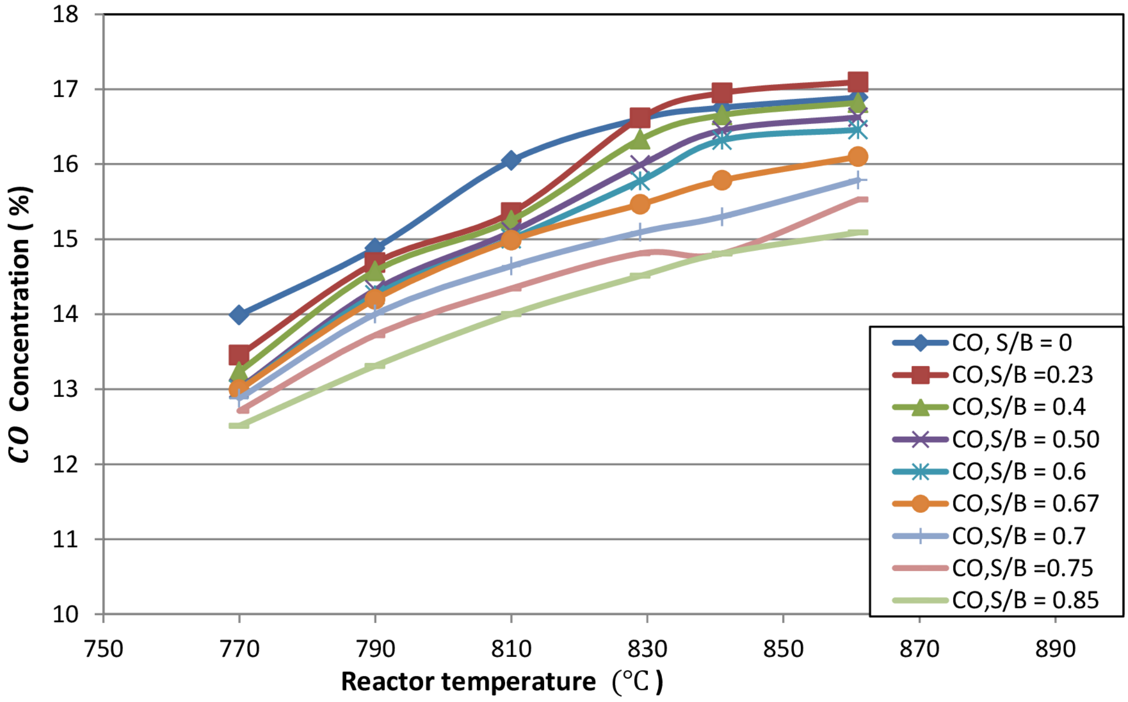


Figure 43 : The effect of $\frac{S}{B}$ and T101 on Carbon monoxide content in produced gas

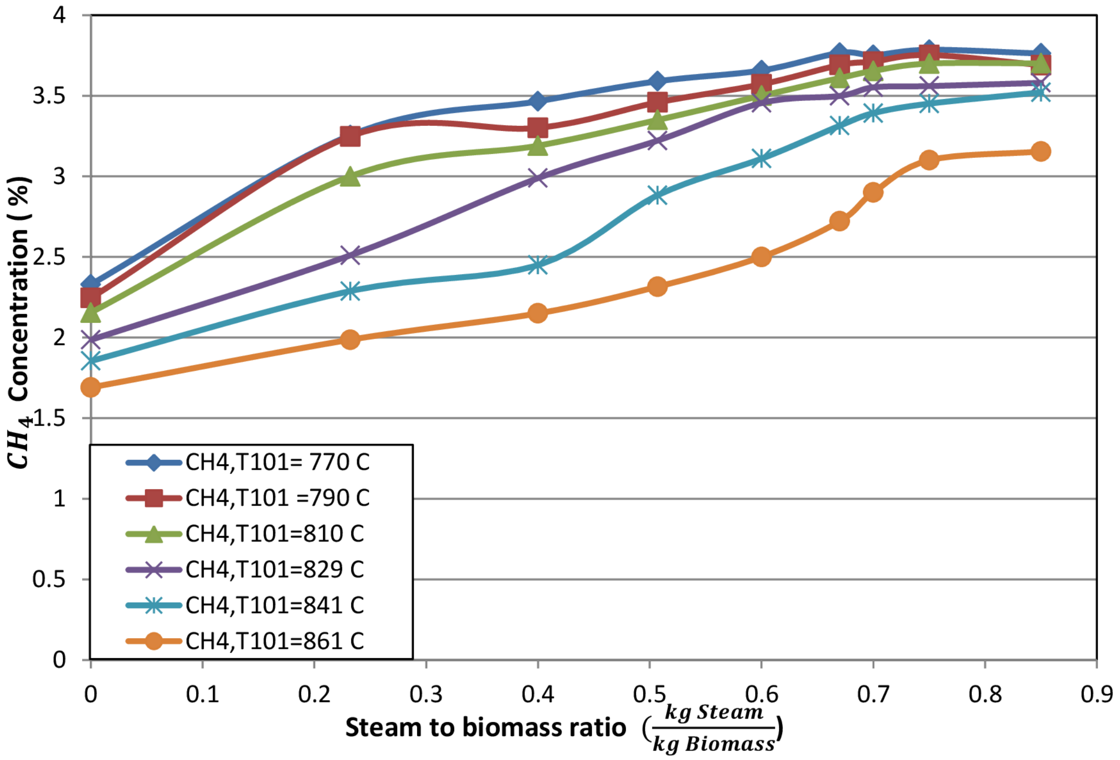


Figure 44: The effect of $\frac{S}{B}$ and T101 on methane content in produced gas

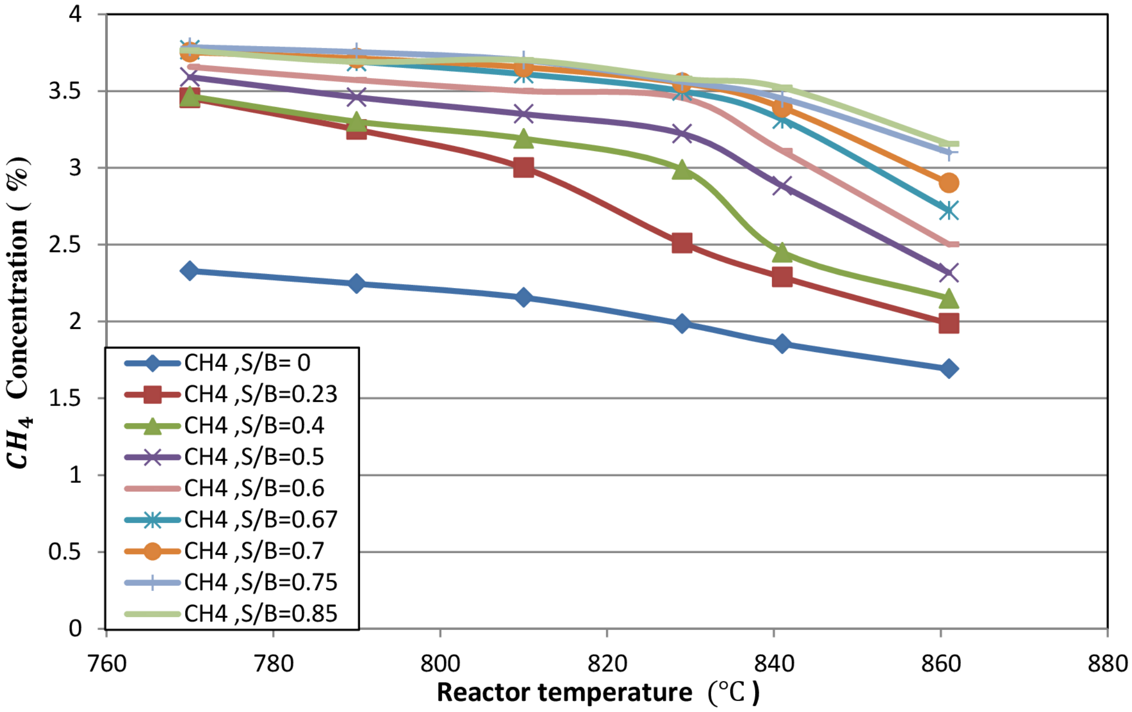


Figure 45 : The effect of $\frac{S}{B}$ and T101 on methane content in produced gas.

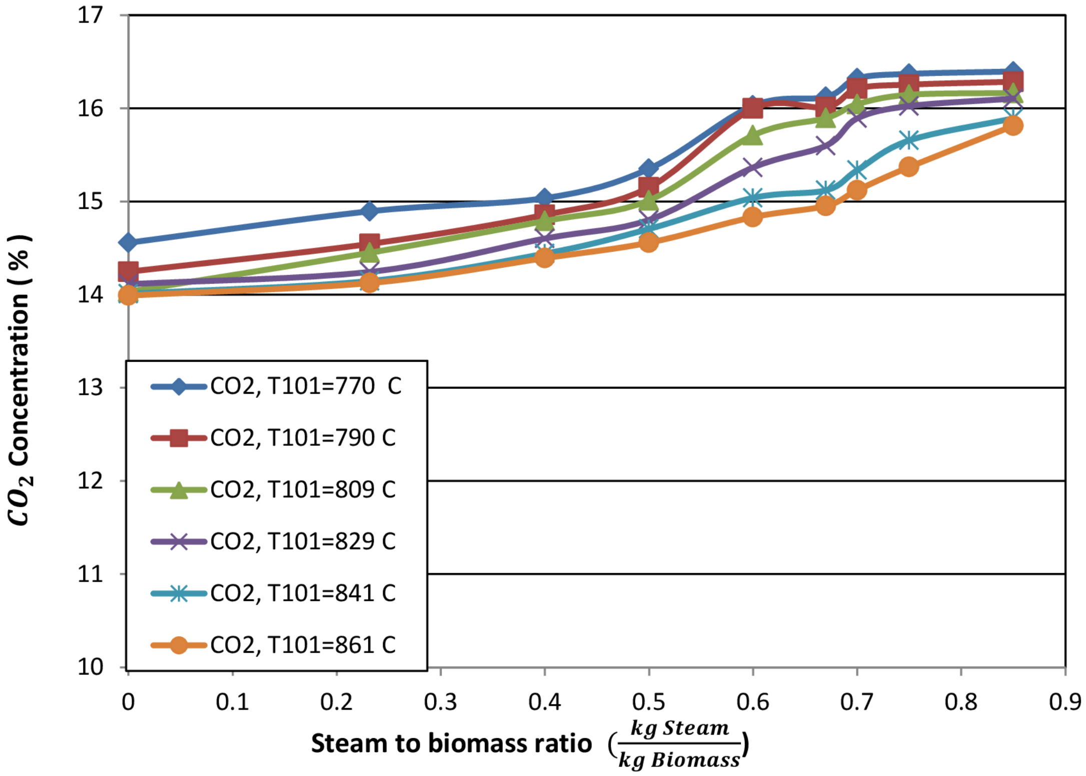


Figure 46 :The effect of $\frac{S}{B}$ and T101 on carbon dioxide content in produced gas

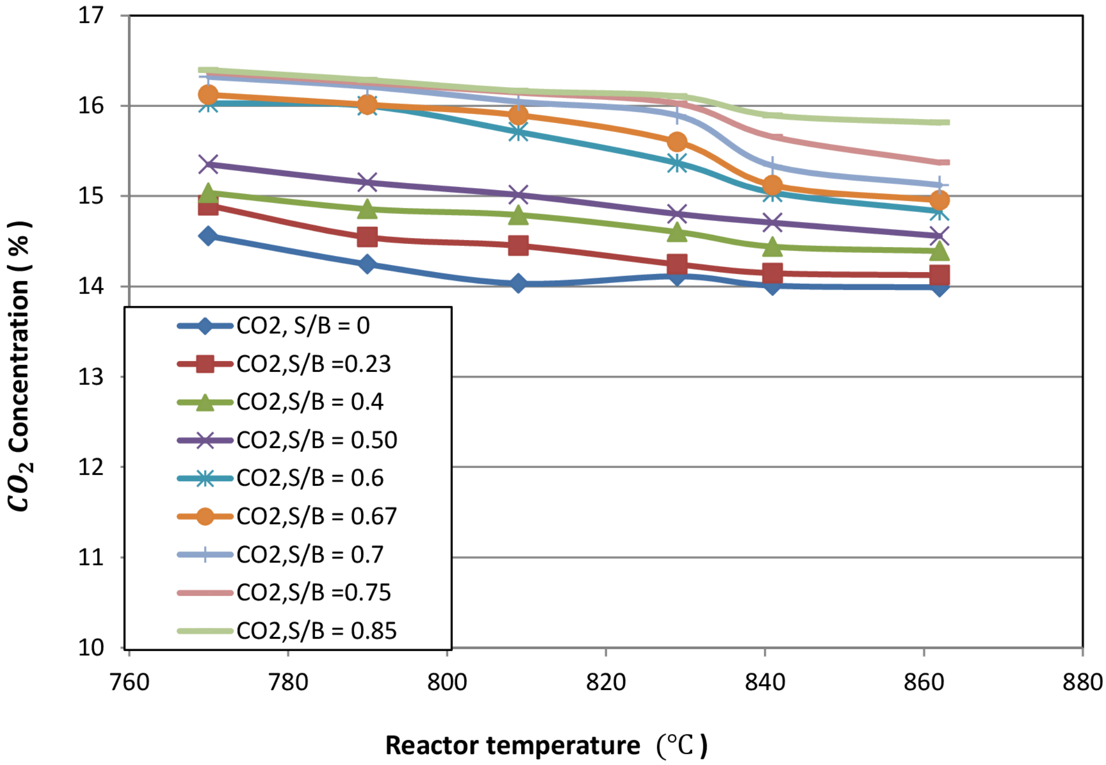


Figure 47: The effect of $\frac{S}{B}$ and T101 on carbon dioxide content in produced gas

