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Abstract:

Biomass is an ideal renewable and clean energy resource. Countries all over the world are paying more and more attention to biomass because it can effectively reduce greenhouse effect due to its zero carbon dioxide emission. Among the biomass utilization technologies, biomass gasification for combined heat and power is an attractive solution for utilizing biomass effectively.

The biomass gasification was studied based on the dual fluidized-bed gasifier developed by the Vienna University of Technology, which has been successfully demonstrated in Güssing, Austria. Aspen Plus V8 was used for the modelling and simulation of the biomass gasification process. The gasifier was modeled using minimum Gibbs free energy method. The key operating parameters including the feed steam temperature, feed air temperature, steam to biomass ratio, and the gasification temperature were varied using the sensitivity analysis block of Aspen Plus. The effects of changing the parameters on the output syngas composition, LHV of the syngas, char split fraction and the gasification efficiency were studied.

The sensitivity analysis results indicated that both preheating the feed steam and air have positive effect on increasing the LHV of the syngas and the gasification efficiency. Preheating air is more effectively than preheating the steam. Increasing the steam to biomass ratio results in the increase of the hydrogen yield and the proportion of hydrogen content in the syngas, while the increase of the S/B had negative effects on increasing the LHV of the syngas and the gasification efficiency. Increasing the gasification temperature resulted in the decrease of the gasification efficiency and the hydrogen yield, while it had positive effect on the increase of the LHV of the syngas. The gasification results behaved a little different when the steam to biomass ratio and the gasification temperature are low.

Base on the results, it was found that the optimum gasification temperature should be kept around 750-850 °C, the steam to biomass ratio should be kept around 0.4-0.6. If excess heat is available it should be used to preheat the feed air.

Telemark University College accepts no responsibility for results and conclusions presented in this report.

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Preface

Biomass is believed to be a promising energy source that can relieve the energy crisis and reduce the damage to the environment in the near future. The current direction of researches is how to utilize the biomass efficiently. One of the options is gasification of biomass for combined heat and power. The aim of this project is to optimize the gasification reactions in order to increase its efficiency using Aspen Plus.

This project requires a solid knowledge of Aspen Plus. In addition the knowledge of biomass properties as well as the understanding of steam gasification process is also required.

I would like to express my gratitude to my supervisor, Prof. Britt Halvorsen for her kind support from the beginning of the thesis until now. She has been always giving me instructive advices and useful suggestions on my work. I am honored to have such a friendly supervisor like her.

I am also indebted to my co-supervisor, Mr. Rajan. K. Thapa, for his professional opinions and suggestions on my thesis.

Special thanks should go to the teachers at the Telmark University College who has helped me and taught me useful knowledge for the last two years.

Last but not least, my gratitude also extends to my families who have been supporting and caring for me all of my life.

I hope this thesis will at least have some contribution to the study for making a better environment.

Natterøy, 2nd June, 2014

Ke Sun

Nomenclature

Abbreviations

BFB	Bubbling Fluidized-bed
CFB	Circulating Fluidized-bed
CHP	Combined Heat and Power
DFB	Dual Fluidized-bed
FICFB	Fast internally circulating fluidized-bed
HHV	Higher Heating Value
LHV	Lower Heating Value
S/B	Steam to Biomass Ratio
MSW	Municipal Solid Waste
RDF	Refuse Derived Fuel

Units

atm	Atmosphere
kg/h	Kilogram per hour
MJ	Mega joule
MJ/kg	Mega joule per kilogram
MJ/Nm ³	Mega joule per normal cubic meter
Nm ³	Normal cubic meter
Scmh	Standard cubic meter per hour

Letters and expressions

$C_{p,dry}$	Specific heat capacity in dry basis
$C_{p,wet}$	Specific heat capacity in wet basis
FC	Fixed carbon
M	Moisture
VM	Volatile matter
vol. %	Volume percentage
wt. %	Weight percentage

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1 Introduction

As the price of oil and gas as well as the energy crisis are continuously increasing, there is a growing demand for the energy which is environmental friendly and less expensive. Biomass is one of the choices among these kinds of energy resources. This oldest source of energy known to the mankind does not make any addition to the earth's carbon dioxide levels. Because most of the biomass grow through photosynthesis by absorbing carbon dioxide from the atmosphere. When it converts to energy, only recently absorbed carbon dioxide will release [1]. Biomass can be reproduced and does not take millions of years to develop, which is considered as a renewable energy. Besides, a wide variety of biomass can be used as raw material for the production of energy such as waste wood chips, agricultural crops and animal waste etc. In this respect, biomass is one of the most promising energy sources in the immediate future.

Biomass can be converted via biochemical route and thermochemical route. For thermochemical conversion, production of thermal energy is the main driver for this conversion. Biomass is converted into gases and then synthesized into the desired chemicals or used directly. Direct combustion, pyrolysis and gasification can be included as thermochemical process [1]. Traditional combustion of biomass shows low efficiency in utilizing energy and therefore cannot compete with fossil fuels. Biomass gasification for combined heat and power (CHP) production offers much higher energy efficiency. This technology has been commercialized successfully in some countries [2].

Gasification is the process which converts the carbonaceous solids into synthesis gas under certain range of temperatures and oxygen-starved conditions [3]. A typical gasification process includes drying, thermal decomposition or pyrolysis, combustion and char gasification. Current Gasifiers can be classified into two types: fixed-bed gasifiers and fluidized-bed gasifiers. During the process, a gasifying agent is needed. It can be oxygen, steam or air [4]. Application of the particular gasifier and the gasifying agent depends on the design capacity of the gasification plant and the desire properties of the product gas respectively.

A successful design and efficient operation of a biomass gasifier is important, and therefore a thorough understanding of the gasification process is required. Since gasification process involves a series of complex reactions, manipulating operation parameters will lead to various results [5]. Despite implementing experiments can be a choice to obtain these parameters, it requires lots of time, energy and resources. Using a mathematic model to simulate and optimize the gasification process is relatively economical and efficient. The aim of this study is to simulate and optimize the gasification process using simulation software Aspen Plus.

2 Problem description

Optimization of biomass gasification reactor using Aspen Plus is the aim of this project. There are some successful stories using biomass gasification technology for the combined heat and power, one is the dual fluidized-bed gasification technology developed by the Vienna University of Technology, which is used in a biomass CHP plant in Güssing, Austria. This study is based on the concept of this reactor.

The dual fluidized-bed gasifier combines a combustion reactor and a gasification reactor. The gasification of biomass takes place in the gasification reactor and non-react char and bed material flow into the combustion reactor where the char is combusted with excess air and heat up the bed material. The hot bed material is then separated by a cyclone and flows back into the gasifier to supply heat for the gasification reaction. Figure 2-1 shows a sketch of a dual fluidized-bed gasifier [6].

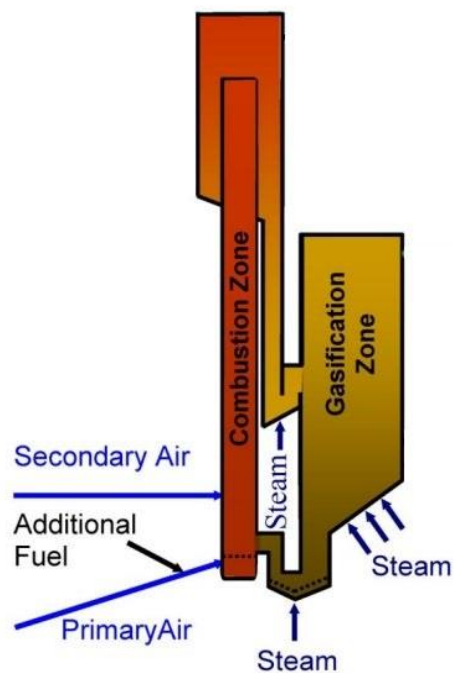


Figure 2-1: Sketch of a dual fluidized-bed gasifier

When modeling the dual fluidized-bed gasifier using Aspen Plus V8, the whole process was broken down into different blocks including the decomposition unit, char separation unit, gasification unit, char combustion unit, and a cyclone. Additional heat was provided for the decomposition of biomass and there is heat transfer between the combustor and the gasifier. Figure 2-2 shows a simplified flowsheet of the dual fluidized-bed gasification process.

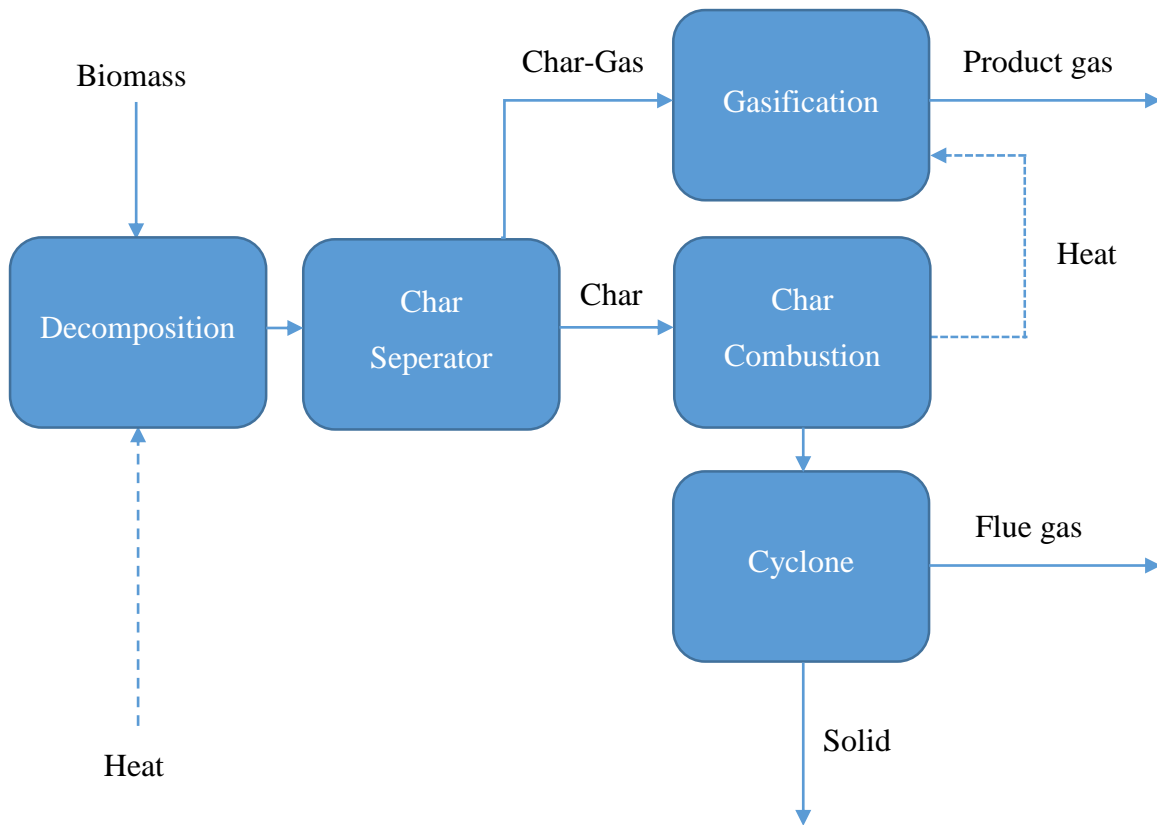


Figure 2-2: Simplified flowsheet of the dual fluidized-bed gasification process

Key operating parameters were varied to study the effects on the gasification results for optimization of the biomass steam gasification reactor. More details will be given in the following chapters.