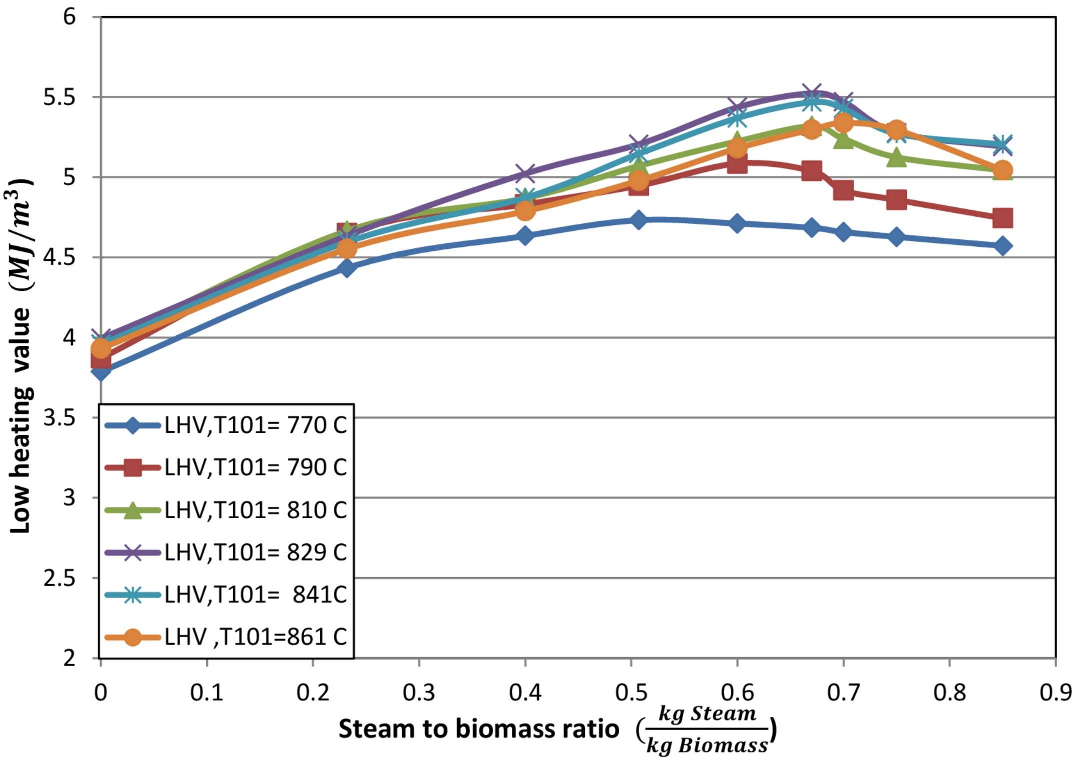


Figure 48 : The effect of $\frac{S}{B}$ and T101 on low heating value of produced gas

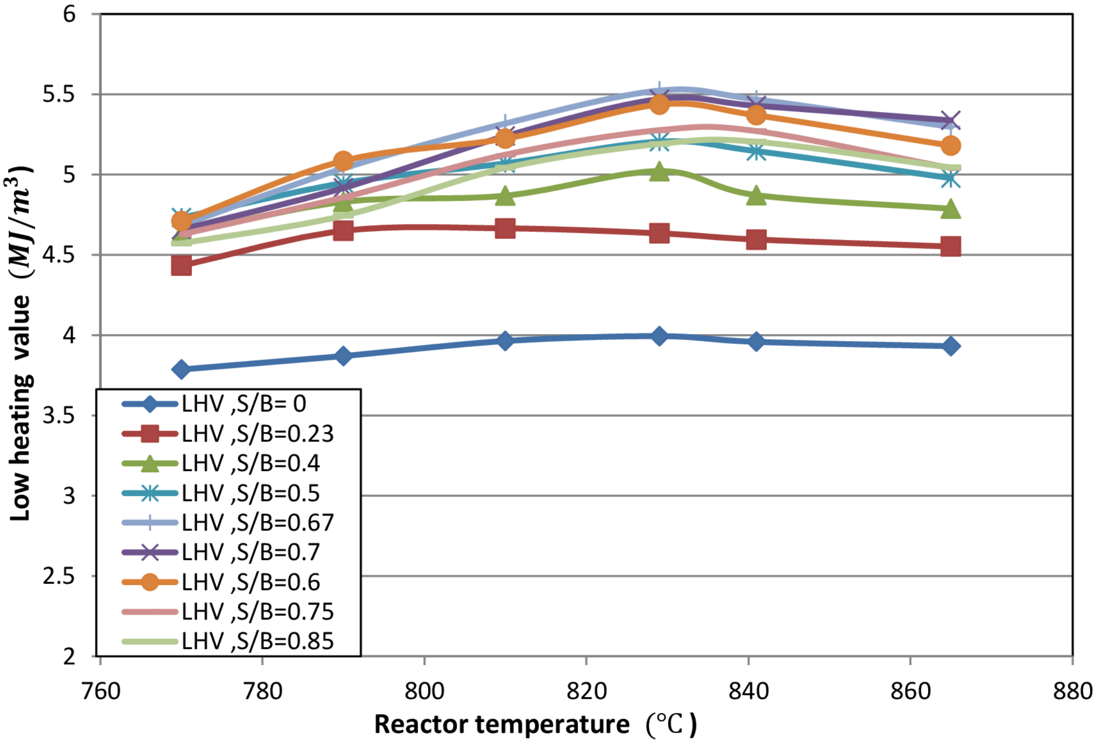


Figure 49 : The effect of $\frac{S}{B}$ and T101 on low heating value of produced gas

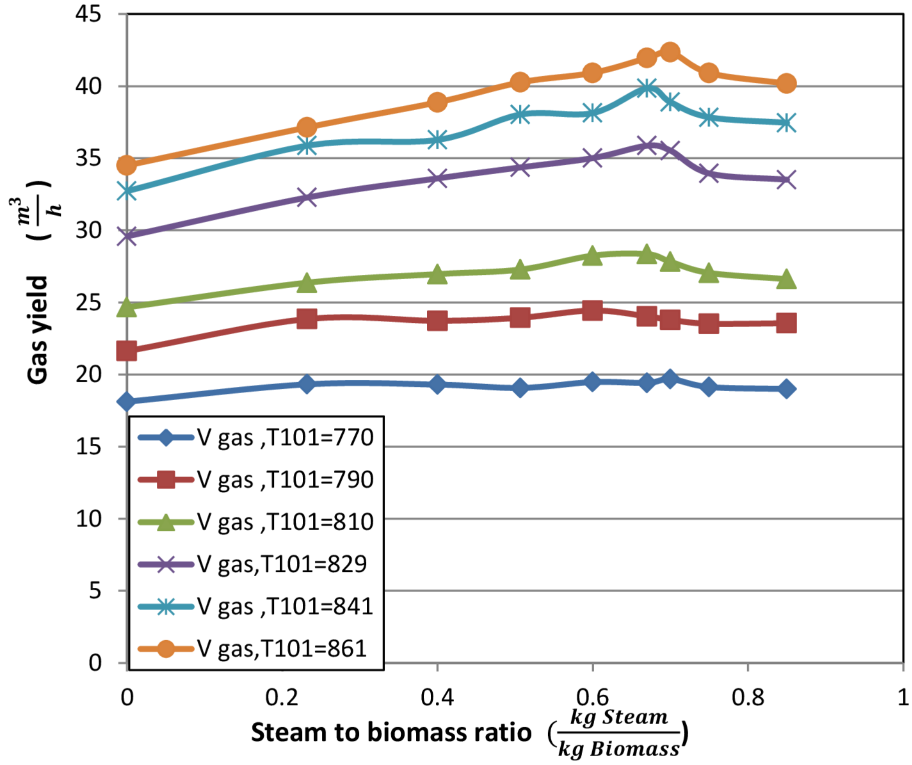


Figure 50: The effect of $\frac{S}{B}$ and T101 on the gas yield

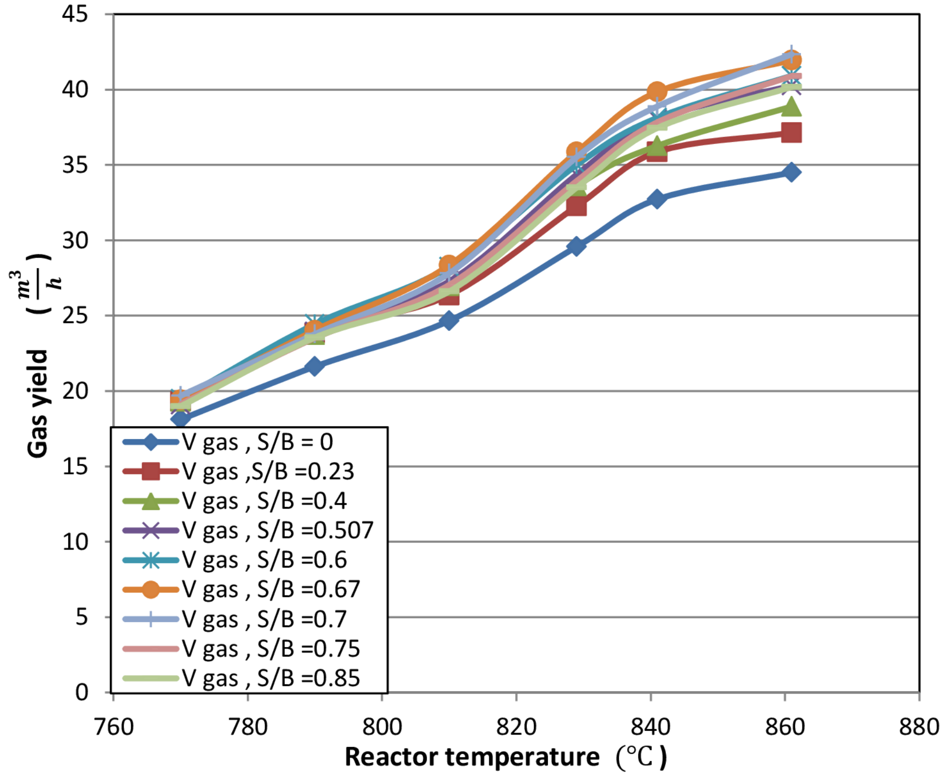


Figure 51 : The effect of $\frac{S}{B}$ and T101 on the gas yield

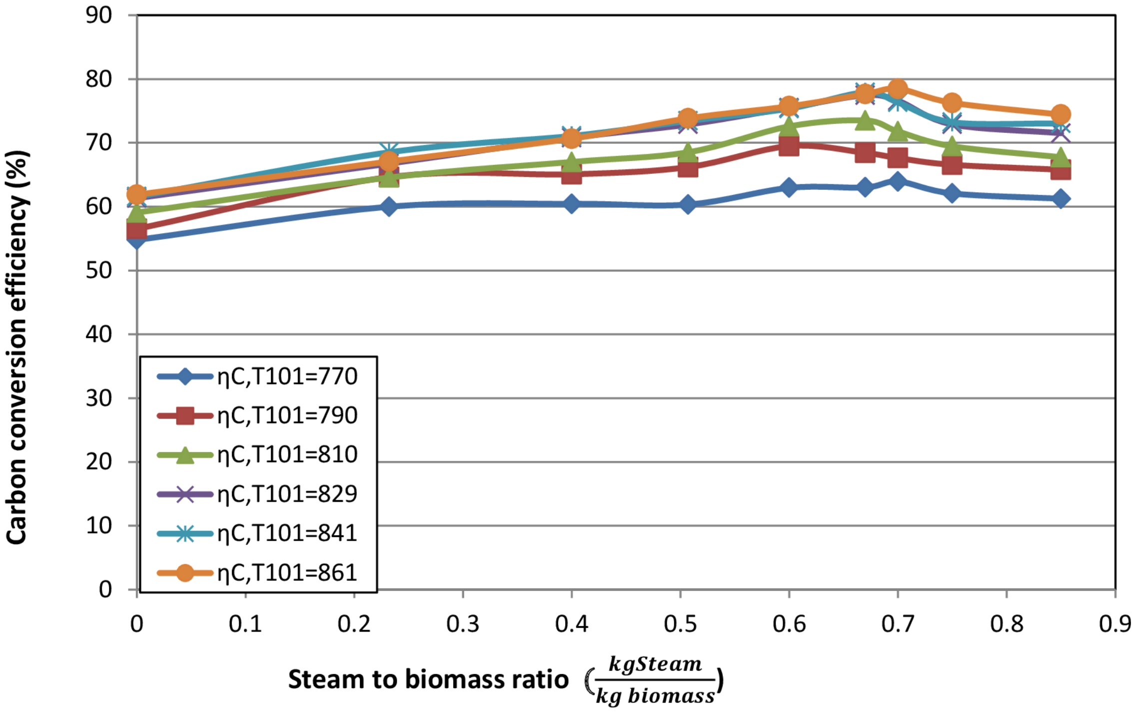


Figure 52 : The effect of $\frac{S}{B}$ and T101 on carbon conversion efficiency

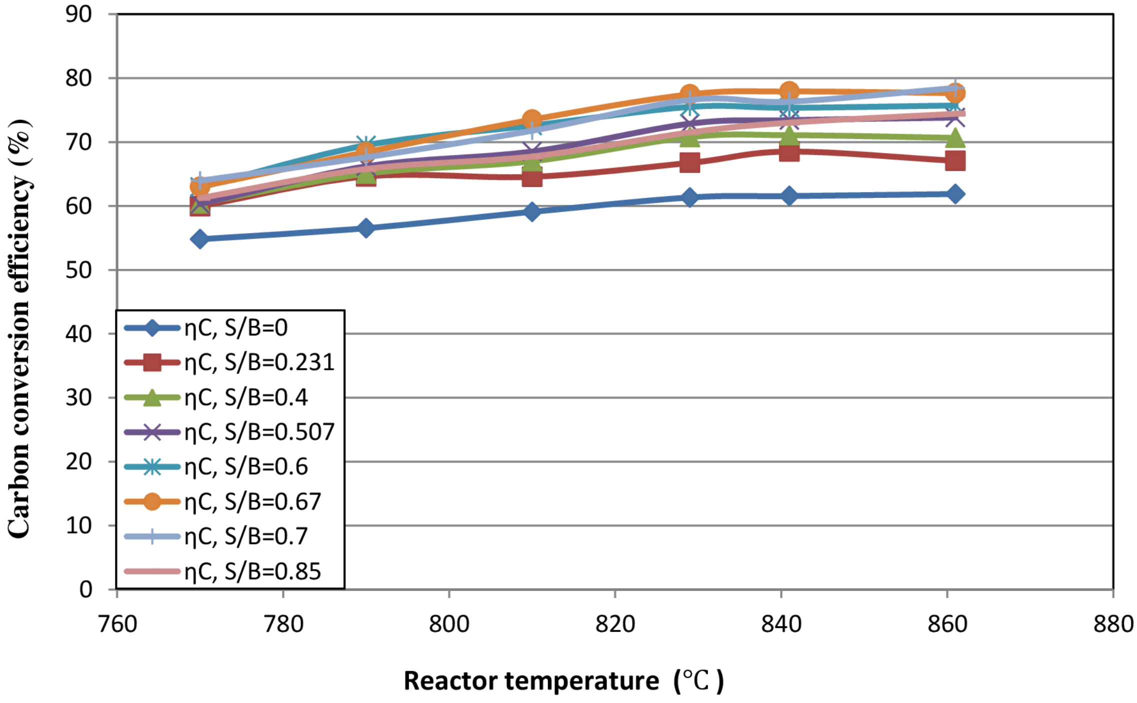


Figure 53: The effect of $\frac{S}{B}$ and T101 on carbon conversion efficiency

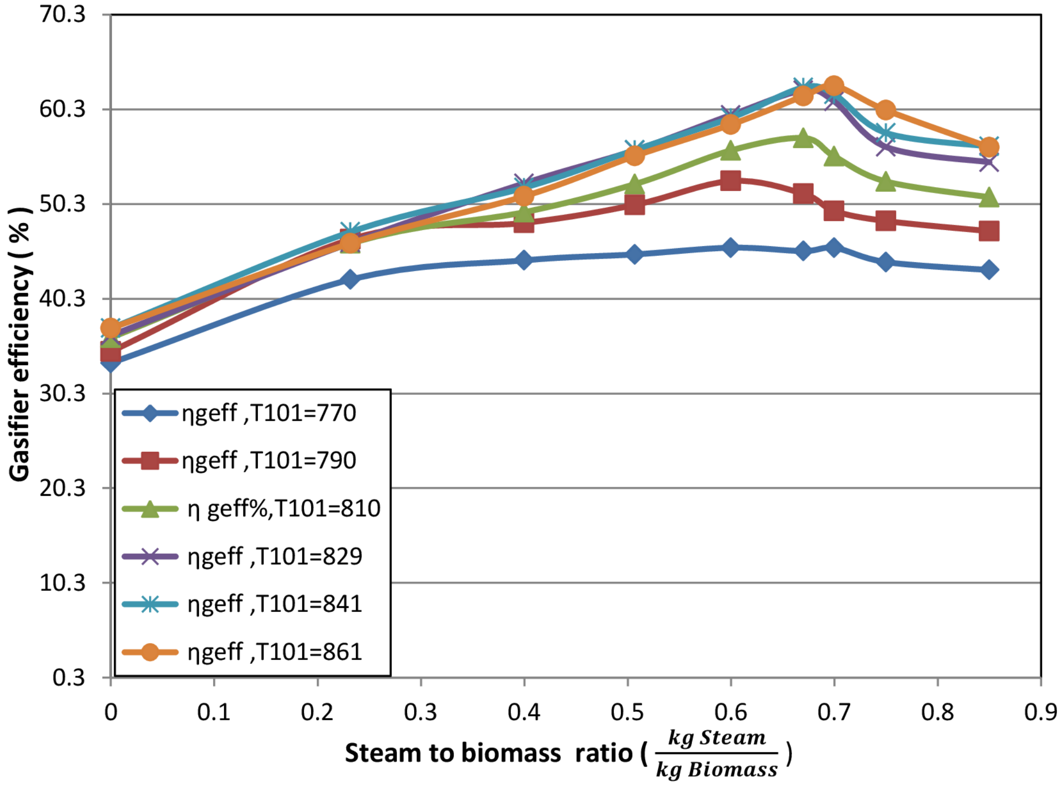


Figure 54: The effect of $\frac{S}{B}$ and T101 on gasifier efficiency

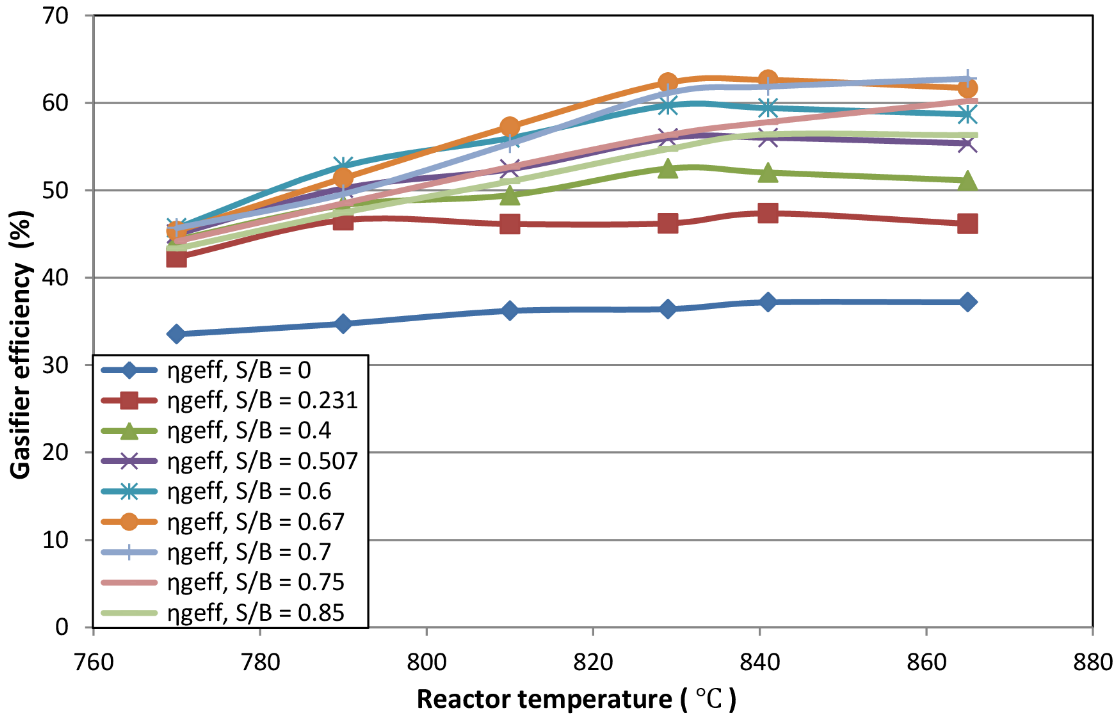


Figure 55 : The effect of $\frac{S}{B}$ and T101 on gasifier efficiency

12.2 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 (paragraph 12.1). 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 Table 8 and Figures 56 to 63.

Table 8: the effect of Tf1 on $(LHV, V_{gas}, \eta_C and\ \eta_{geff})$

$TF1$ (°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= 20-21$\left(\frac{m^3}{h}\right)$					