3 Theory

This chapter contains the fundamental knowledge of the biomass, gasification process as well as the introduction of the simulation software Aspen Plus.

3.1 Biomass

Biomass refers to any organic materials which come from plants or animals that is alive or recently dead [7]. As a sustainable energy resource, botanical biomass grow through photosynthesis by absorbing carbon dioxide from the atmosphere in the presence of water and sunlight. Biological species consume botanical or other biological species to support their lives. Microorganisms break down the dead organisms into constituent parts and potential energy. The amount of carbon dioxide which releases through the combustion or the microbial decomposition of the biomass was absorbed by the biomass in the recent past. As a result, utilizing biomass as an energy resources does not increase the global CO₂ emission level. Thus, biomass is considered as green-house gas neutral.

3.1.1 Types of Biomass

There are many ways to classify the biomass. Generally, it can be divided into two main groups: virgin biomass and waste biomass. Table 3-1 shows a detailed classification of biomass [1, 8].

Table 3-1: Types of biomass

Virgin Biomass	Woody biomass
	Herbaceous biomass
	Energy crops
Waste Biomass	Agricultural waste
	Municipal waste
	Industrial waste
	Forestry waste

Virgin biomass or primary biomass comes from plants directly. Woody biomass includes trees, vines, shrubs and bushes. Herbaceous biomasses are the plants that die annually at the end of the growing season. Energy crops are those plants exclusively for producing energy. These corps have high energy density and short growth period. The cost for cultivation is relatively low since those energy crops require little fertilizer or water. Energy crops like willow, poplar, and switch grass are widely used for energy production [1].

Waste biomass or secondary biomass is the biomass derived from virgin biomass during the different stages of its production or come from the industrial and municipal wastes. Agricultural wastes mainly include straw, sugar beet leaves and animal manure. Forestry wastes contain bark, wood blocks and leaves etc. Industrial wastes come from the sawdust during the production of lumber and demolition of wood products. Waste oil and fat are also included in the industrial waste. Municipal wastes comprise municipal solid waste (MSW), sewage and landfill gas. MSW is an important source as the combustible part can be used for the production of refuse derived fuel (RDF).

3.1.2 Composition of biomass

Biomass is constituted by a variety of complex organic compounds, moisture (M), and a few inert solids called ash (ASH). The organic compounds consist carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and small amount of chlorine (Cl) and sulfur (S).

The composition of biomass is one of the necessary information which needs to know for designing a biomass gasifier or a combustor. Ultimate analysis and proximate analysis are two types of composition analysis method which are mostly used.

For ultimate analysis, the basic elements of the hydrocarbon fuel are analyzed. Together with the moisture (M) and ash (ASH) of the fuel, a typical ultimate analysis can be expressed as:

$$C + H + O + N + S + Cl + M + ASH = 100\% \quad (3.1)$$

Elements in the equation (3.1) represent the mass percentage of the corresponding elements in the fuel. Table 3-2 shows the ultimate analysis of different biomass compared with other fuels.

For proximate analysis, the composition of hydrocarbon fuel is given as volatile matter (VM), fixed carbon (FC), moisture (M), and ash (ASH). Volatile matter is the vapor released when heating the fuel. Fixed carbon is the solid carbon which remains after devolatilization of the pyrolysis process. Proximate analysis can be expressed as:

$$FC + VM + M + ASH = 100\% \quad (3.2)$$

Table 3-3 shows the proximate analysis of corncobs and rice husk [9].

Table 3-2: Ultimate analysis of some biomass and fossil fuels (dry basis, wt. %)

Fuel	C	H	N	S	O	Ash	Source
Redwood	53.5	5.9	0.1	0	40.3	0.2	[10]
Maple	50.6	6.0	0.3	0	41.7	1.4	[10]
Douglas fir	52.3	6.3	9.1	0	40.5	0.8	[10]
Douglas fir (bark)	56.2	5.9	0	0	36.7	1.2	[10]
Straw-rice	39.2	5.1	0.6	0.1	35.8	19.2	[10]
Husk-rice	38.5	5.7	0.5	0	39.8	15.5	[10]
Paper	43.4	5.8	0.3	0.2	44.3	6.0	[11]
MSW	47.6	6.0	1.2	0.3	32.9	12.0	[12]
Animal waste	42.7	5.5	2.4	0.3	31.3	17.8	[10]
Lignite	62.5	4.38	0.94	1.41	17.2	13.4	[1]
Coal	65.8	4.88	0.86	1.0	16.2	11.2	[13]
Anthracite	83.7	1.9	0.9	0.7	10.5	2.3	[14]
Petcoke	82	0.5	0.7	0.8	10.0	6.0	[14]

Table 3-3: Proximate analysis of corncobs and rice husk (dry basis, wt. %)

Fuel	FC	VM	ASH
Corncoobs	18.5	80.1	1.4
Husk-rice	16.7	65.5	17.9

3.1.3 Thermodynamic properties of biomass

Biomass gasification process involves a series of thermochemical reaction. Therefore in order to achieve proper reactions in different stages and to optimize the process, the study of the biomass thermodynamic properties is necessary. Specific heat capacity, heating value, and ignition temperature of biomass are described in the chapter. Heat of reaction for the gasification reactions will be discussed later.

Specific heat capacity or specific heat in short indicates the heat capacity of a substance. It is heavily influenced by the temperature. The moisture and the type of biomass also affect the specific heat. Table 3-4 lists the specific heat correlation equation of different types of wood and wood char [1].

Table 3-4: Specific heat of wood and wood char

Fuel	Specific heat in KJ/kg·K	Validity (°C)	Source
Dry wood	$C_{p,dry} = 0.1031 + 0.003867T$		
Wet wood	$C_{p,wet} = [(C_{p,dry} + 4.19M_{dry})/(1 + M_{dry})] + A$ M_{dry} is the moisture fraction on dry basis, T in K, and $A = (0.02355T - 1.32M - 6.191)M_{dry}$	-	[15]
Wood char	$C_{p,dry} = 1.39 + 0.00386T$	420-1720	[15]
Softwood	$0.00546T + 0.524$	40-140	
Char from softwood	$-0.0038 \times 10^{-3}T^2 + 0.00598T - 0.795$	40-413	[16]
Wood	$C_{p,dry} = 0.1031 + 0.003867T$ $[(C_{p,dry} + 4.19M)/(1 + 0.01M)] + Ac$ $Ac = M(-0.06191 + 2.36 \times 10^{-4}T - 1.33 \times 10^{-4}M)$	7-147	[17]
Various wood	$C_{p,dry} = 0.266 + 0.00116(T - 273)$ $C_{p,wet} = C_{p,dry}(1 - M_{wet}) + 4.19M_{wet}$ M_{wet} is the moisture fraction on wet basis	0-106	[18]

Heating value is the maximum heat released when certain amount of a fuel has completely combusted in the presence of air at standard conditions (25 °C, 1 atm). Heating value depends on the phase of water produced after the combustion of the fuel. If the water is in gas phase, the value of heat release is called the lower heating value (LHV). When the water vapor condenses into liquid, the value of the total heat release is called the higher heating value (HHV). The difference between the lower heating value and the higher heating value is the latter includes the latent heat of vaporization [19]. Table 3-5 lists the higher heating values of different biomass compared with other fuels [1].

Ignition temperature of a biomass is an important thermodynamic property when designing a gasification plant. During the gasification process, the combustion is required for providing

energy for the drying and pyrolysis process. Reactions occur in the gasification part are mainly endothermic, therefore the combustion can also provide energy for the endothermic reactions. Table 3-6 lists the ignition temperatures of some biomass compared with other fuels [1].

Table 3-5: Higher heating values of some biomass and fossil fuels (kJ/kg)

Fuel	HHV (KJ/kg)	Source
Redwood	21,028	[10]
Maple	19,958	[10]
Douglas fir	21,051	[10]
Douglas fir (bark)	22,098	[10]
Straw-rice	15,213	[10]
Husk-rice	15,376	[10]
Paper	17,613	[11]
MSW	19,879	[12]
Animal waste	17,167	[10]
Lignite	24,451	[1]
Coal	26,436	[13]
Anthracite	27,656	[14]
Petcoke	28,337	[14]

Table 3-6: Ignition temperatures of some biomass and fossil fuels

Fuel	Ignition Temperature (°C)	Volatile Matter in Fuel (dry ash-free wt. %)	Source
Wheat straw	220	72	[20]
Poplar wood	235	75	[20]
Eucalyptus	285	64	[20]
High volatile coal	667	34.7	[21]
Medium volatile coal	795	20.7	[21]
Anthracite	927	7.3	[21]

3.2 Gasification

3.2.1 Gasification theory

Gasification is the process that converts the carbonaceous solids into synthesis gas under certain range of temperatures and oxygen-starved conditions. A typical gasification process includes drying and pyrolysis, combustion and char gasification. Figure 3-1 illustrates the gasification process paths.

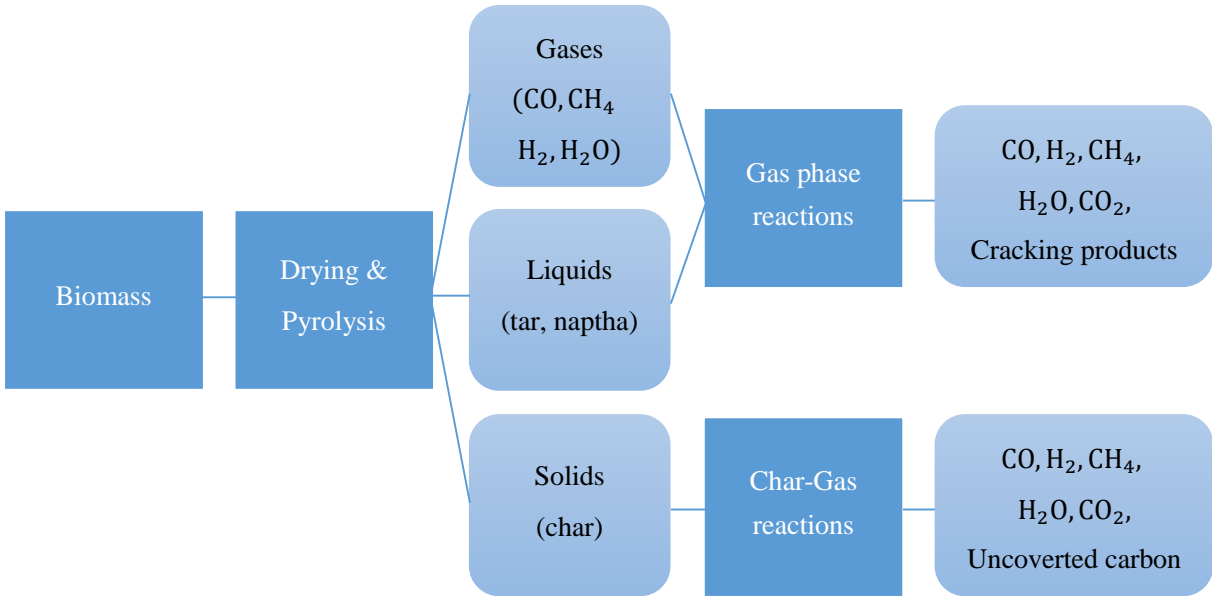


Figure 3-1: Reaction sequence of the gasification process

Biomass is first preheated in order to dry the biomass for the further use. It then undergoes thermal decomposition or pyrolysis in the absence of oxygen. In the pyrolysis part, the biomass breaks down into volatiles, liquids including tar and heavy hydrocarbons, and carbonaceous solid known as char. Gasification then occurs in the presence of a gasifying medium. The gasifying medium can be oxygen, air, or steam. The choice of gasifying medium will affect the product gas composition and its heating value. During the gasification part, both the gas-solid reactions and the gas-phase reactions happens. Usually there is char combustion for producing heat in order to support most of endothermic gasification reactions as well as the energy required by the drying and pyrolysis parts [1]. Table 3-7 lists the main reactions taking place in a gasifier.