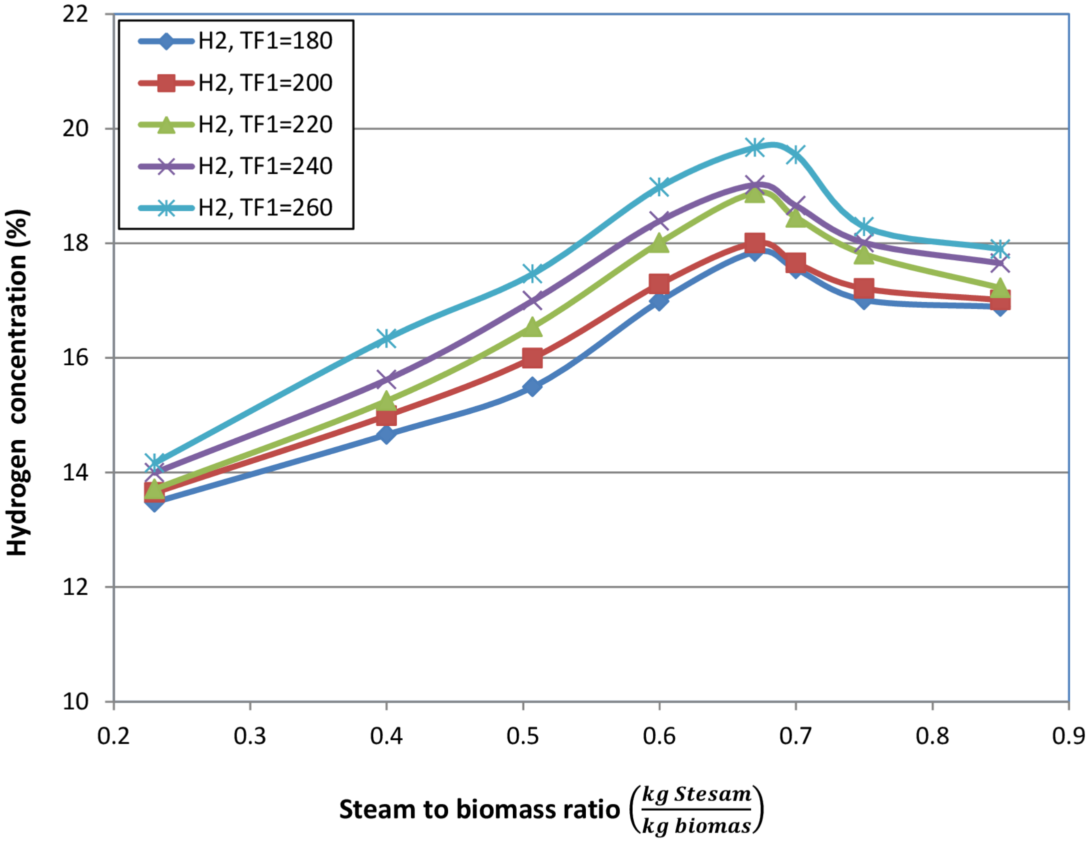


Figure 56 : The effect of $\frac{S}{B}$ and $Tf1$ on hydrogen content

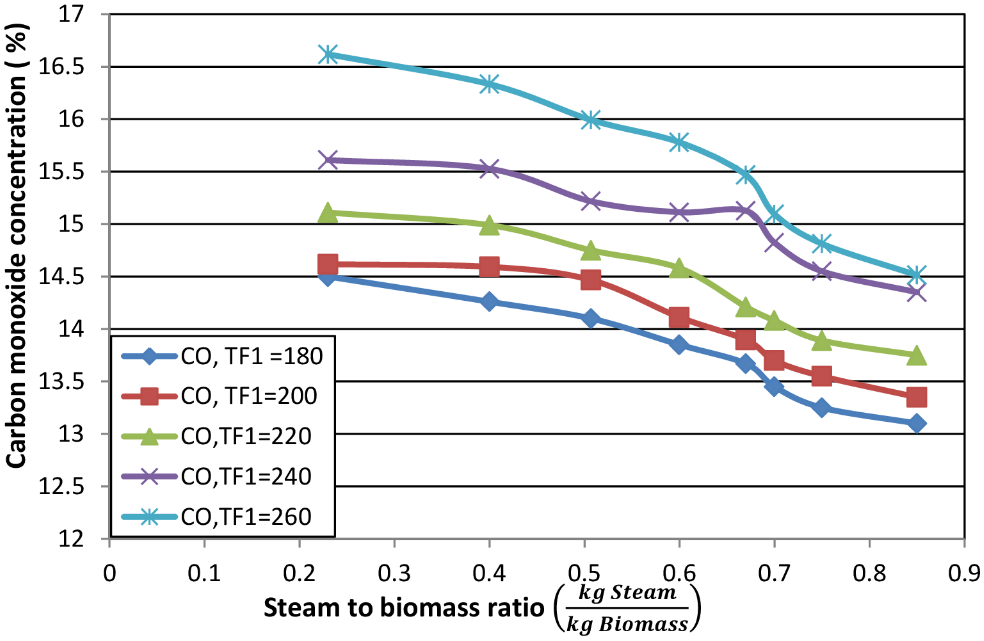


Figure 57 : The effect of $\frac{S}{B}$ and $Tf1$ on carbon monoxide content

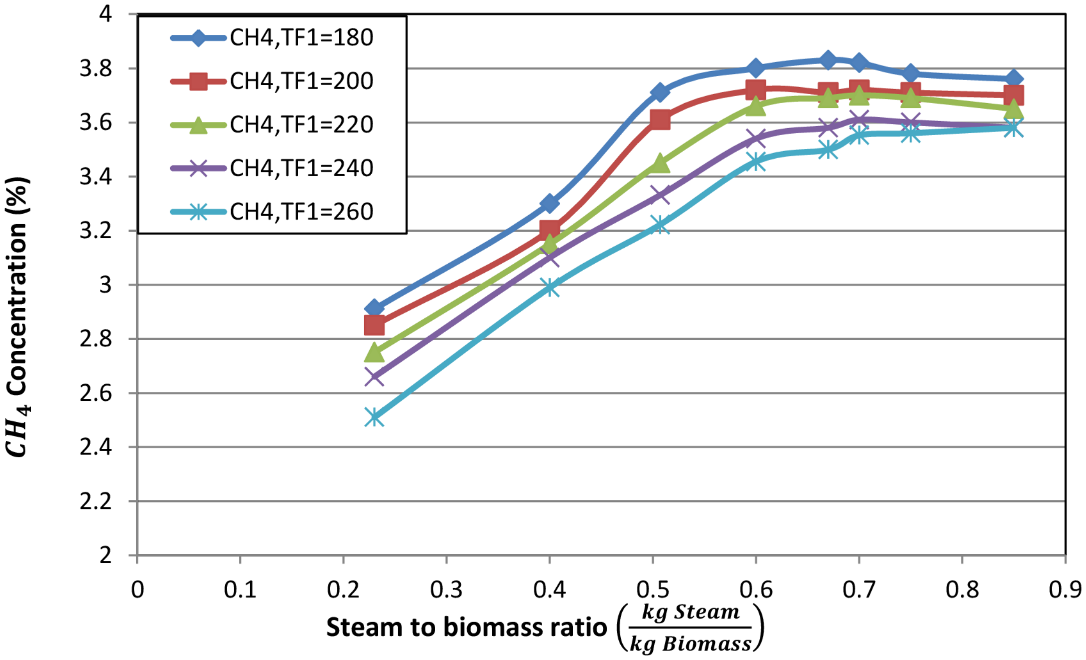


Figure 58 :The effect of $\frac{S}{B}$ and $Tf1$ on methane content

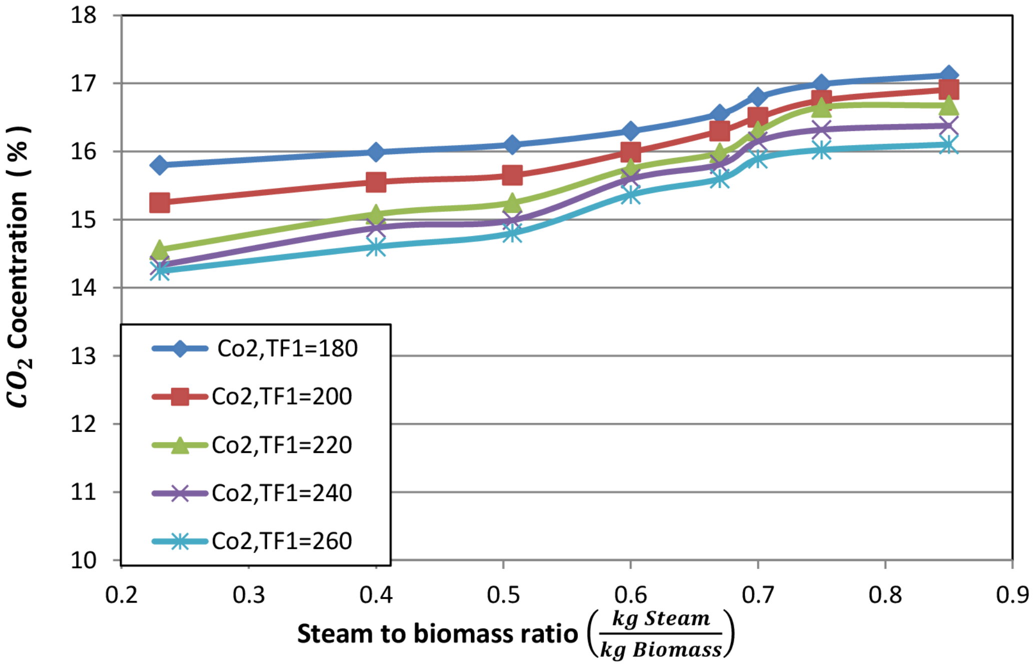


Figure 59 :The effect of $\frac{S}{B}$ and $Tf1$ on methane content

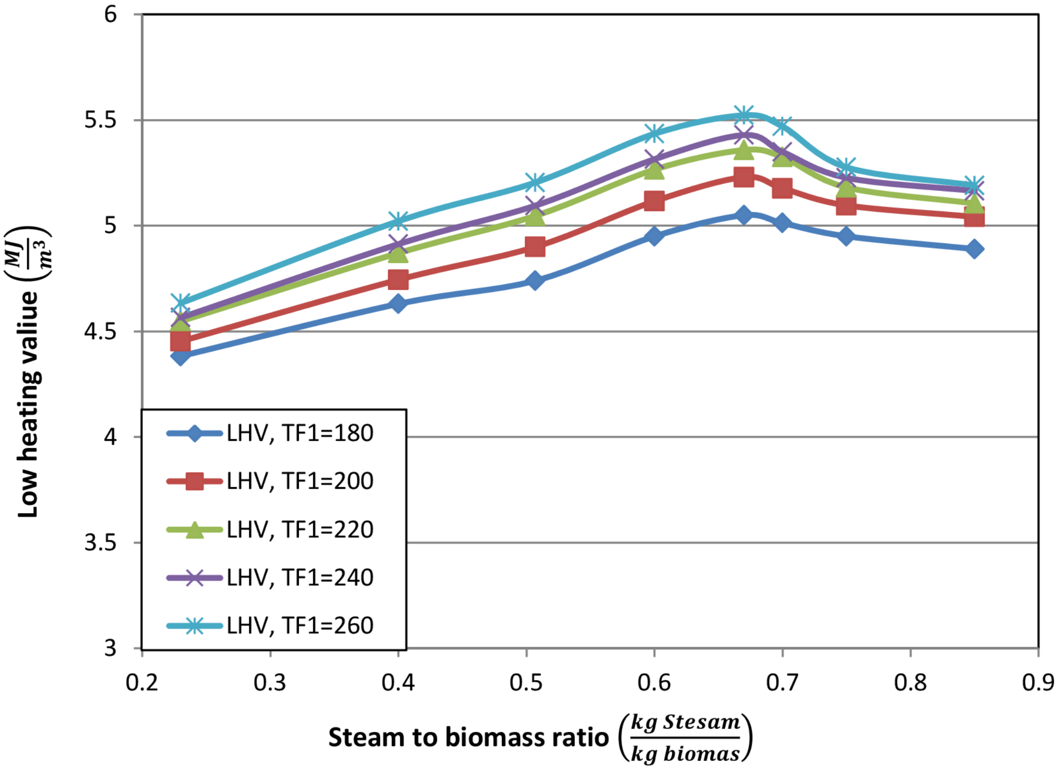


Figure 60 : The effect of $\frac{S}{B}$ and $Tf1$ on low heating value

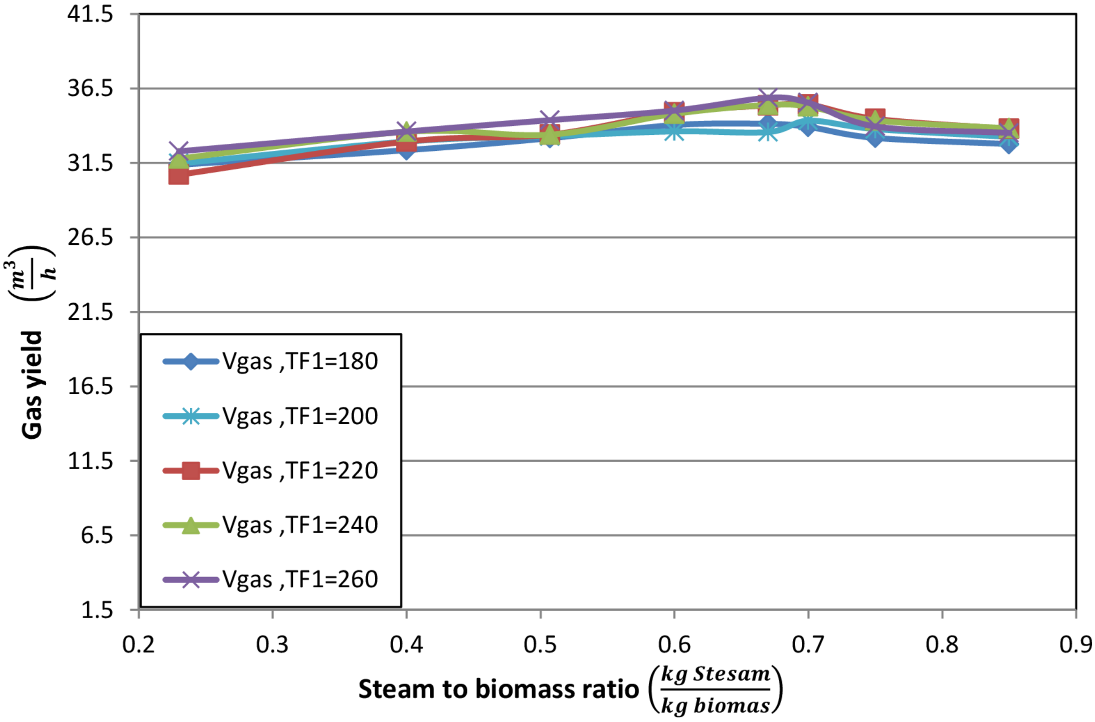


Figure 61: The effect of $\frac{S}{B}$ and $Tf1$ on gas yield

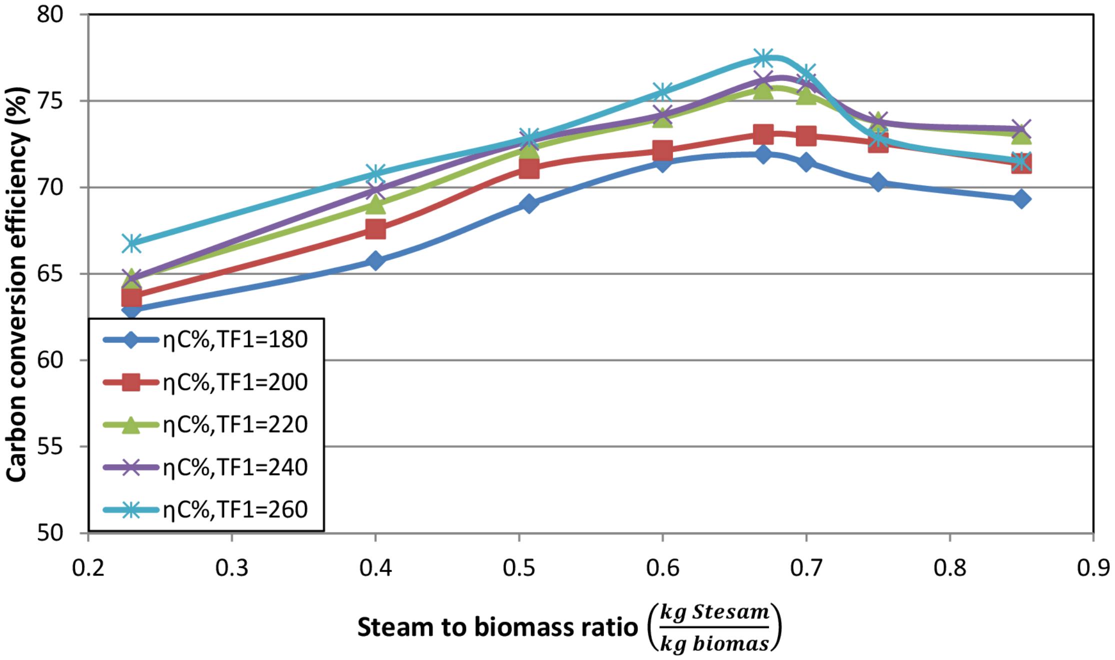


Figure 62 : The effect of $\frac{S}{B}$ and $Tf1$ on low carbon conversion efficiency

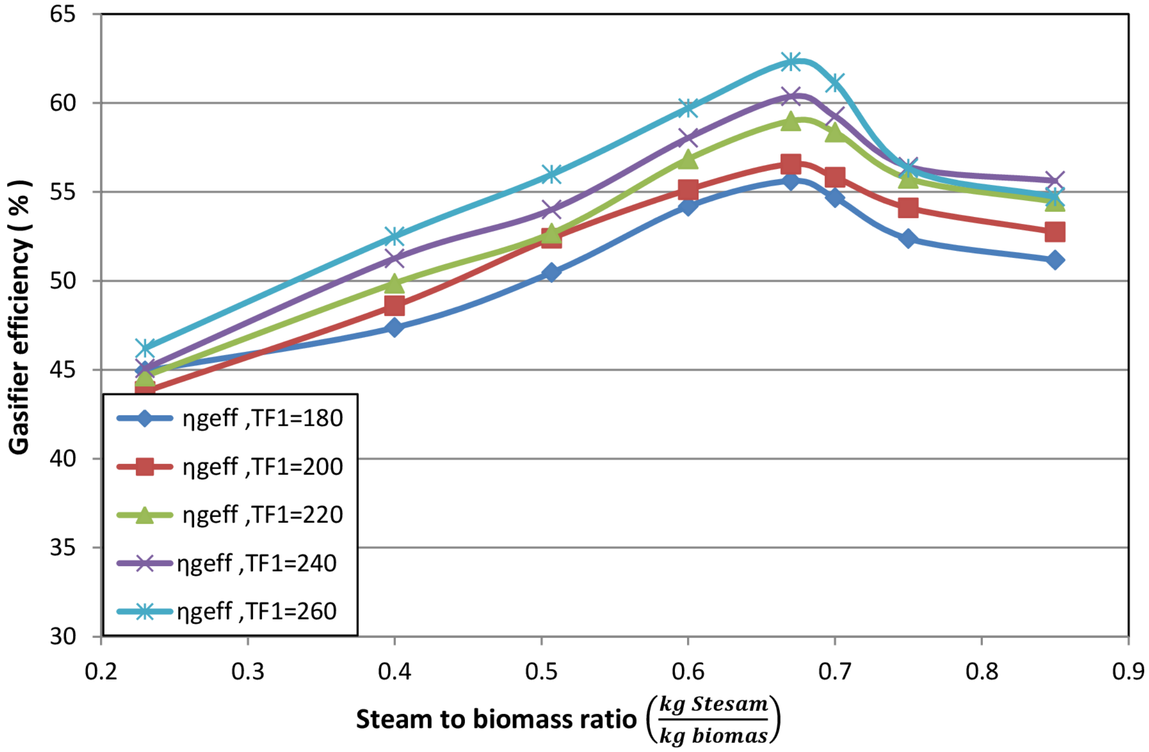


Figure 63 : The effect of $\frac{S}{B}$ and $Tf1$ on gasifier efficiency

12.3 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 (℃),biomass flow rate B=23 $\left(\frac{kg}{h}\right)$,steam temperature Tf1=260 (℃)).