Table 3-7: Main reactions taken place in the gasifier [1, 22, 23].

Reaction	Chemical equation	Reaction kinetic (mol/m ³ s)
Char gasification (R1)	$C + H_2O \leftrightarrow CO + H_2$ +131 kJ/mol	$r_f = 1.372m_s T \exp\left(\frac{-22645}{T}\right) [H_2O]$ $r_b = 1.044 \times 10^{-4} m_s T^2 \exp\left(\frac{-6319}{T} - 17.29\right) [H_2][CO]$
Boudouard (R2)	$C + CO_2 \leftrightarrow 2CO$ +172 kJ/mol	$r_f = 1.272m_s T \exp\left(\frac{-22645}{T}\right) [CO_2]$ $r_b = 1.044 \times 10^{-4} m_s T^2 \exp\left(\frac{-2363}{T} - 20.92\right) [CO_2]^2$
Methane decomposition (R3)	$\frac{1}{2} CH_4 \leftrightarrow \frac{1}{2} C + H_2$ +74.8 kJ/mol	$r_f = 0.151m_s T^{0.5} \exp\left(\frac{-13578}{T} - 0.372\right) [CH_4]^{0.5}$ $r_b = 1.368 \times 10^{-3} m_s T \exp\left(\frac{-8078}{T} - 7.087\right) [H_2]$
Water-gas shift (R4)	$CO + H_2O \leftrightarrow CO_2 + H_2$ -41.2 kJ/mol	$r_f = 7.68 \times 10^{10} \exp\left(\frac{-36640}{T}\right) [CO]^{0.5} [H_2O]$ $r_b = 6.4 \times 10^9 \exp\left(\frac{-13578}{T} - 0.372\right) [H_2]^{0.5} [CO_2]$
Steam reforming (R5)	$CH_4 + H_2O \leftrightarrow CO + 3H_2$ +206 kJ/mol	$r_f = 3.0 \times 10^5 T \exp\left(\frac{-15042}{T}\right) [CO]^{0.5} [H_2O]$ $r_b = 0.0265 T \exp\left(\frac{-32900}{T}\right) [CO][H_2]^2$

3.2.2 Type of gasifiers

Based on the gas-solid contacting mode, gasifiers can be classified as (i) fixed or moving bed gasifiers, (ii) fluidized bed gasifiers and (iii) entrained-flow bed gasifiers [1]. Entrained-flow bed gasifiers is not suitable for biomass, therefore it will not be discussed in this section. Figure 3-2 shows a detailed classification of gasifiers.

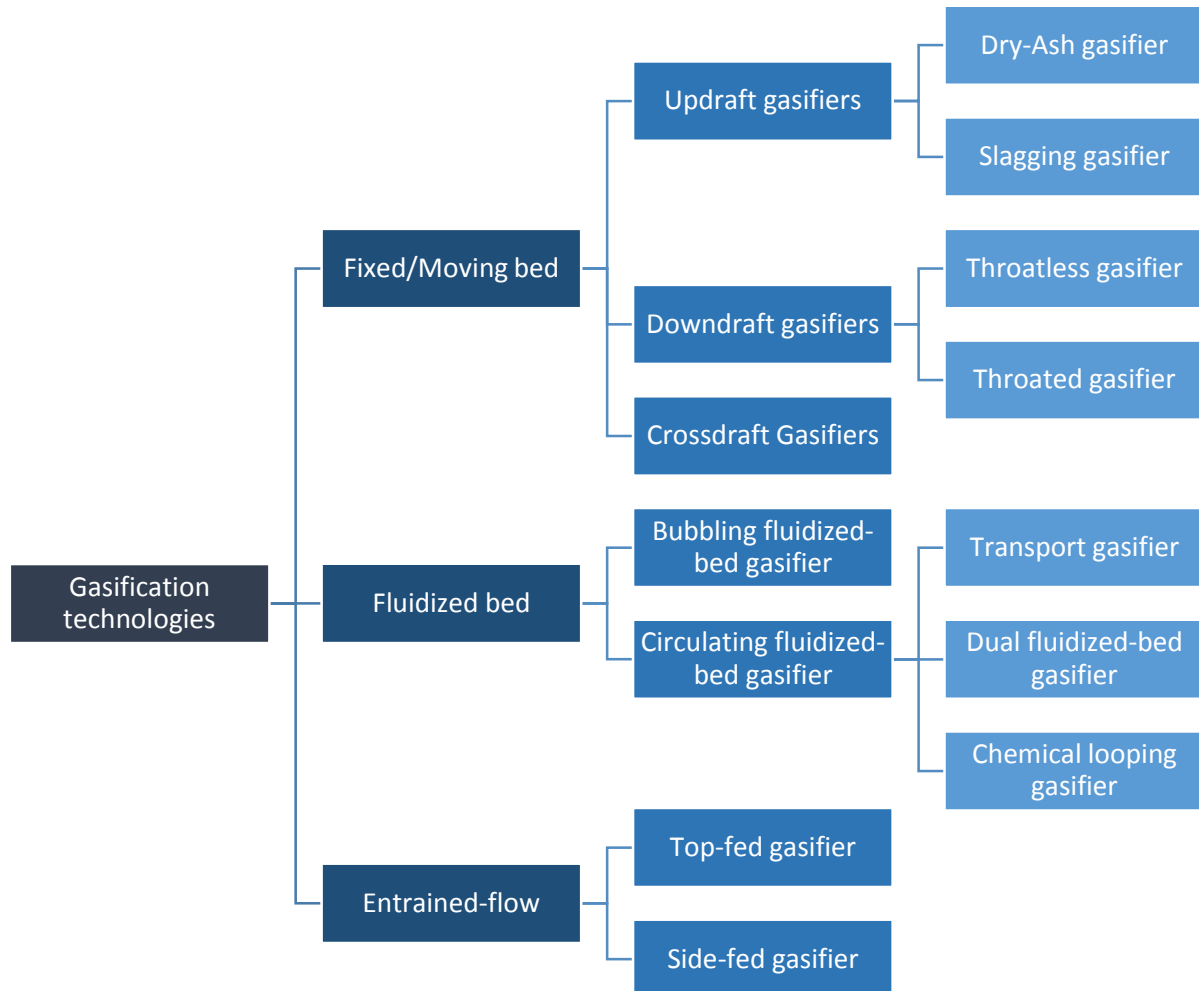


Figure 3-2: Detailed classification of gasifiers based on the gas-solid contacting mode

3.2.2.1 Fixed-Bed/Moving-bed Gasifiers

Fixed-bed or moving-bed gasifiers are the most common gasifiers for producing syngas. This type of gasifiers is easy to build and operate. Besides, Fixed-bed gasifiers can also be built in a small size. With these advantages, they are widely used in the industry.

A typical fixed-bed gasifier is the updraft gasifier. In this reactor, fuel is fed from the top and moves downward through the drying, pyrolysis, reduction and the combustion zone. While the

gasifying agent is fed from the bottom and moves upward. Figure 3-3 shows a schematic of an updraft gasifier. High cold-gas efficiency is an advantage of the updraft gasifier [1].

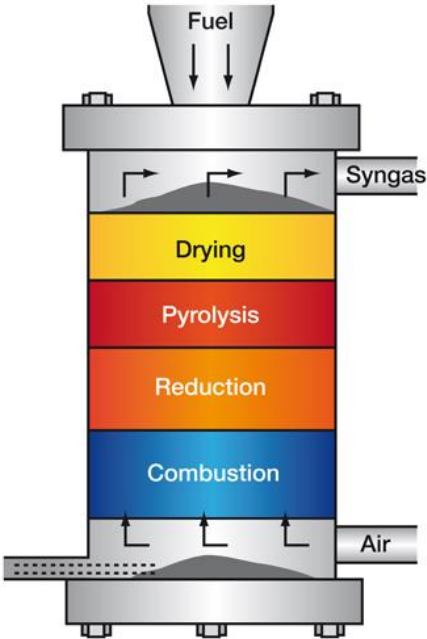


Figure 3-3: Schematic of an updraft gasifier.

In a downdraft gasifier, gasifying agent is fed at a certain height below the top as it is shown in the Figure 3-4. The fuel is fed at the top through the drying, pyrolysis, combustion and reduction zones. The product gas then flows out from the lower zone. Compared with the updraft gasifier, it has lower tar production rate [1].

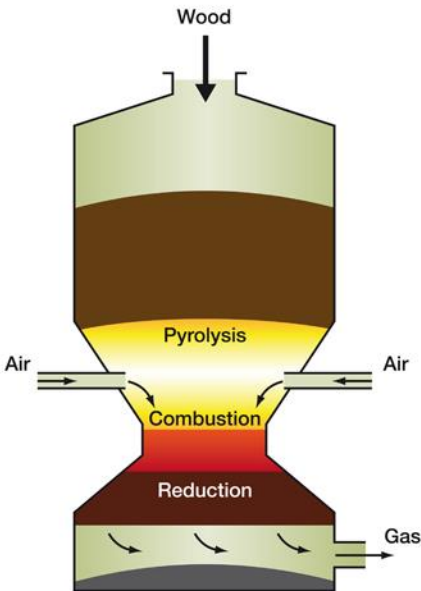


Figure 3-4: Schematic of a downdraft gasifier.

In a crossdraft gasifier, the air flows in from the side of the gasifier while the fuel is fed from the top as it is shown in the Figure 3-5. A combustion zone and a gasification zone are formed around the entrance of the air. The heat released by the combustion zone is conducted radially to support the pyrolysis of the fuel. The product gas flows out from the sidewall opposite to the entrance of air. The crossdraft gasifier has a quick response time and can be implemented for small-scale biomass units [1].

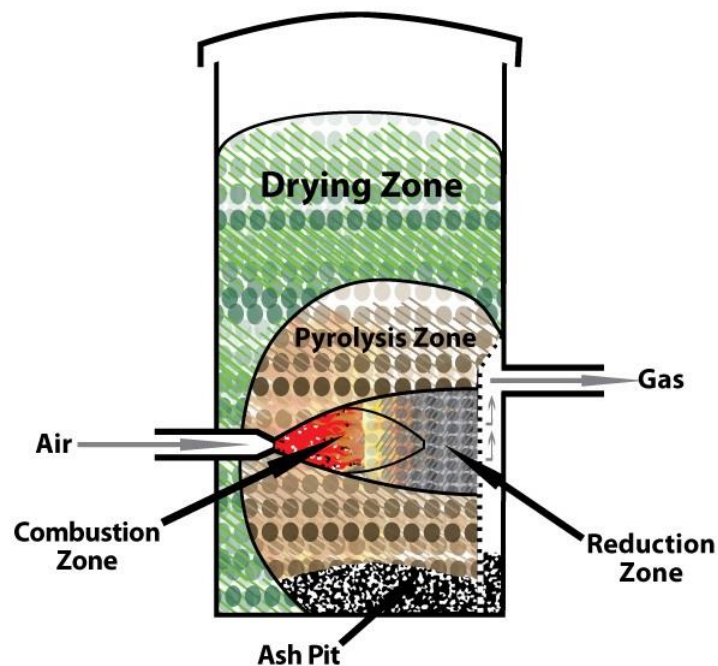


Figure 3-5: Schematic of a crossdraft gasifier.

3.2.2.2 Fluidized-bed gasifiers

The fluidized bed gasifiers have been successfully implemented for coal gasification. Compared with the fixed bed gasifier, the greater uniform temperature distribution in gasification zone is achieved by using bed material to cause the fluid and solid mixture behaving as a fluid under certain conditions. The fluidized-bed gasifiers can be classified into two main types: bubbling fluidized-bed gasifier and circulating fluidized-bed gasifier.

In a bubbling fluidized-bed gasifier, air is fed at the bottom through the grid. Above the grid, the fuel is introduced into the vessel while the bed material is fed at the opposite side of the wall. The product gas goes into a cyclone where the solid particle is separated. Figure 3-6 shows a schematic of a Mitsubishi bubbling fluidized-bed gasifier.

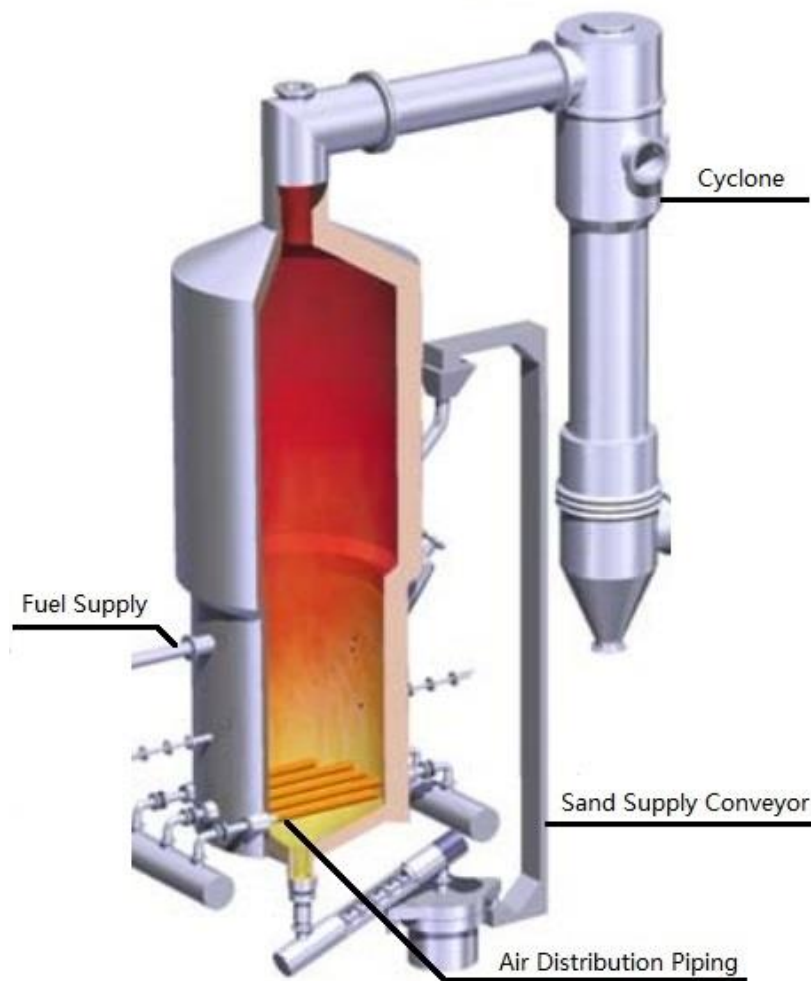


Figure 3-6: Schematic of a bubbling fluidized-bed gasifier.

A circulating fluidized-bed (CFB) gasifier is composed by a vessel called riser, a cyclone and a solid recycle device. Figure 3-7 shows a schematic of a Mitsubishi circulating fluidized-bed gasifier. Unlike the bubbling fluidized-bed gasifier, the separated bed material is recycled into the riser, thus a circulation of the bed material between the riser and the cyclone. In a circulating fluidized-bed gasifier, the fluidization velocity is higher than the velocity in the bubbling fluidized-bed gasifier. There are many commercial applications based on the circulating fluidized-bed technology.

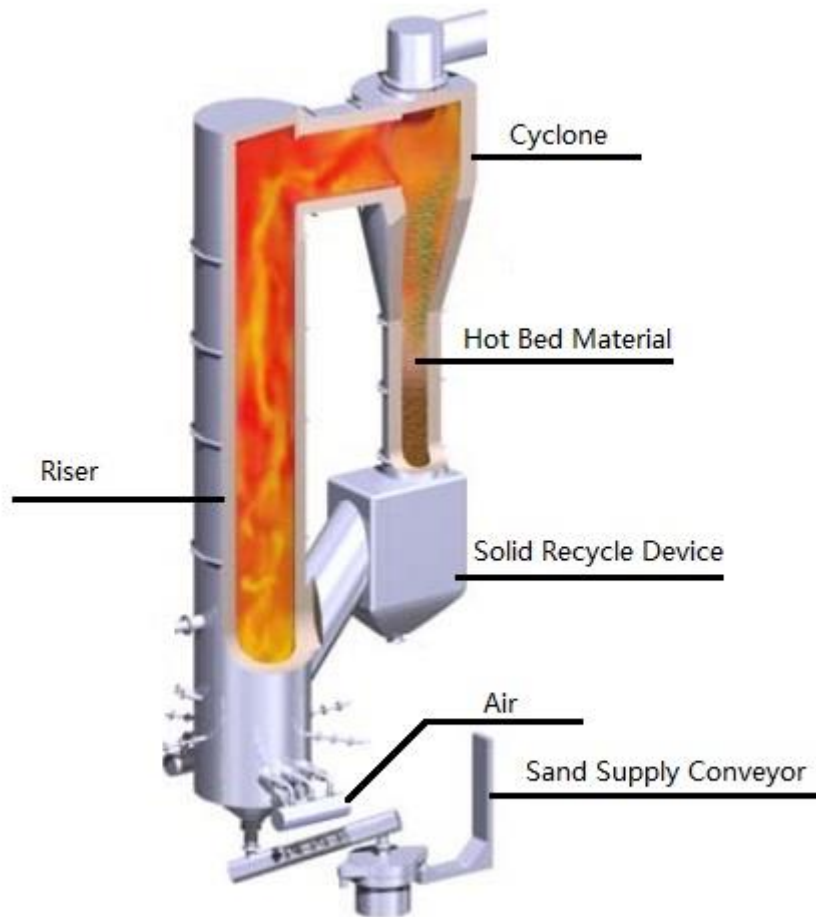


Figure 3-7: Schematic of a circulating fluidized-bed gasifier.

3.2.3 Dual fluidized-bed gasifier

If air is chosen to be the gasifying agent, there is a problem that the product gas will be diluted by the nitrogen in the air. This problem can be solved by using oxygen as the gasifying agent. But air separation will consume a lot of energy and the cost can be expensive. The dual fluidized-bed gasifier (DFBG) designed by the Vienna University of Technology has overcome this problem [24]. They built a 8 MW_{fuel} combined heat and power plant in Güssing, Austria, based on the dual fluidized-bed technology [25]. Table 3-8 lists the characteristic data of this CHP-plant [26].

A dual fluidized-bed gasifier combines a bubbling fluidized-bed gasifier and a circulating fluidized-bed combustor. The biomass is fed into the bubbling fluidized-bed gasifier where drying, pyrolysis and gasification take place. Steam is used for the gasifying agent. The product gas then goes into a cyclone where solid particles are separated. Residual char and bed material flow into the combustor through a chute where the unreacted char is combusted to heat up the bed material in the presence of air. The product is then goes into a cyclone where the hot bed

material is separated and flows back to the gasifier. The heat carried by the bed material supports the reactions in the gasifier. Figure 3-8 shows a schematic of dual fluidized-bed gasifier. This system is easy to achieve auto stabilization because if the gasification temperature changes, the amount of the residual char will change and thereby changing the energy support for the gasification and stabilizes the temperature. Figure 3-9 shows the principal of a dual fluidized-bed gasifier clearly. The high quality product syngas has high H₂ content and high heating value. Table 3-9 lists the detailed data of the Dual fluidized-bed gasifier in Güssing.

Table 3-8: Characteristic data of the CHP plant in Güssing [25, 26].

Startup of gasifier	November 2001
Fuel type	Wood chips
Fuel power	8 MW
Electrical output	2 MW
Thermal output	4.5 MW
Electrical efficiency	25.0%
Thermal efficiency	56.3%
Electrical/thermal output	0.44
Total efficiency	81.3%

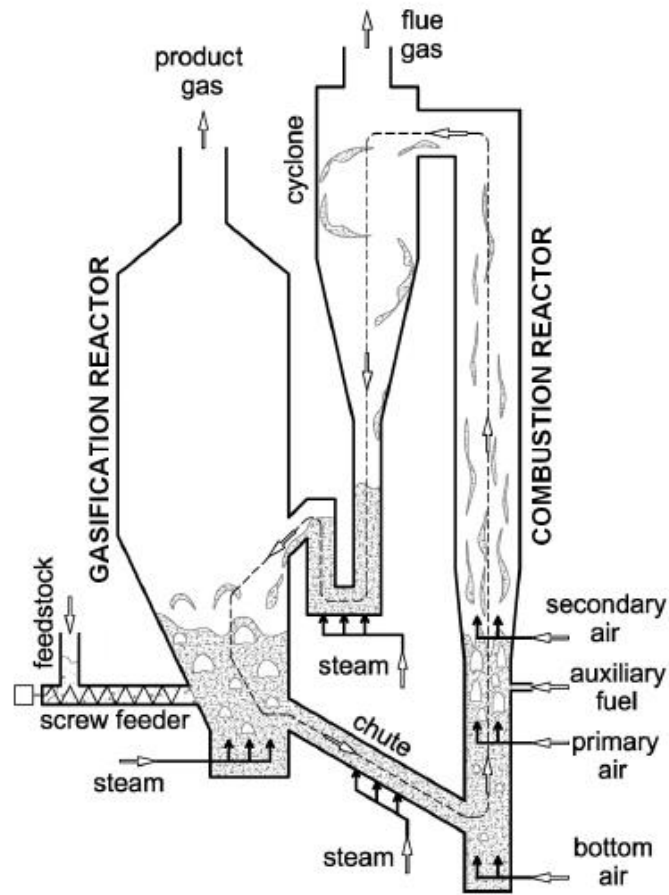


Figure 3-8: Schematic of a circulating fluidized-bed gasifier [27].