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 gas samples analysis have been reported in Table: 9 and Figures 64 to 73.

Table 9: the effect of ER on on $(LHV, V_{gas}, \eta_C and\ \eta_{geff})$

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 $\left(\frac{kg}{h}\right)$; $\frac{S}{B}$ = 0.68			

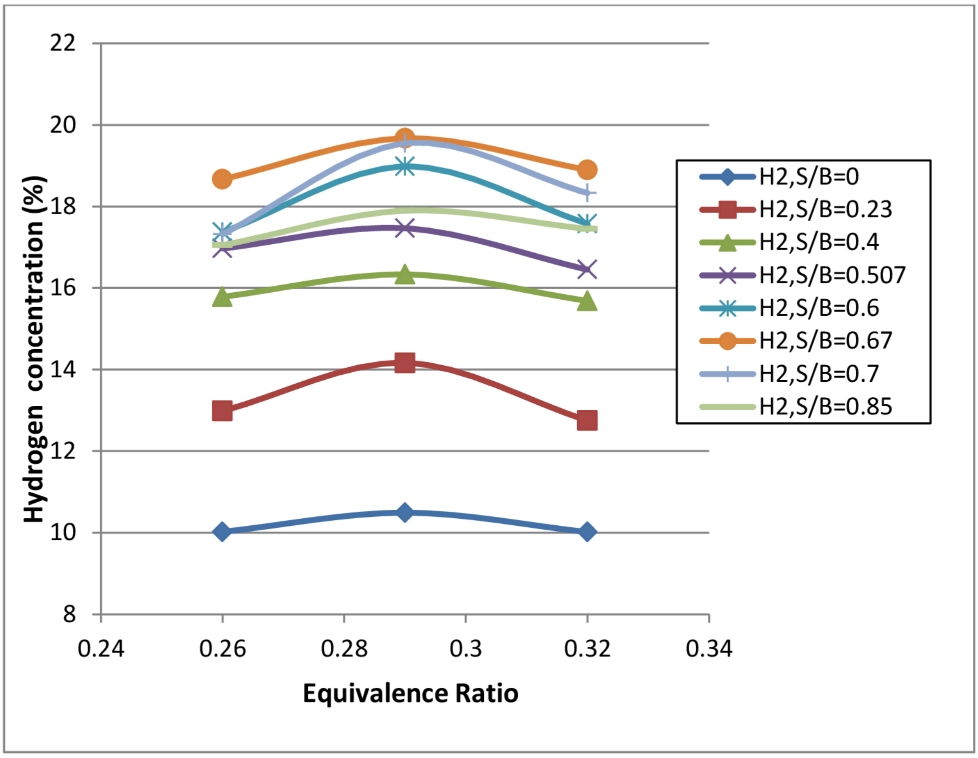


Figure 64 : The effect of $\frac{S}{B}$ and ER on hydrogen content

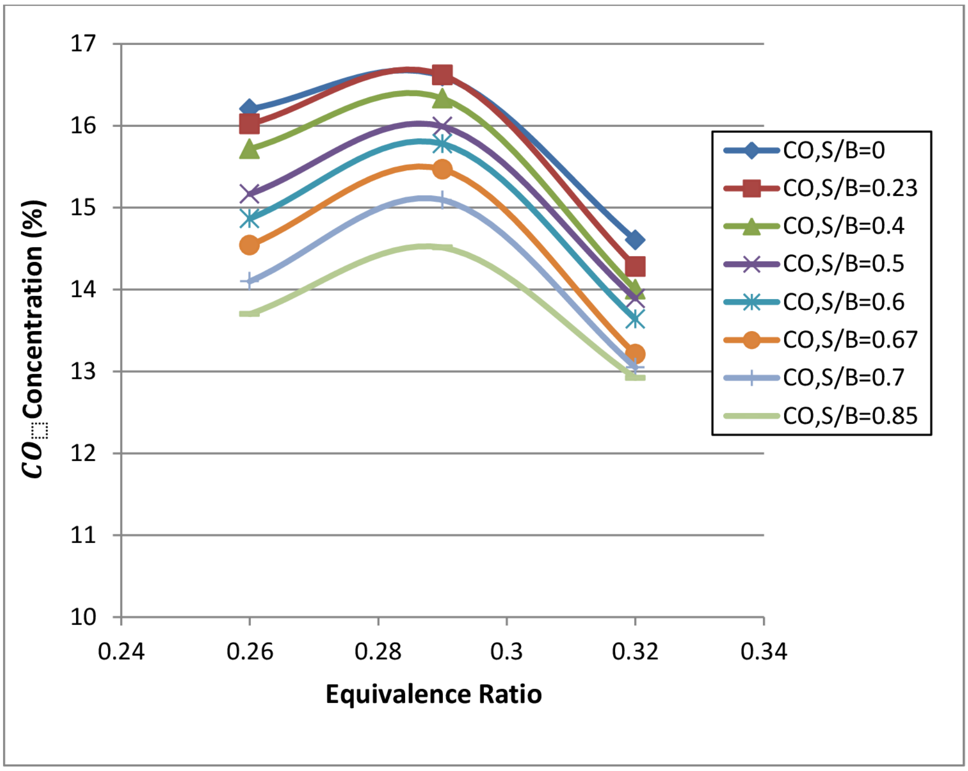


Figure 65 : The effect of $\frac{S}{B}$ and ER on carbon monoxide content

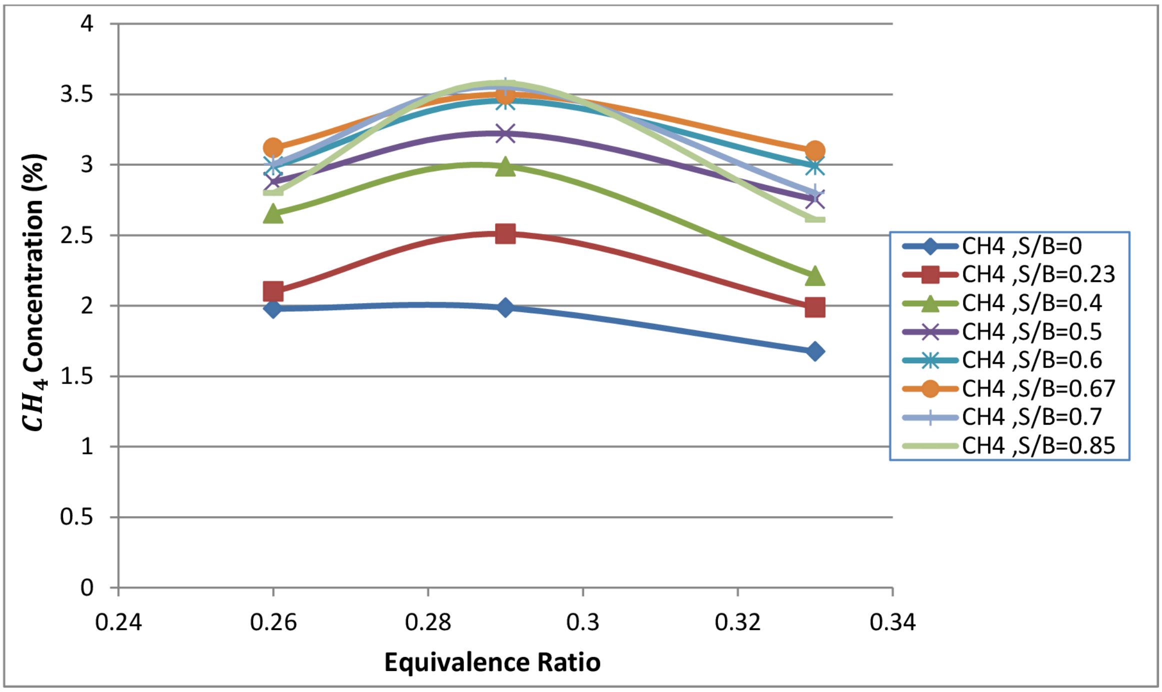


Figure 66 : The effect of $\frac{S}{B}$ and ER on methane content

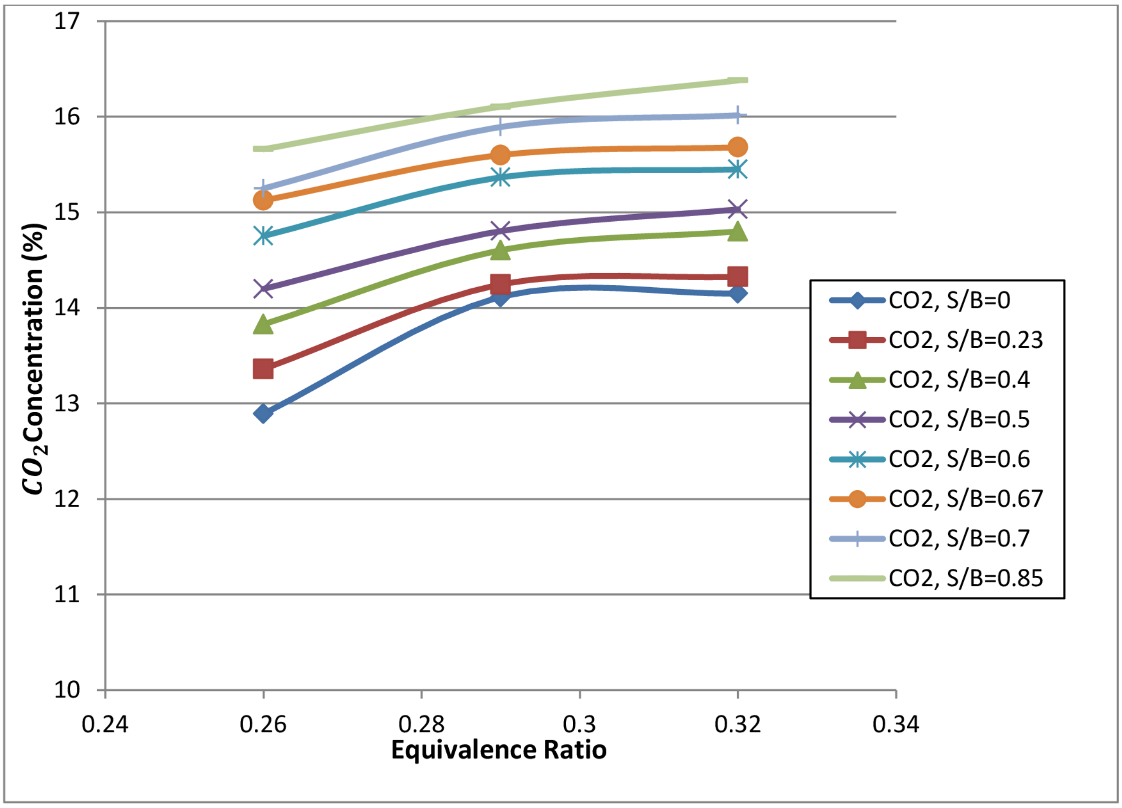


Figure 67 : The effect of $\frac{S}{B}$ and ER on carbon dioxide content