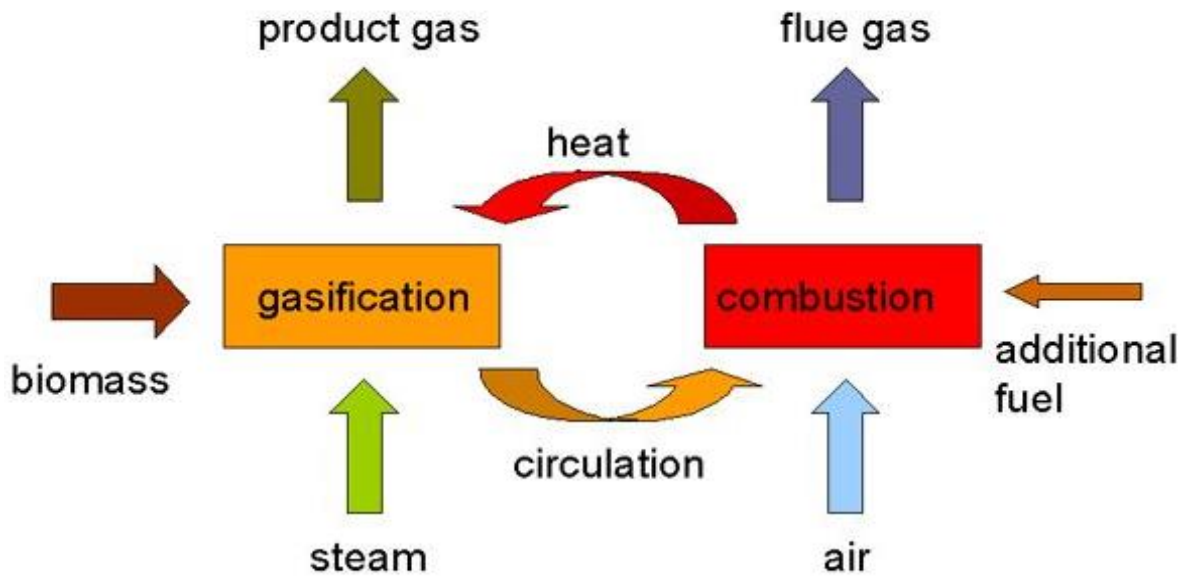


Figure 3-9: Principal of dual fluidized-bed gasifier [27].

Table 3-9: Detailed of the Dual fluidized-bed gasifier in Güssing [25, 28].

Gasifier	
Parameter	Value
Type	BFB
Gasifying agent	Steam
Bed material	Olivine
Feedstock	Wood chips
Capacity (Kg/h)	2000
Temperature (°C)	850
Pressure	Atmospheric
Internal diameter (cm)	220
Effective total height (m)	6
Combustor	
Parameter	Value
Type	CFB
Temperature	930
Pressure	Atmospheric
Circulation ratio C/F	50 kg/kg dry biomass
Internal diameter (cm)	85
Total height (m)	9.7
Product (vol. %, dry basis)	
Hydrogen	35-45
Carbon monoxide	20-30
Carbon dioxide	15-25
Methane	8-12
Nitrogen	3-5

3.3 Aspen Plus introduction

Aspen Plus is a market-leading comprehensive chemical process modeling tool, used by the world's leading chemistry organizations and related industries. It originated from a joint project called Advanced System for Process Engineering (ASPEN) which is started by the Massachusetts Institute of Technology (MIT) and the US Department of Energy in the 1970's and finished in 1981. AspenTech was founded in the same year and the ASPEN project was commercialized by AspenTech called Aspen Plus [29].

Aspen Plus is used in the industrial chemical process modeling, simulation, optimization, sensitivity analysis and economic evaluation. It provides the comprehensive physical property models and the library of unit operation models, fast and reliable process simulation functions, and advanced calculation method. With the physical property database and the operation models provided by Aspen Plus, engineers are able to simulate actual plant behavior effectively and accurately thereby improve the productivity and reduce the costs [30].

Aspen Plus has been widely used for simulating coal conversion. Literatures like coal gasification simulation, coal hydrogasification processes and integrated coal gasification combined cycle (IGCC) power plants have been already published [31]. There are also detailed guides about modeling and simulation coal conversion published by AspenTech [32, 33]. However, there are not many researches related to the modeling and simulation of biomass gasification process in a dual fluidized-bed gasifier [34].

3.4 Gasifier simulation models

Commercial plants require optimal operating parameters to achieve maximum interest. The operating parameters are often obtained by conducting experiments on pilot plants. Although accurate data can be obtained through the experiments, it is always expensive and takes a lot of time to get the results. Furthermore, the optimum parameters are often size dependent. The experimental results may not be the optimum in the real plants. Modeling or simulation of a plant may not predict the process very accurate, but a good simulation model can help the engineers find out the effects of changing different parameters on the process results thereby optimizing the operating conditions efficiently [1]. Gasifier simulation models can be classified into four groups [1, 35], they are:

- Thermodynamic equilibrium
- Kinetic
- Computational fluid dynamics (CFD)
- Artificial neural network (ANN)

In Aspen Plus, thermodynamic equilibrium and kinetic models are often used to simulate the gasification process.

3.4.1 Thermodynamic equilibrium models

The basic principle of using thermodynamic equilibrium models is the equilibrium state gives the maximum conversion under certain conditions. In these models, the reactions are considered to be zero-dimensional and they are independent with time. The reaction kinetics and the reactor hydrodynamics are not considered in the thermodynamic equilibrium models. The stoichiometric and nonstoichiometric methods are used to determine the thermodynamic equilibrium [1]. Because biomass gasification involves a series of complex reactions, the stoichiometric model are not suitable for this situation as every reaction should be considered in this model. The nonstoichiometric method is frequently used when simulating gasification process using Aspen Plus.

For nonstoichiometric method, the reacting system has minimum Gibbs free energy when the equilibrium is reached. This method is also called Minimization of the Gibbs free energy method. The advantage of minimization of the Gibbs free energy method is no specific reaction mechanism is needed to solve the problem, only the elemental composition of the feed is needed for the input, which can be obtained from its ultimate analysis [1]. Therefore the nonstoichiometric method is particular suitable for biomass gasification simulation as the exact chemical formula of biomass is unknown and the gasification reaction mechanisms are very complicated. Ramzan et al. simulated a fixed-bed gasifier using the minimization of Gibbs free energy method for the modeling [36]. Doherty et al. developed a simulation of biomass gasification in a dual-fluidized bed gasifier (called the FICFB gasifier by the authors) [34]. Gibbs free energy minimization with temperature approach method was applied in this simulation. He et al. simulated the biomass gasification process in a DFB gasifier developed by Mid Sweden University using Aspen Plus [37]. The minimization of Gibbs free energy method is also used for modeling the gasifier in this simulation.

3.4.2 Kinetic models

Thermodynamic equilibrium model has its limitation for the reaction time is not considered in this model. Sometimes the simulation results may be a little different from the real situation. The kinetic models consider the reaction kinetics and reactor hydrodynamics. The reaction results include the product composition and overall gasifier performance after a finite time are given by a kinetic model [1]. Though a kinetic model can give accurate results, parameters such as reaction rate, residence time of particles and reactor hydrodynamics are involved in a kinetic model which significantly increase the workload and the complex of the modeling. Because biomass gasification involves a series of complex reactions, each reaction mechanism needs to

be studied. In Aspen Plus, the external Fortran subroutines for hydrodynamics and kinetics are needed for simulating biomass gasification process [5]. Therefore the solid knowledge of Fortran programming is required. Besides, the kinetic models has more accuracy at relatively low operating temperatures ($< 800\text{ }^{\circ}\text{C}$), because the reaction rate is slow and the time for the conversion is long under lower temperatures. At higher temperature the equilibrium models may be more suitable than the kinetic models [1]. Abdelouahed et al. simulated a Dual fluidized-bed gasification process using Aspen Plus based on the Tunzini Nessi Equipment Companies' (TNEE) technology [2]. The kinetic model was used and bed hydrodynamics were neglected. Nikoo and Mahinpey simulated an atmospheric fluidized-bed gasifier using kinetic model [31]. Both hydrodynamics and reaction kinetics were considered simultaneously.

4 Simulation of biomass gasification in a dual fluidized-bed gasifier using Aspen Plus

This chapter describes the simulation of biomass gasification in a dual fluidized-bed gasifier using Aspen Plus V8 in detail. Process description, components, physical properties, block specification and sensitivity analyses are introduced in this chapter.

4.1 Process description

In Aspen Plus, there is no particular gasifier model ready for use, therefore to model a dual fluidized-bed gasifier, it is necessary to separate the whole process into different blocks that can be simulated with the existing models provided by Aspen Plus. Figure 4-1 shows the flowsheet of this simulation process.

Biomass is fed as a non-conventional component into a decomposition reactor-PYR which converts the biomass into conventional components by calculate its ultimate analysis and proximate analysis. Heat Q1 is supported for the decomposition process. A calculator is used to determine the yield of the components. Then the decomposition mixture goes into a separator-SEP where a portion of char is separated and flows into the combustor. The char is combusted in the combustor-COM with excess air, the heat Q is generated to support the endothermic reactions in the gasifier-GASIFIER. The split fraction of char is varied until the gasification temperature is reached at certain degrees. This is done by setting a design specification block. The rest of char with gases from the separator-SEP are fed in the presence of steam into the gasifier-GASIFIER where the gasification takes place. The gasifier was modeled based on the minimization of Gibbs free energy model. Therefore the RGIBBS reactor provided in Aspen Plus was chosen as a gasifier. The outlet stream from the gasifier is expressed as AFT-GAS. After the char combustion, the unreacted char and air is separated in a cyclone-CYCLONE into solid and flue gas.

According to the features of Aspen Plus and the thermodynamic equilibrium model used for this simulation, the following assumptions were made in this simulation of biomass gasification process:

- Steady state operation
- Zero-dimensional
- Particle size is not considered
- Uniform temperature distribution for the biomass particle
- Pressure drops are neglected

- Heat loss for the reactors are neglected
- Tar formation is not considered
- Char is 100% carbon
- Equilibriums for all the reactions is reached in the gasifier
- 90% of char is burned in the combustor
- Cyclone efficiency is 85%
- Ash comes from the biomass is considered as inert, it does not react with other components.
- All elements that compose the biomass yield into char, H_2 , O_2 , N_2 , Cl_2 , S.

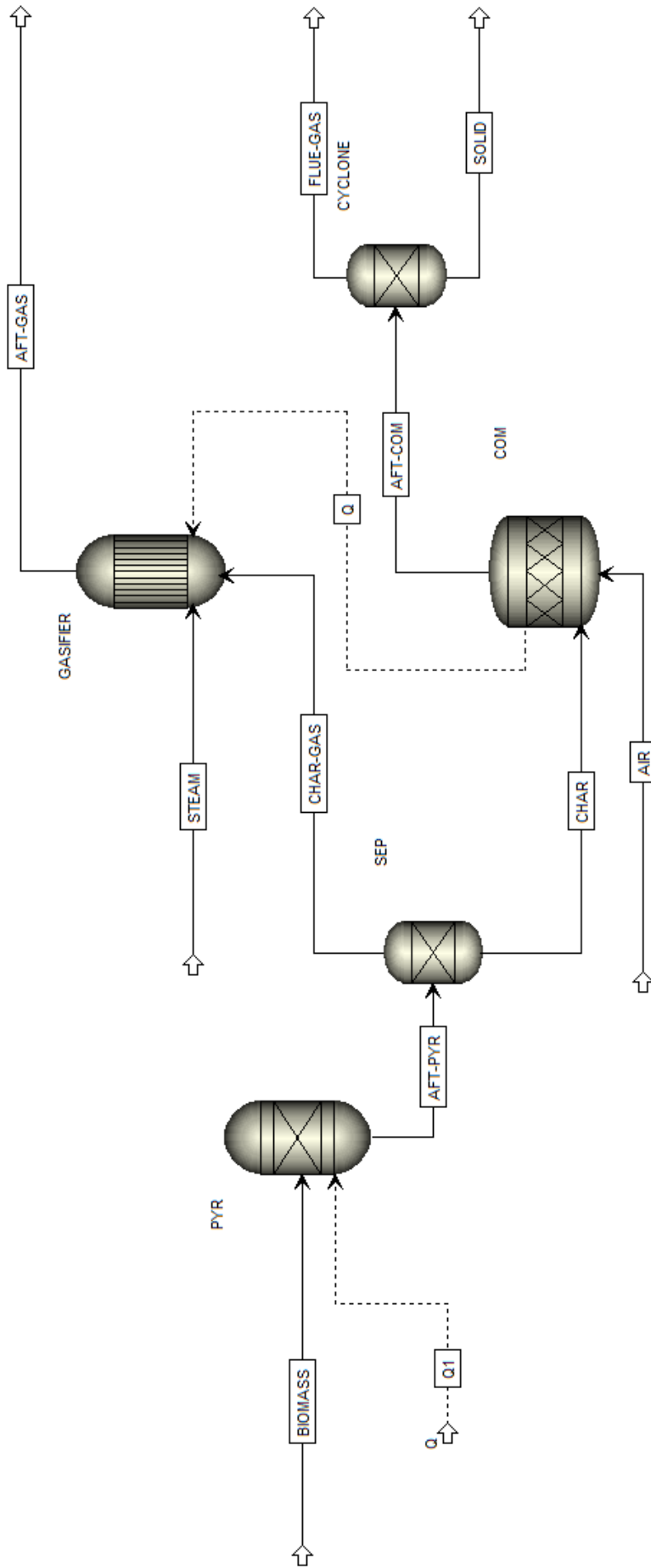


Figure 4-1: Flowsheet of biomass gasification process in a dual fluidized-bed gasifier

4.2 Components

At the beginning of simulation, all the components were specified properly. Table 4-1 lists the components modeled in the simulation. Because the uncertainty of exact formulas of biomass and ash, they were defined as nonconventional solid components. For these components, only enthalpy and density were calculated during the simulation. Aspen Plus includes special models for estimating both enthalpy and density for coal-derived materials. These models can be used to estimate biomass properties as well since biomass can be considered as coal-derived material. More details will be discussed in the next section.

Table 4-1: Detailed data of the components modeled in the simulation.

Component ID	Type	Component name	Formula
BIOMASS	Nonconventional	-	-
C	Solid	CARBON-GARAPHITE	C
CO2	Conventional	CARBON-DIOXIDE	CO2
CO	Conventional	CARBON-MONOXIDE	CO
H2	Conventional	HYDROGEN	H2
H2O	Conventional	WATER	H2O
N2	Conventional	NITROGEN	N2
O2	Conventional	OXYGEN	O2
CH4	Conventional	METHANE	CH4
CL2	Conventional	CHLORINE	CL2
S	Conventional	SULFUR	S
ASH	Nonconventional	-	-
HCL	Conventional	HYDROGEN-CHLORIDE	HCL
NH3	Conventional	AMMONIA	H3N
H2S	Conventional	HYDROGEN-SULFIDE	H2S
SO2	Conventional	SULFUR-DIOXIDE	O2S

4.3 Physical properties

The PK-BM property method was selected as the global property method for this model. This method uses the Peng Robinson cubic equation of state with the Boston-Mathias alpha function for all the thermodynamic properties, which is suitable for the nonpolar or mildly polar mixtures such as hydrocarbons and light gases. The PK-BM property method is recommended for the gas processing, refinery, and petrochemical applications [38].

Since biomass and ash were defined as nonconventional components, only the density and enthalpy were calculated during the simulation. HCOALGEN was selected as the enthalpy model for both biomass and ash, the density model was DCOALIGT. Different empirical correlations for heat of combustion, heat of formation and heat capacity are included in the HCOALGEN model. Table 4-2 lists the correlations and the corresponding code value for the enthalpy properties used in this model. The density method DCOALIGT is based on equations from IGT (Institute of Gas Technology) [32].

Table 4-2: Specifications for the nonconventional components enthalpy model

Model Parameter	Biomass and Ash	
	Code Value	Correlation
Heat of Combustion	1	Boie correlation
Standard Heat of Formation	1	Heat-of-combustion-based correlation
Heat Capacity	1	Kirov correlation
Enthalpy Basis	1	Elements in their standard states at 298.15K and 1 atm

Components attributes comprises the ultimate analysis, proximate analysis, and sulfur analysis for the biomass and ash, which were required once the enthalpy model and density model were specified. Table 4-3 lists the compositions of the biomass and ash based on their ultimate, proximate and sulfur analysis. Usually the data of sulfur analysis is not given in most of the references. In this model, all the sulfur was specified as “organic”. Because wood chips was used as the feedstock in this simulation which has very low contents of sulfur. Therefore, there is no effluence to the simulation results.

The stream class for global was specified as “MIXCINC”. This option was for the situation when both conventional and nonconventional solids are present, but there is no particle size distribution. Here, “MIX” stands for “MIXED” substream, “CI” represents for “CISOLID” substream, “NC” stands for Nonconventional substream.

Table 4-3: Compositions of Biomass and ash (wt. %) [34].

Ultimate analysis (dry basis)	Biomass	Ash
Carbon	51.19	0
Hydrogen	6.08	0
Oxygen	41.3	0
Nitrogen	0.2	0
Sulfur	0.02	0
Chlorine	0.05	0
Ash	1.16	100

Proximate analysis	Biomass	Ash
Volatile matter (dry basis)	80	0
Fixed carbon (dry basis)	18.84	0
Ash (dry basis)	1.16	100
Moisture (moisture-included basis)	20	0

Sulfur analysis (dry basis)	Biomass	Ash
Pyritic	0	0
Sulfate	0	0
Organic	0.02	0

4.4 Stream specification

The detailed specifications for biomass, air, steam, and Q1 as feed streams are listed in Table 4-4.

Table 4-4: Specifications for the inlet streams

Stream	Component	Temperature	Pressure	Mass flow rate	Source
BIOMASS	Specified as its ultimate, proximate and sulfur analysis	25 °C	1 atm	2000 kg/h	
AIR	21% O ₂ 79% N ₂ (Volume fraction)	450 °C	1 atm	Air to biomass ratio is 1.12	[34]
STEAM	H ₂ O	450 °C	1 atm	Steam to biomass ratio (S/B) is 0.6	[34]
Q1	-	25 °C for both begin and end temperature	-	-	

The mass flow rate of air and steam was calculated by setting calculator blocks. The air to biomass ratio is defined as:

$$\text{Air to Biomass ratio} = \dot{m}_{\text{air}} / \dot{m}_{\text{biomass}} \quad (4.1)$$

The steam to biomass ratio (S/B) is defined as:

$$\text{S/B} = (\dot{m}_{\text{moisture content in biomass}} + \dot{m}_{\text{steam}}) / \dot{m}_{\text{dry biomass}} \quad (4.2)$$

The heat required for the decomposition process was calculate by setting a calculator block.

4.5 Blocks specification

After specifying the inlet streams, all the blocks were specified according to the design operating condition. Table 4-5 gives a brief description of the unit operation blocks presented in the flowsheet. Table 4-6 gives the detailed operating parameters for the blocks.

Table 4-5: Description of the blocks used in the modeling





Module name	Scheme	Block ID	Description
RYield		PYR	Reactors where stoichiometry and kinetics are unknown or unimportant but a yield distribution is known. In this simulation PYR was used for the conversion of the non-conventional stream BIOMASS into conventional components (C, H ₂ , O ₂ , Cl ₂ , N ₂ , S). A calculator block was used to determine the composition of the products.
Sep		SEP CYCLONE	Separates inlet stream components into multiple outlet streams, based on specified flows or split fractions. In this simulation, SEP was used for split a portion of char into the combustor to provide heat for the gasification reaction. The split fraction was controlled by a design specification block. CYCLONE was used to separate the product mixture after the combustion into the flue gas and the unreact char
RStoic		COM	Models stoichiometric reactor with specified reaction extent or conversion. In this simulation, COM was used for modeling the char combustion reaction. Excess air was fed.
RGibbs		GASIFIER	RGibbs reactor does not require the knowledge of the reaction stoichiometry. It uses Gibbs free energy minimization with phase splitting to calculate equilibrium. RGibbs also allows restricted equilibrium specifications for systems that do not reach complete equilibrium. In this simulation GASIFIER was used for modeling the gasification reaction.

Table 4-6: Operating parameters for the blocks

Block ID	Temperature (°C)	Pressure (atm)	Specification
PYR	25	1	Component yields were determined by a calculator block
SEP	-	-	Char split fraction was determined by a design specification block.
COM	900	1	Combustion reaction was specified as: $C + O_2 \rightarrow CO_2$ 99% of C is converted
GASIFIER	850	1	Calculate phase equilibrium and chemical equilibrium. Products determined by RGibbs model. RGibbs considers all components as products
CYCLONE	-	-	Typical cyclone separation efficiency is 0.85. Therefore the split fraction of char was specified as 0.85.

4.6 Calculator Specification

In this simulation, three calculators were implemented. The variables for each calculator need were defined and the Fortran statements was entered.

4.6.1 Calculator 1

Calculator 1 was used to determine the product composition after the decomposition reactor. Table 4-7 shows the definition of the import variables using category **Streams** created in the Calculator 1.

Table 4-7: Definition of the import variables for the Calculator 1

Variable Name	Type	Stream	Substream	Component	Attribute	Elements
ULT	Compattr-Vec	BIOMASS	NC	BIOMASS	ULTANAL	
WATER	Compattr-Var	BIOMASS	NC	BIOMASS	PROXANL	1

ULT is the vector defined for accessing the values in the ultimate analysis of the biomass. WATER is the variable corresponding to the first element in the proximate analysis of the biomass, which is the value of the moisture. Here, ULTANAL and PROXANL stand for ultimate analysis and proximate analysis respectively.

The definition of the export variables using category **Blocks** is listed in Table 4-8.

Table 4-8: Definition of the export variables for the Calculator 1

Variable Name	Type	Block	Variable	ID1	ID2
H2O	Block-Var	PYR	MASS-YIELD	H2O	MIXED
ASH	Block-Var	PYR	MASS-YIELD	ASH	NC
C	Block-Var	PYR	MASS-YIELD	C	CISOLID
H2	Block-Var	PYR	MASS-YIELD	H2	MIXED
N2	Block-Var	PYR	MASS-YIELD	N2	MIXED
CL2	Block-Var	PYR	MASS-YIELD	CL2	MIXED
S	Block-Var	PYR	MASS-YIELD	S	MIXED
O2	Block-Var	PYR	MASS-YIELD	O2	MIXED

Here ID1 stands for the corresponding components. ID2 stands for the classification of the component.

The Fortran statements was entered as below:

```
FACT = (100 - WATER) / 100
H2O = WATER / 100
ASH = ULT(1) / 100 * FACT
C = ULT(2) / 100 * FACT
H2 = ULT(3) / 100 * FACT
N2 = ULT(4) / 100 * FACT
CL2 = ULT(5) / 100 * FACT
S = ULT(6) / 100 * FACT
O2 = ULT(7) / 100 * FACT
```

Here FACT is the factor to convert the ultimate analysis to a wet basis.

This calculator block was executed before the PYR block operation.

4.6.2 Calculator 2

Calculator 2 was used to determine the air mass flow rate. Table 4-9 shows the definition of the variables using category **Streams** created in the Calculator 2.