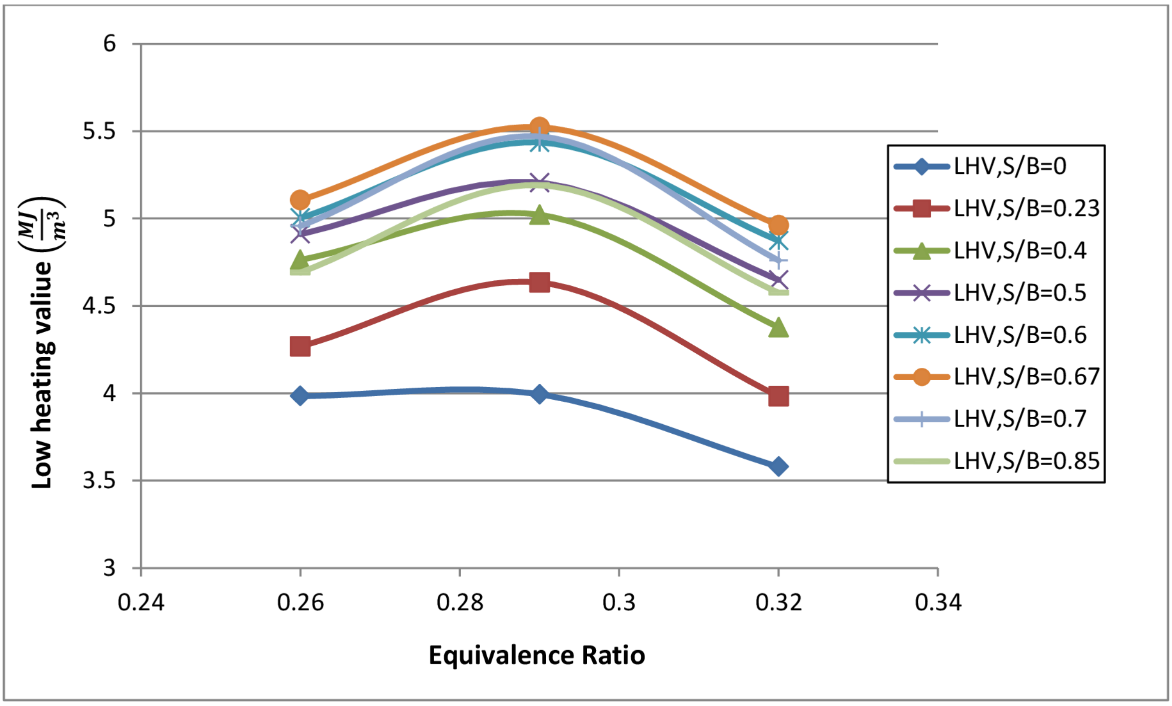


Figure 68 : The effect of $\frac{S}{B}$ and ER on low heating value

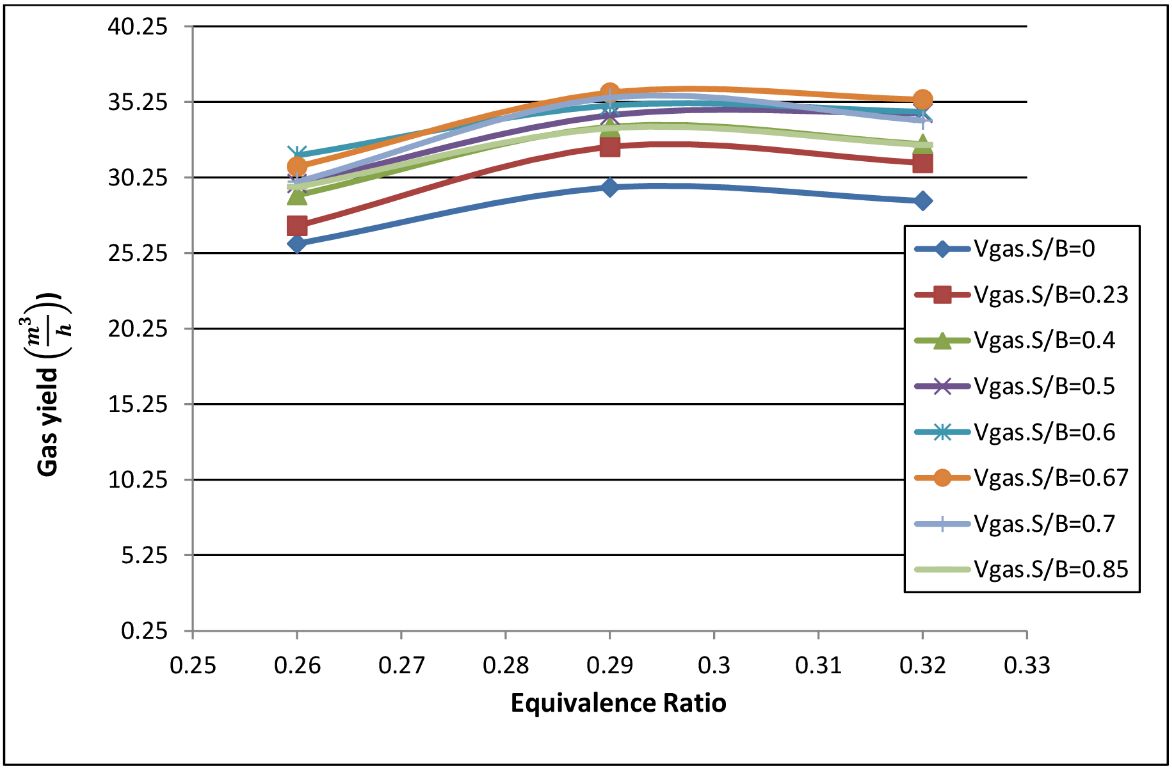


Figure 69: The effect of $\frac{S}{B}$ and ER on gas yield

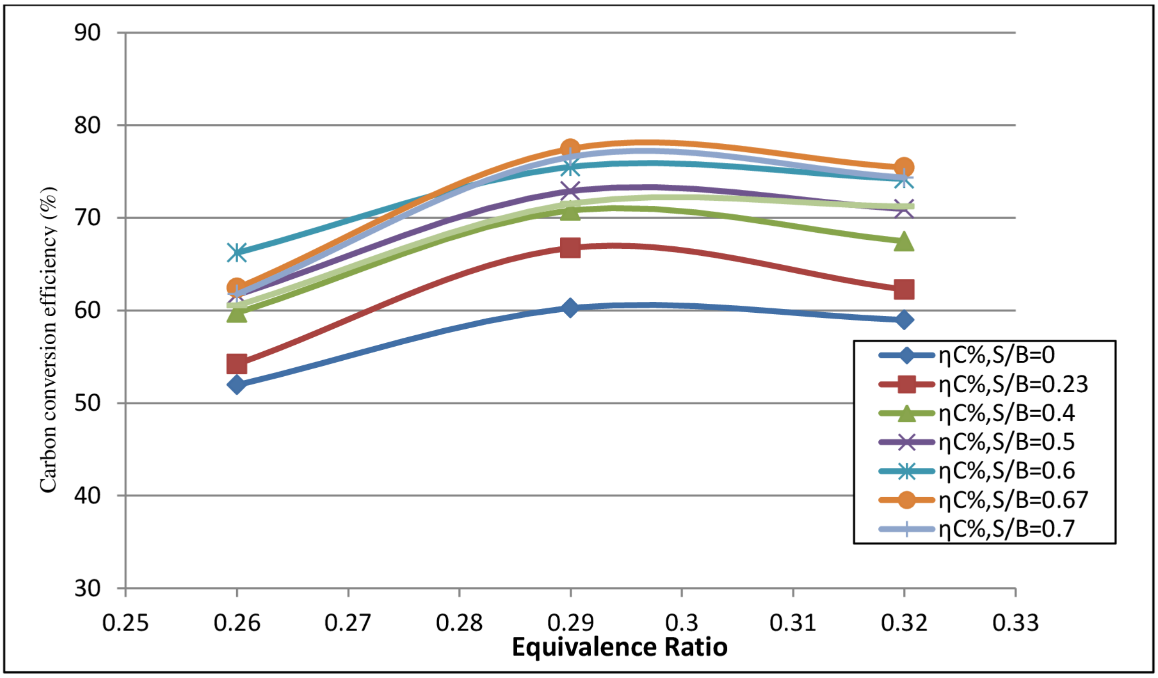


Figure 70 : The effect of $\frac{S}{B}$ and ER on carbon conversion efficiency

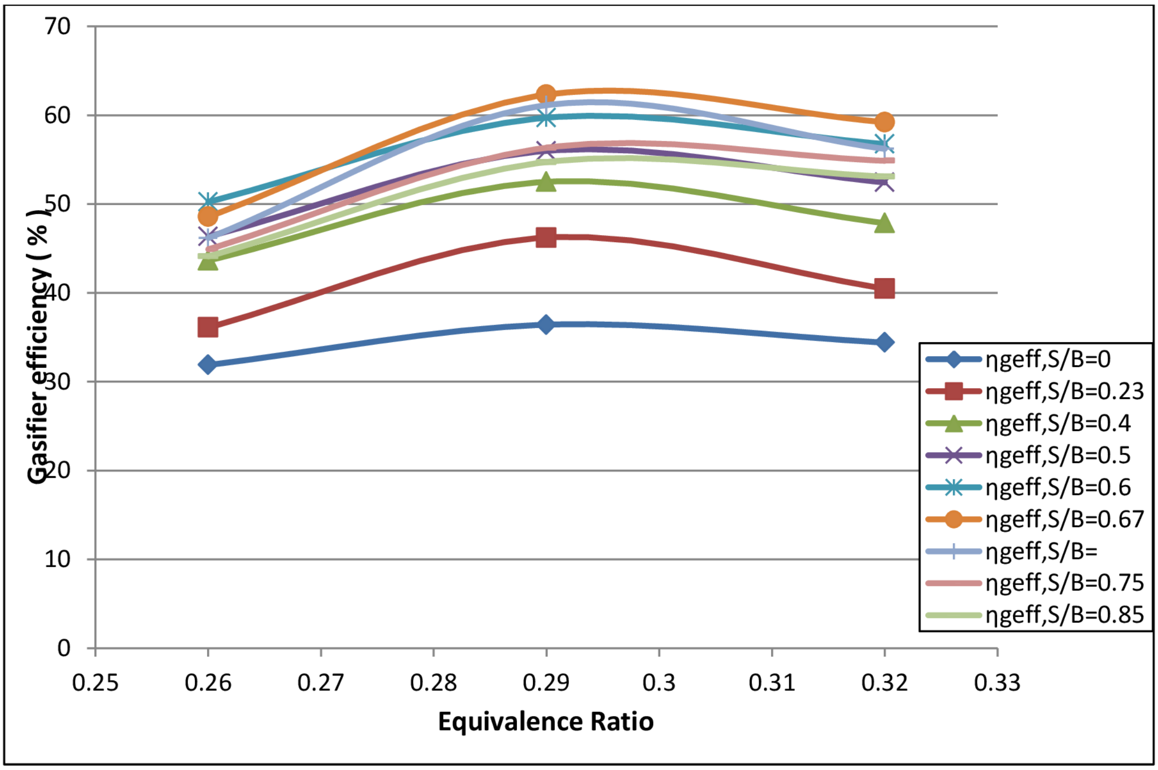


Figure 71 : The effect of $\frac{S}{B}$ and ER on gasifier efficiency

12.4 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 to 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 72 shows produced gas composition, Figure 73 shows Low heating value of gas , Figure 74 shows gas yield rate and Figure 75 shows gasifier efficiency and carbon efficiency.