Table 4-9: Definition of the variables for the Calculator 2

Variable Name	Variable Classification	Type	Stream	Substream	Variable
BIOMASS	Import	Stream-Var	BIOMASS	NC	MASS-FLOW
AIR	Export	Stream-Var	AIR	MIXED	MASS-FLOW

The Fortran statements was entered as below:

```
AIR=1.12*BIOMASS
```

This calculator block was executed at the beginning of the simulation.

4.6.3 Calculator 3

Calculator 3 was used to determine the steam mass flow rate. Table 4-10 shows the definition of the variables using category **Streams** created in the Calculator 3.

Table 4-10: Definition of the variables for the Calculator 3

Variable Name	Variable Classification	Type	Stream	Substream	Variable	Component
BIOMASS	Import	Stream-Var	BIOMASS	NC	MASS-FLOW	-
MOISTURE	Import	Mass-Flow	AFT-PYR	MIXED	-	H2O
STEAM	Export	Stream-Var	STEAM	MIXED	MASS-FLOW	-

The Fortran statements was entered as below:

$$\text{STEAM}=0.6*(\text{BIOMASS}-\text{MOISTURE})-\text{MOISTURE}$$

This calculator block was executed at the beginning of the simulation.

4.7 Sensitivity analyses

In Aspen Plus, sensitivity analysis is a tool for determining how a process reacts to varying key operating and design variables. In order to optimize the gasification process, sensitivity analyses were set for the study of the gasification performance. During the sensitivity analyses, one operating parameter was varied while the others remained the same.

In this simulation, gasification temperature was varied from 650 to 1100 °C. Steam to biomass ratio was varied from 0.3-1.0. Steam temperature was varied from 150-1000 °C. Excess air temperature was varied from 25-1025 °C. LHV and composition of the product gas, char split fraction, and gasification efficiency were analyzed. Gasification efficiency or cold gas efficiency is defined as:

$$\text{Gasification efficiency} = \frac{\text{LHV}_{\text{gas}}(\text{MJ}/\text{Nm}^3) \cdot \dot{V}_{\text{gas}}(\text{Nm}^3/\text{h})}{\text{LHV}_{\text{biomass}}(\text{MJ}/\text{kg}) \cdot \dot{m}_{\text{biomass}}(\text{kg}/\text{h})} \quad (4.3)$$

The LHV of biomass is 19.09 MJ/kg [34].

5 Results

5.1 Sensitivity analysis: Steam temperature

In this case, steam temperature was varied from 150-1000 °C while other parameters remained unchanged. The syngas composition, gasification efficiency, char split fraction and the LHV of syngas were studied. For all the syngas compositions results, the compositions are given in volume fraction, dry and NH₃, H₂S, HCl free. Figure 5-1 shows the effect of the steam temperature on the syngas composition (vol. % dry basis).

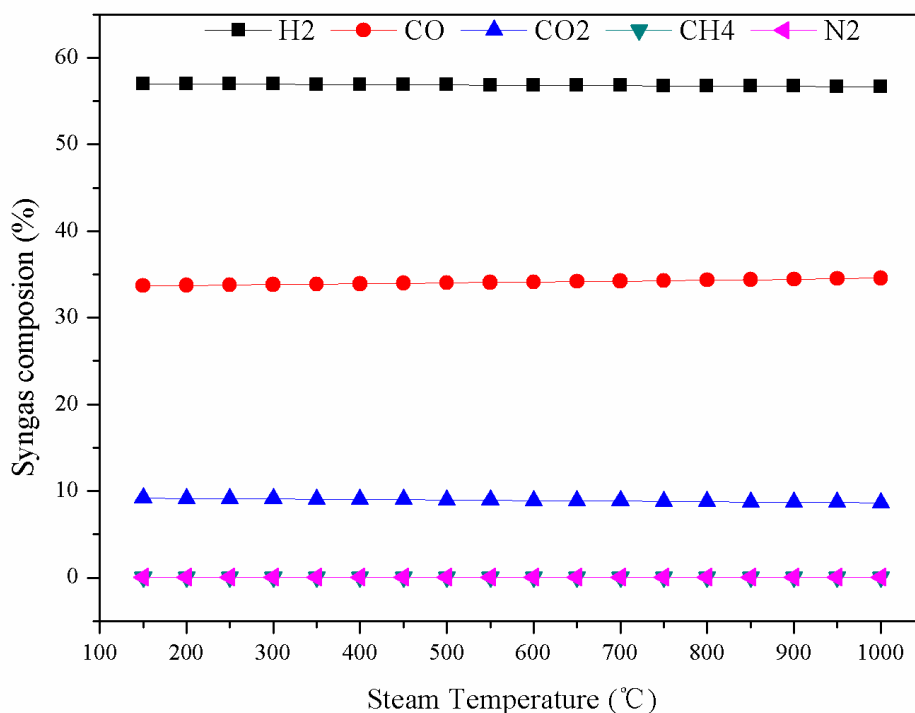


Figure 5-1: Effect of the steam temperature on the syngas composition.

As the steam temperature increases from 150-1000 °C, CO rises from 33.69% to 34.56%. Both H₂ and CO₂ decrease. H₂ drops from 57.00% to 56.66% and CO₂ from 9.18% to 8.64%. Both CH₄ and N₂ contents are very low. (0.05% and 0.08%).

The effect of the steam temperature on the char split fraction is illustrated on Figure 5-2. When the steam temperature increases from 150 to 1000 °C, the char split fraction decreases from 0.137 to 0.108.

The effect of the steam temperature on the LHV of the syngas is illustrated on Figure 5-3.

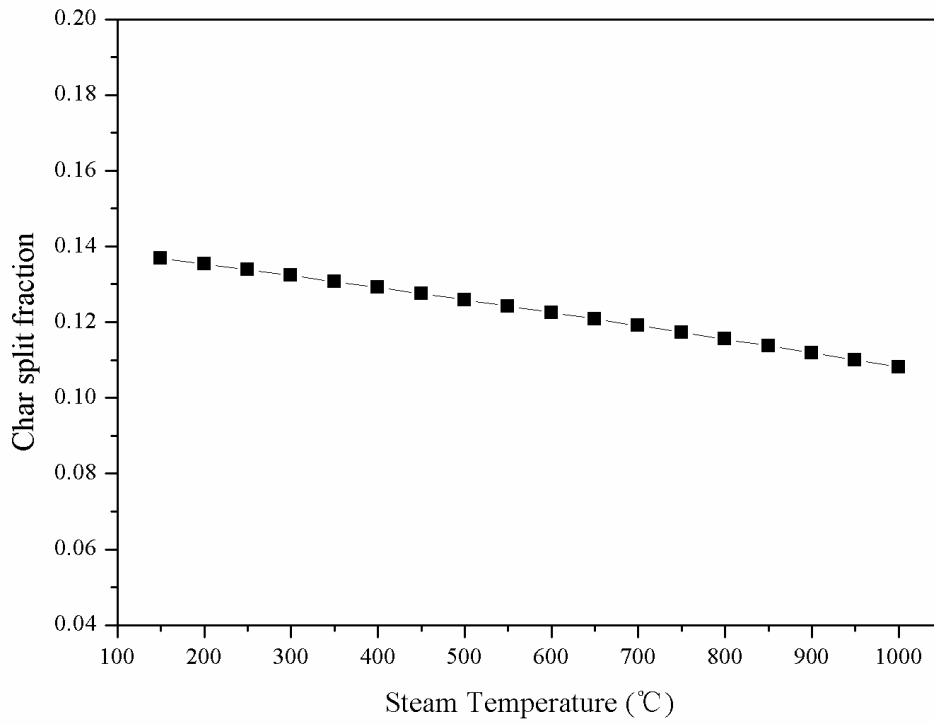


Figure 5-2: Effect of the steam temperature on the char split fraction.

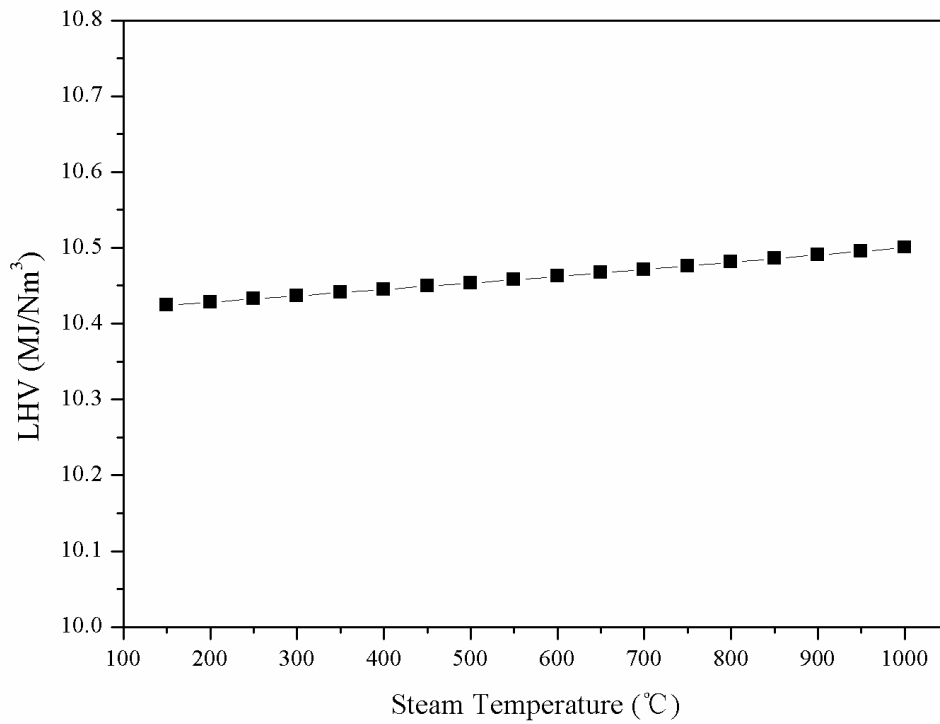


Figure 5-3: Effect of the steam temperature on the LHV of the syngas.

When the steam temperature increases from 150-1000 °C, the LHV of the syngas increases from 10.42 to 10.50 MJ/Nm³.

The effect of the steam temperature on the gasification efficiency is illustrated on Figure 5-4.

When the steam temperature increases from 150-1000 °C, the gasification efficiency increases from 76.16% to 79.11%.

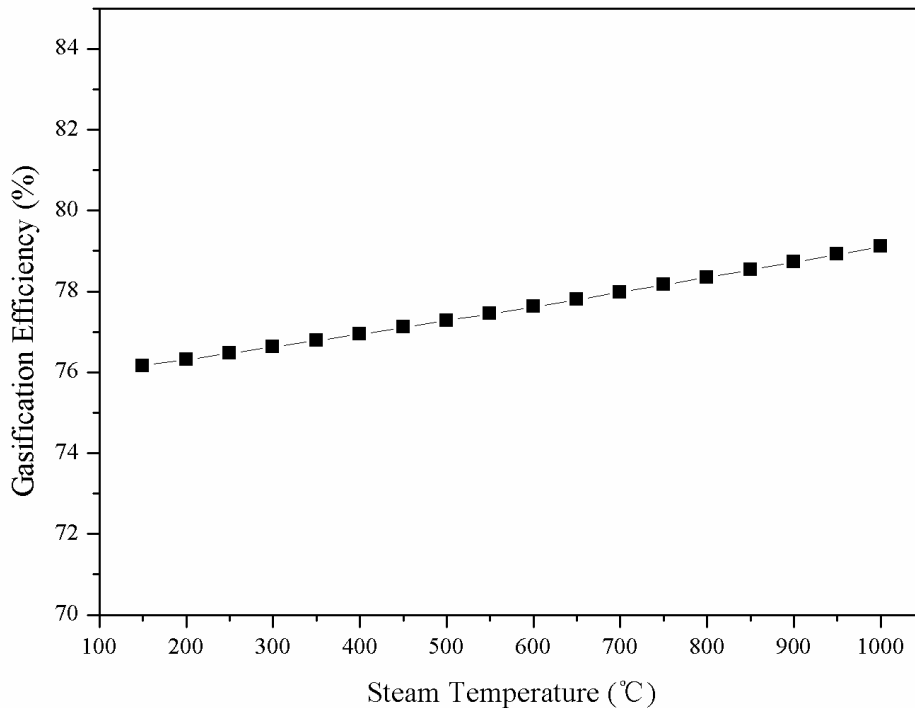


Figure 5-4: Effect of the steam temperature on the gasification efficiency.