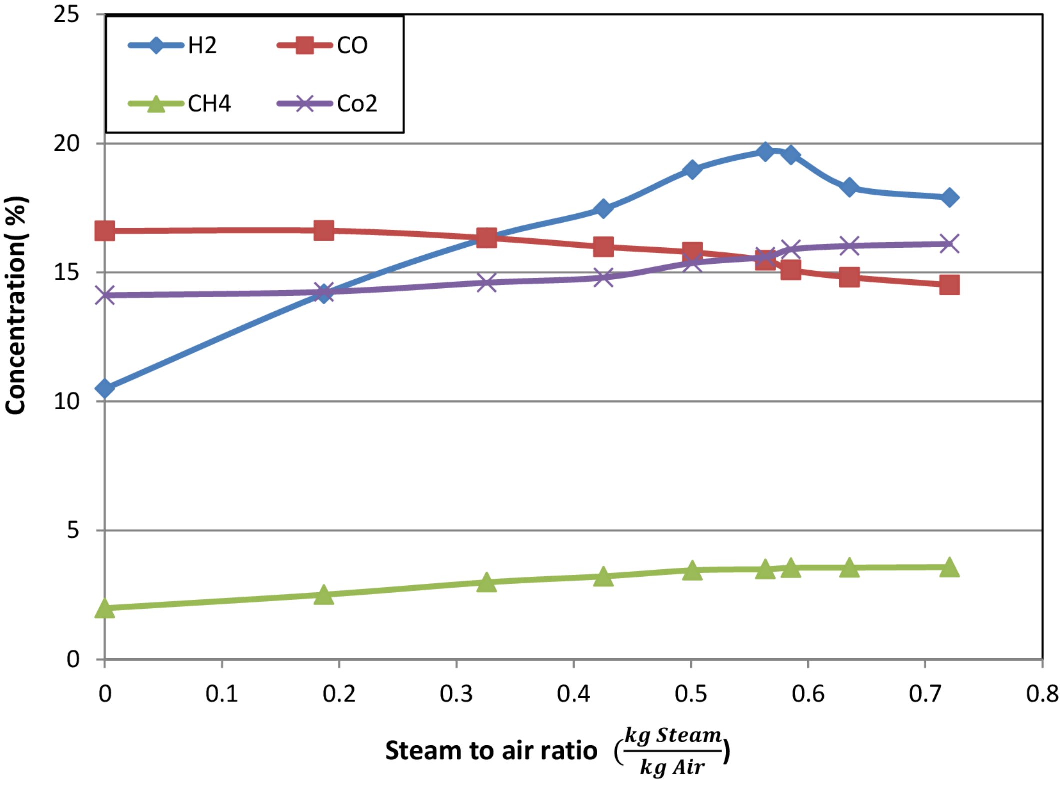


Figure 72 : The effect of $\frac{S}{A}$ on gas composition

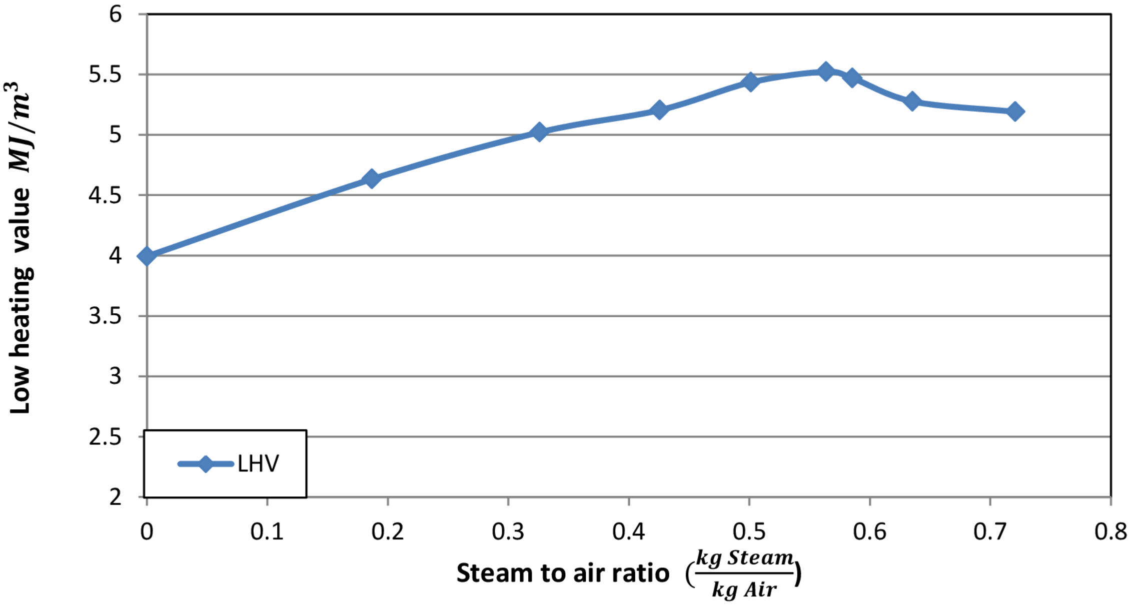


Figure 73 : The effect of $\frac{S}{A}$ on low heating value

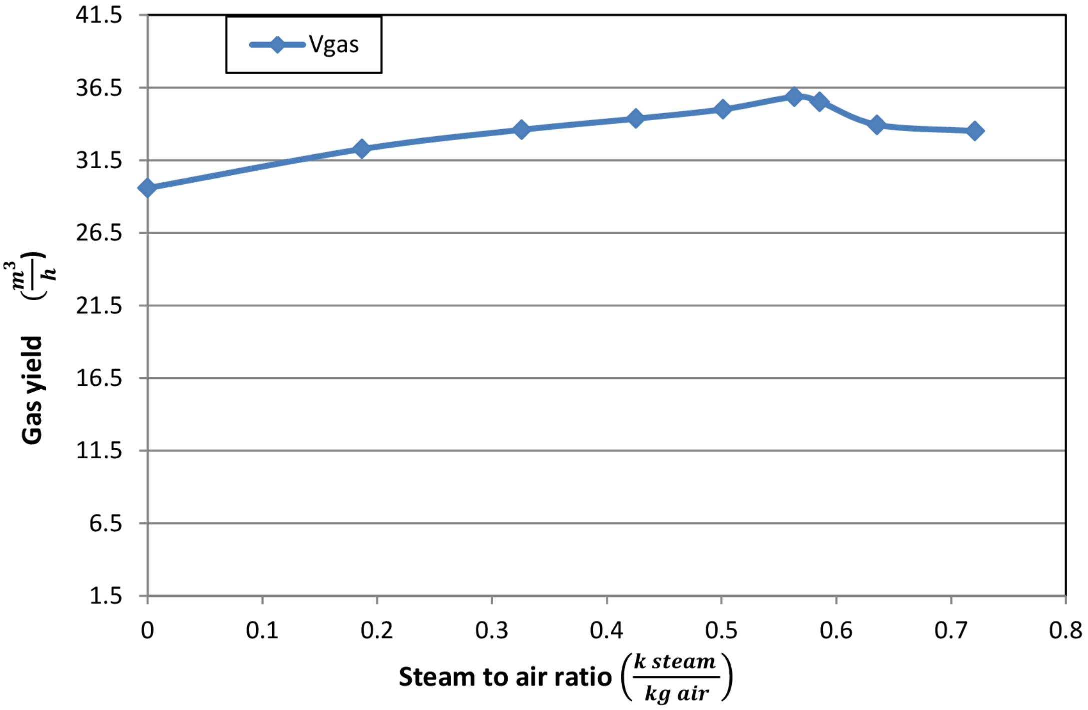


Figure 74 : The effect of $\frac{S}{A}$ on gas yield

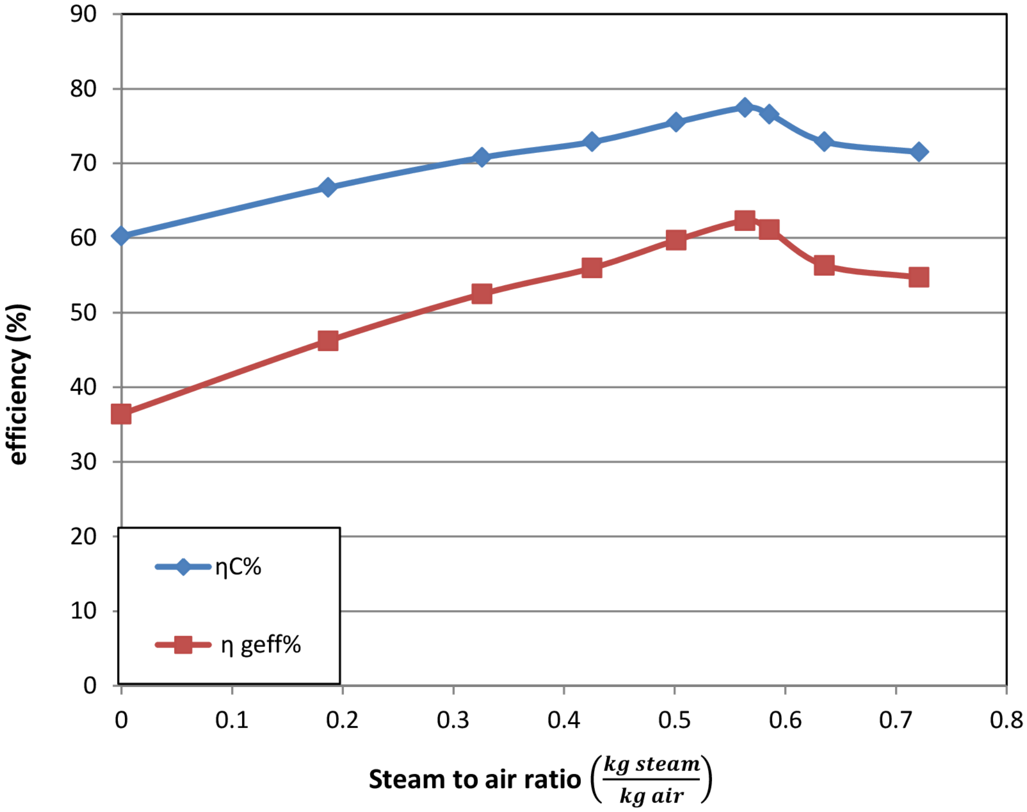


Figure 75 : The effect of $\frac{S}{A}$ on carbon conversion efficiency and gasifier efficiency

12.5 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 (see paragraph 11.3).

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 76 ,77 and 78 .

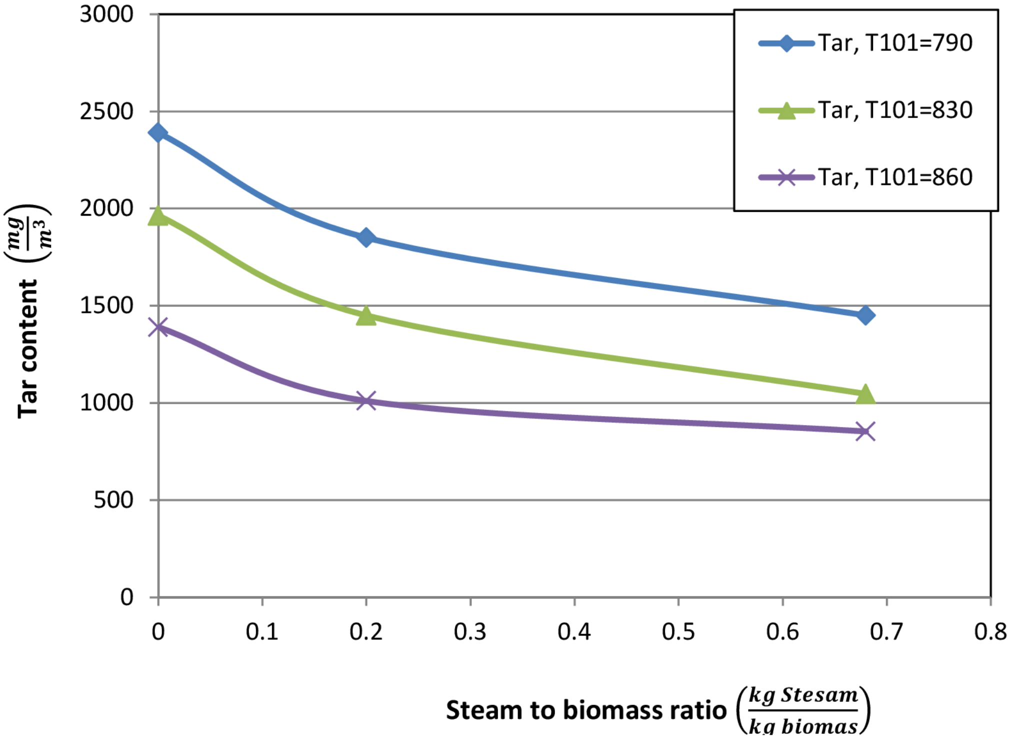


Figure 76 : The effect of $\frac{S}{B}$ and T101 on tar content

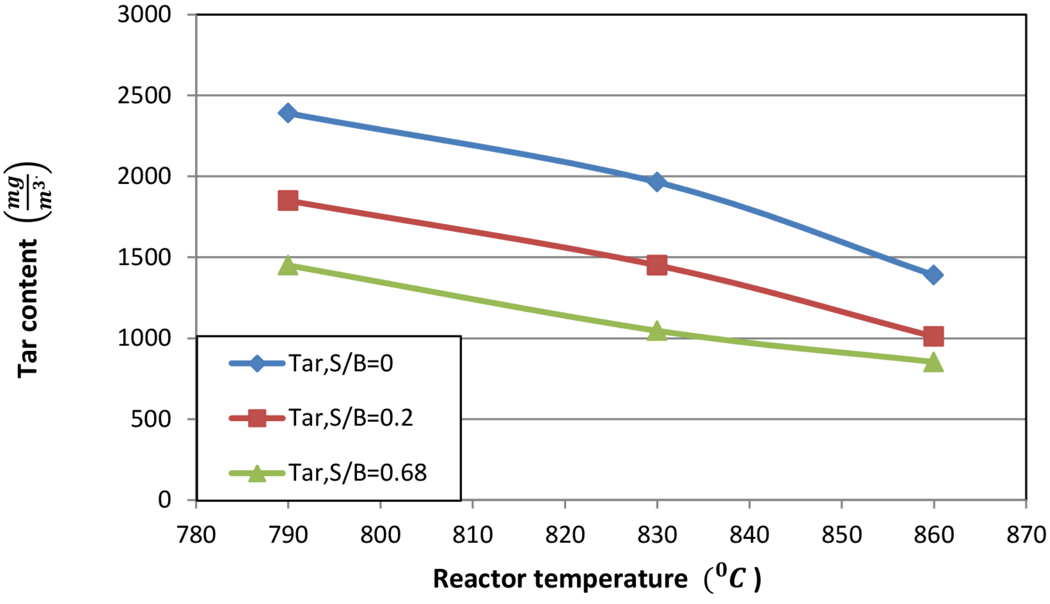


Figure 77 : The effect of $\frac{S}{B}$ and T101 on tar content

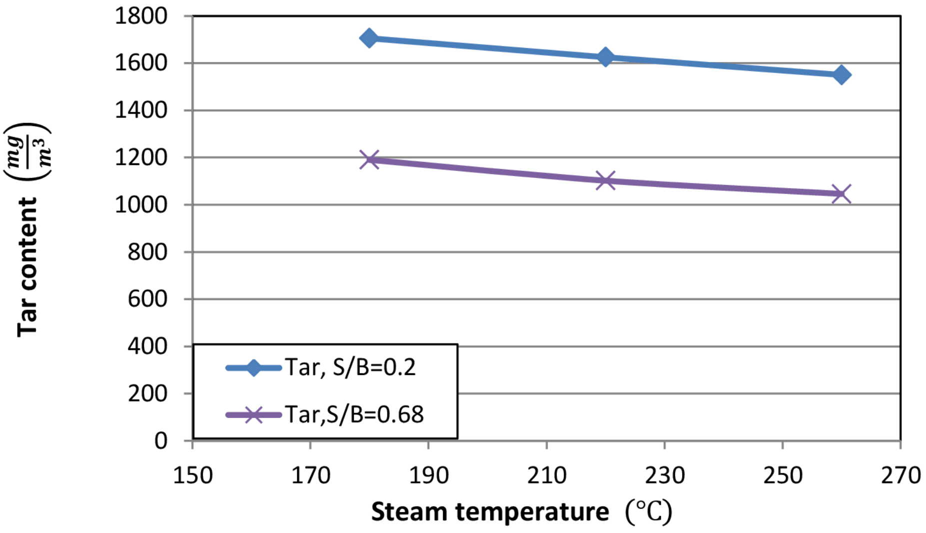


Figure 78 : The effect of $Tf1$ on tar content

12.6 The Evaluation of Experiments and Discuss the Results

12.6.1 The Effect of Reactor Temperature T101

Figures 40 to 55, show, 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 (°C) in 20 (°C) increments, temperature of steam was$Tf1 = 260$ °C.

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

Figures 40 and 41 show, 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 26 and 27 will be enhanced with increase of temperature which leads to increase of hydrogen concentration.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \ -206\ KJ \ldots\ldots..26$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 - 165\ KJ \ldots\ldots27$$

- The water–gas reaction Equation 4 is endothermic, and favor high temperature and low pressure [2]. But this equation produces hydrogen and carbon monoxide at the same molar rate, they have the same molar concentration at balance state (see Figure 10)[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 42 and 43 show, 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 5, it can be seen that this reaction will be improved by high temperature, so high temperature enhances carbon monoxide formation (see figure 9a,b).
- The water–gas reaction Equation 4, will be activity by high temperature , as mentioned previously (see figure 10a,b)
- 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 26 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 :

Figures 44 and 45 show, 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 (see figure 11a,b) [5].
- Cracking of the methane at high temperature [37].
- Equation 26 and 27 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 :

  Figures 46 and 47 show, 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 5, will be more activity so the carbon dioxide decreasing and carbon monoxide increasing (see figure 10a,b)[5].

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

  Figures 48 and 49 show, 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 52 and 53 show, 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 5 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} :

  Figures 54 and 55 show, 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 $\left(CO, H_2, C_xH_y\right)$ 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 :

  Figures 50 and 51 show, 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 °C ,where $H_2 = 19.7\ \%$, $CO = 16.8\ \%$ and $LHV = 5.53\ \left(\frac{MJ}{m^3}\right)$.

12.6.2 The Effect of Steam to Biomass Ratio

Figures 40 to 55 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 Figures 40 and 41, 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 40 and figure 41, that best steam to biomass ratio increases by reactor temperature T101 , it can be represented by the figure 80 .

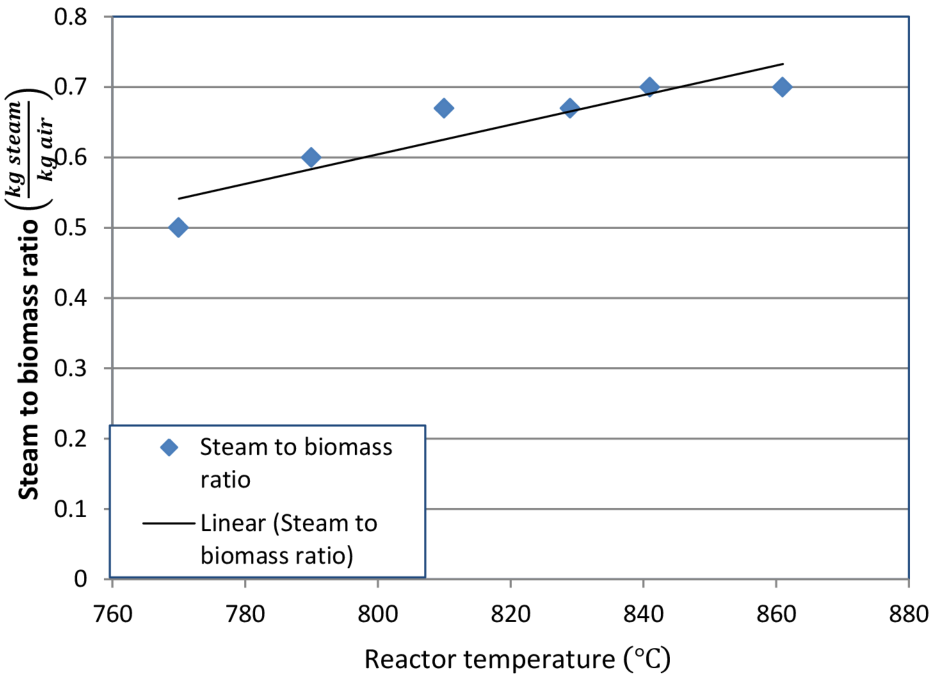


Figure 79: The effect of T101 on the best of steam to biomass ratio $\frac{S}{B}$

From the Figure 79, 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:

$$\frac{S}{B} = 0.0025T101 - 1.4 \quad \ldots\ldots 28$$

From Equation 28 , 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 °C) ,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 6, will be activate with steam and it leads to increase in the ratio of hydrogen to carbon monoxide in the gas [5].
- Equations 26 and 27 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 °C (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:

Figures 42 and 43 show, 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 6, will be 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:

Figures 44 a 45 show, 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. Figures 46 and 47, 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 :

  figures 48 and 49 show , 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 :

  figures 52 and 53, show , 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 5, 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} :

  Figures 54 and 55 show , that the effect of 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 :

  Figures 50 and 51 show 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 $T101 = 830\ °\mathrm{C}$ was $\frac{S}{B} = 0.67\ \left(\frac{kg\ steam}{kg\ biomass}\right)$.

12.6.3 The Effect of Steam Temperature $Tf1$:

Figures 56 to 63 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 $T101 = 830°\mathrm{C}$, ER about 0.29, B about $23\left(\frac{kg}{h}\right)$, F1 about $21\left(\frac{m^3}{h}\right)$, steam rate was varied from 0 to 20 kg/h also steam to biomass ratio varied from 0 to 0.85 $\left(\frac{kg_{steam}}{kg_{biomass}}\right)$.

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 26 and 27 ,the water–gas reaction Equation 4, Boudouard reaction Equation 5, 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 figure 56 and carbon monoxide in produced gas figure 57 by increasing steam temperature, while the concentration of methane figure 58 and carbon dioxide figure 59 decrease with rising steam temperature, also increase each of low heating value , gas yield , carbon conversion efficiency and gasifier efficiency with steam temperature ,as it is clear in Figure 60, 61, 62 and 63, respectively.

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

12.6.4 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 64, that hydrogen content changed little in the range of ER, while gas yield at the beginning increased, then decreased as it is shown in Figure 69.

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 9 and Figures 64 to 74, 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 Figures 70 and 69, Respectively.

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: $2C + O_2 \rightarrow 2CO$

Combustion reaction : $C + O_2 \rightarrow CO_2$

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.

12.6.5 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°C, B = 23$\left(\frac{kg}{h}\right)$ The tests results is cleared in Figures 72 to 75.

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 6, and Equations 26 and 27, will be improved, Therefore it can be seen from Figure 72, that hydrogen and carbon dioxide are increased, but carbon monoxide is decreased by steam, and each of low heating value Figure 73, gas yield Figure 74, carbon conversion efficiency and gasifier efficiency Figure 75, have been increased.

But the excessive increase of steam at steam temperature 261 °C (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 $\left(\frac{\mathrm{kg_{steam}}}{\mathrm{kg_{air}}}\right)$ at our experiment conditions.

12.6.6 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 [26].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[35].Therefore Tar content will be decreased by increasing each of reactor temperature T101 and steam to biomass ratio $\frac{S}{B}$.

From figures(76 to 78) show, 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 $\frac{S}{B} = 0.67\left(\frac{\mathrm{kg_{steam}}}{\mathrm{kg_{biomass}}}\right)$ in the same range of increasing temperature.

From Figure 78 show that tar content decreases with increasing $Tf1$ because high steam temperature will be improved reaction temperature.

12.7 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 $T101 = 830°C, \frac{S}{B} = 0.68$ 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 80 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 $\left(\frac{mg}{m^3}\right)$

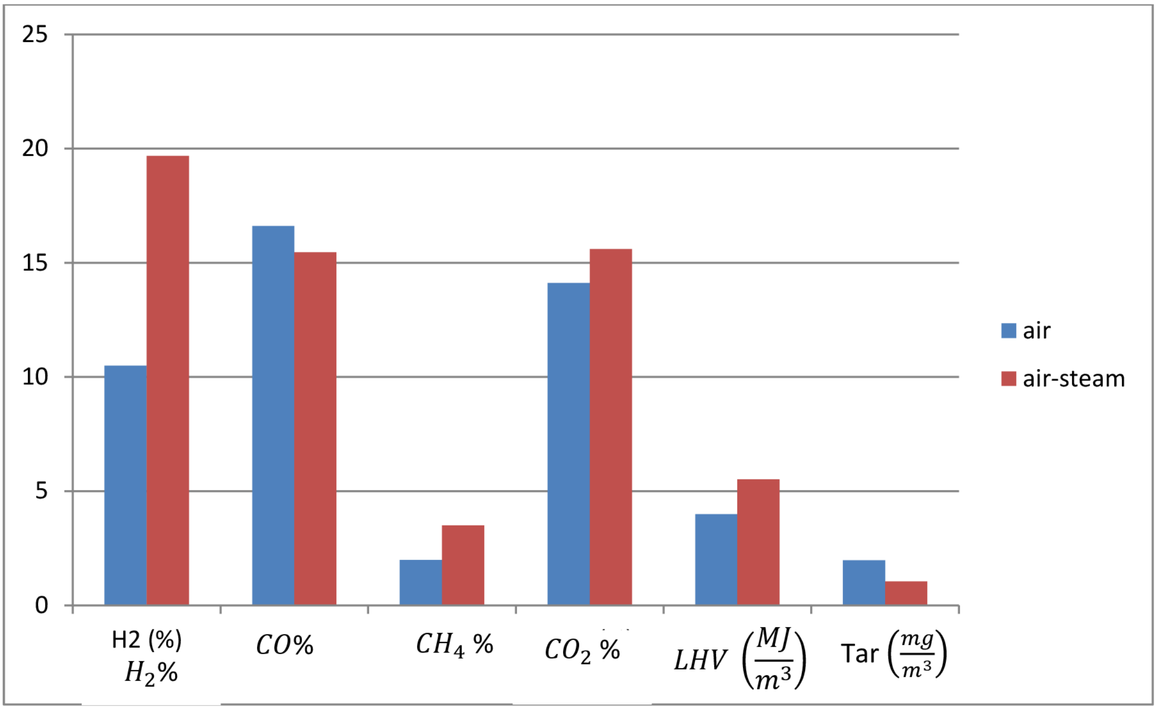


Figure 80: Comparison between the properties of produced gas by using steam /air and air as gasifying agent at the best parameters

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 experimental 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 $T101 = 830°\mathrm{C}, Tf1 = 261°\mathrm{C}$ 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°C 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 $T101 = 830°\mathrm{C}, \frac{S}{B} = 0.68$ and $ER = 0.29$. $Tf1$ i is the highest possible temperature for our experiment is about 261 °C., where H_2 increased from 10.3 to 19.67 % , CH_4 from 2 to 3.5 % , LHV from 3.9 to 5.52 $\left(\frac{MJ}{m^3}\right)$ 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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List of Figures:

List of Symbols and Abbreviations

Symbol	Nomenclature	Unit
H	The amount of hydrogen per kilogram of fuel	(%)
C	The amount of carbon per kilogram of fuel	(%)
N	The amount of nitrogen per kilogram of fuel	(%)
O_d	The amount of oxygen per kilogram of fuel	(%)
$LHV_{biomass}$	Low heating value of fuel	$\left(\frac{MJ}{kg\ biomass}\right)$
$HHV_{biomass}$	High heating value of fuel	$\left(\frac{MJ}{kg\ biomass}\right)$
T101	The temperature measured at the bottom of the reactor (primary zone)	(℃)
T102	The temperature measured in the middle part of the reactor	(℃)
T104	The temperature measured at the top of the reactor	(℃)
T107	Gas temperature measured in outlet of reactor	(℃)
TF1	The temperature of air or mixture steam and air in inlet of reactor	(℃)
F1	Flow rate of primary air or mixture of steam and air	$\left(\frac{m^3}{h}\right)$
F2	Flow rate of secondary air	$\left(\frac{m^3}{h}\right)$
F3	Flow rate of tertiary air	$\left(\frac{m^3}{h}\right)$
F107	Gas flow rate	$\left(\frac{m^3}{h}\right)$
Ppal	Tank pressure	Pa
DPfv	Bed pressure difference	Pa
P107	Outlet gas pressure	Pa
N_2	Content of nitrogen in gas produced	(%)

A	Dry air supply rate	$\left(\frac{kg_{air}}{kg_{biomass}}\right)$
B	Biomass flow rate	$\left(\frac{kg}{h}\right)$
ρ_{air}	Specific weight of air it has been calculated by the equation of state	$\left(\frac{kg}{m^3}\right)$
R_{air}	Ideal air constant, it is about.	$\left(\frac{J}{kg.K}\right)$
P_{atm}	Atmospheric pressure	(Pa)
ER	Equivalence ratio	(%)
$\frac{S}{A}$	Steam to air ratio	$\left(\frac{kg_{steam}}{kg_{air}}\right)$
$\frac{S}{B}$	Steam to biomass ratio	$\left(\frac{kg_{steam}}{kg_{biomass}}\right)$
η_C	Carbon conversion efficiency	(%)
η_{geff}	Gasifier efficiency	(%)
V_{gas}	Gas yield	$\left(\frac{m^3}{h}\right)$
M_{gas}	Gas yield	$\left(\frac{kg_{mol\ gas}}{kg_{biomass}}\right)$
$\sum HHV_{gas}$	High heating value of produced gas	$\left(\frac{MJ}{kg\ \ Biomass}\right)$
LHV	Low heating value of produced gas	$\left(\frac{MJ}{kg\ \ Biomass}\right)$
A_{min}	Stoichiometric air which has been calculate	$\left(\frac{kg\ air}{kg\ biomass}\right)$
ICT	The Institute of Chemical Technology, Prague	
BUT	Technical University in Brno	
FB	Fluidized bed	
EMS	The electronic measuring system	
MJ	Measuring unit	