5.2 Sensitivity analysis: Air temperature

In this case, air temperature was varied from 25-1025 °C while other parameters remained unchanged. The syngas composition, gasification efficiency, char split fraction and the LHV of syngas were studied. Figure 5-5 shows the effect of the air temperature on the syngas composition (vol. % dry basis).

As the air temperature increases from 25-1025 °C, CO rises from 33.13% to 35.20%. Both H₂ and CO₂ decrease. H₂ drops from 57.21% to 56.41% and CO₂ from 9.52% to 8.25%. Both CH₄ and N₂ contents are very low. (0.05% and 0.08%).

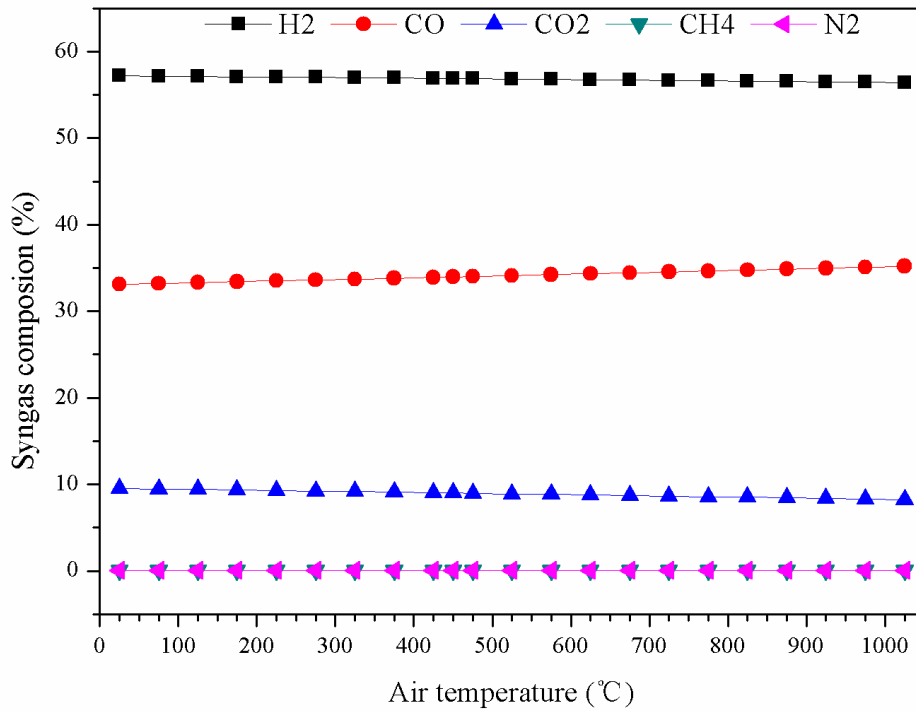


Figure 5-5: Effect of the air temperature on the syngas composition.

The effect of the air temperature on the char split fraction is illustrated on Figure 5-6. When the air temperature increases from 25-1025 °C, the char split fraction decreases from 0.155 to 0.087.

The effect of the air temperature on the LHV of the syngas is illustrated on Figure 5-7. When the air temperature increases from 25-1025 °C, the LHV of the syngas increases from 10.38 to 10.56 MJ/Nm³.

The effect of the steam temperature on the gasification efficiency is illustrated on Figure 5-8. When the air temperature increases from 25-1025 °C, the gasification efficiency increases from 74.32% to 81.31%.

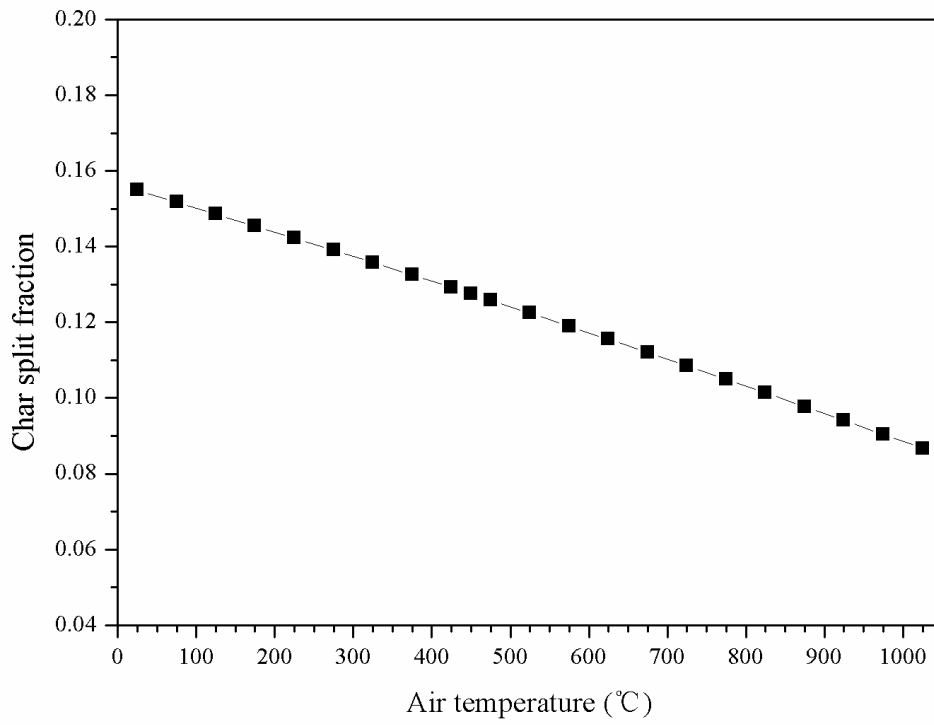


Figure 5-6: Effect of the air temperature on the char split fraction.

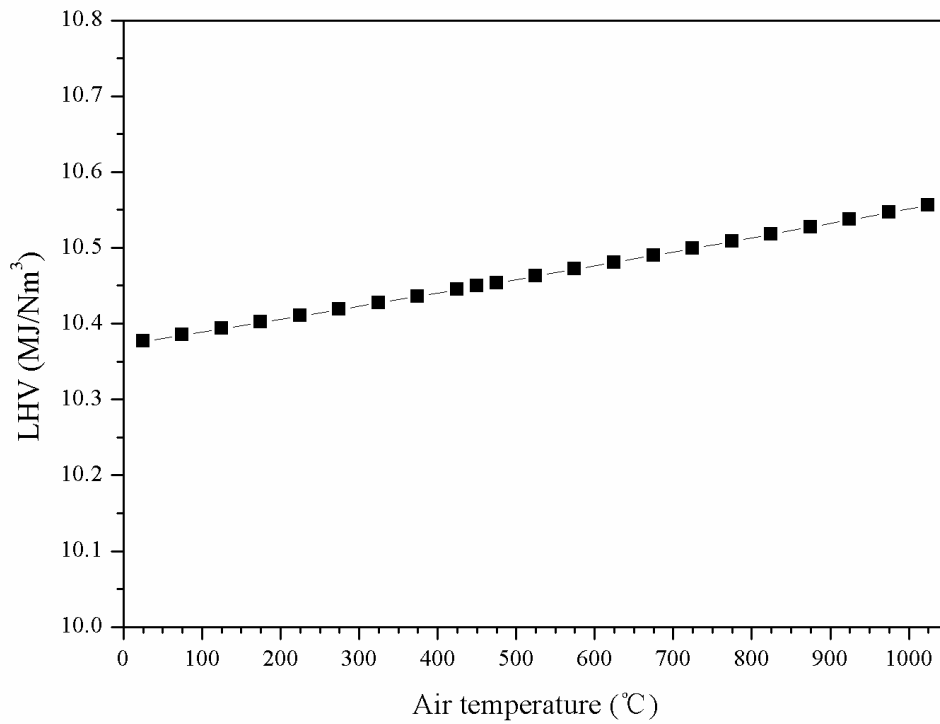


Figure 5-7: Effect of the air temperature on the LHV of the syngas.

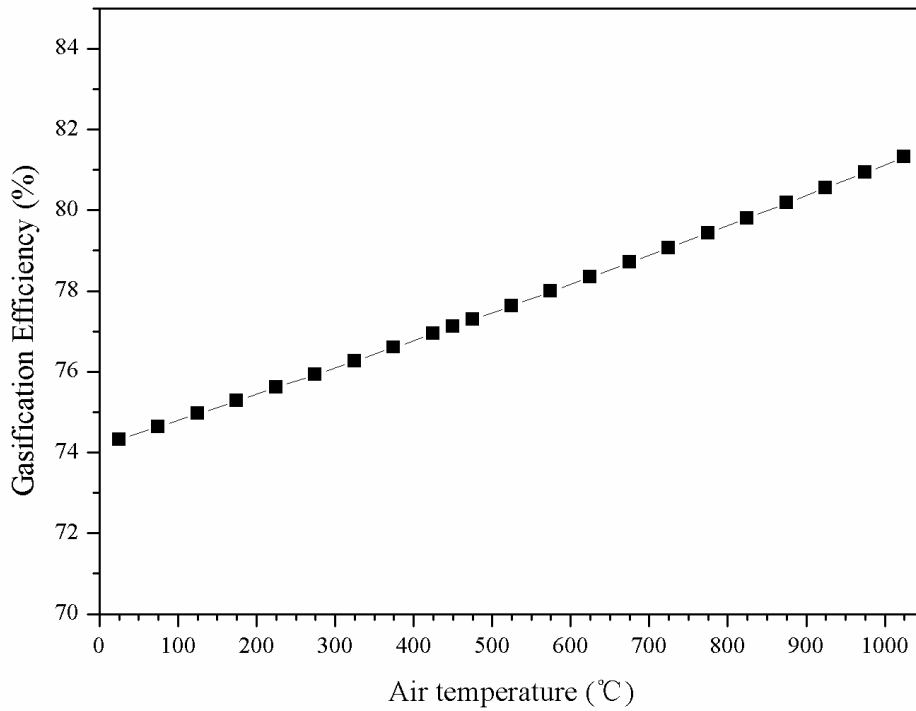


Figure 5-8: Effect of the air temperature on the gasification efficiency.

5.3 Sensitivity analysis: Steam to biomass ratio

In this case, steam to biomass ratio was varied from 0.3-1.0 while other parameters remained unchanged. The syngas composition, gasification efficiency, char split fraction and the LHV of syngas were studied. Figure 5-9 shows the effect of the steam to biomass ratio on the syngas composition (vol. % dry basis).

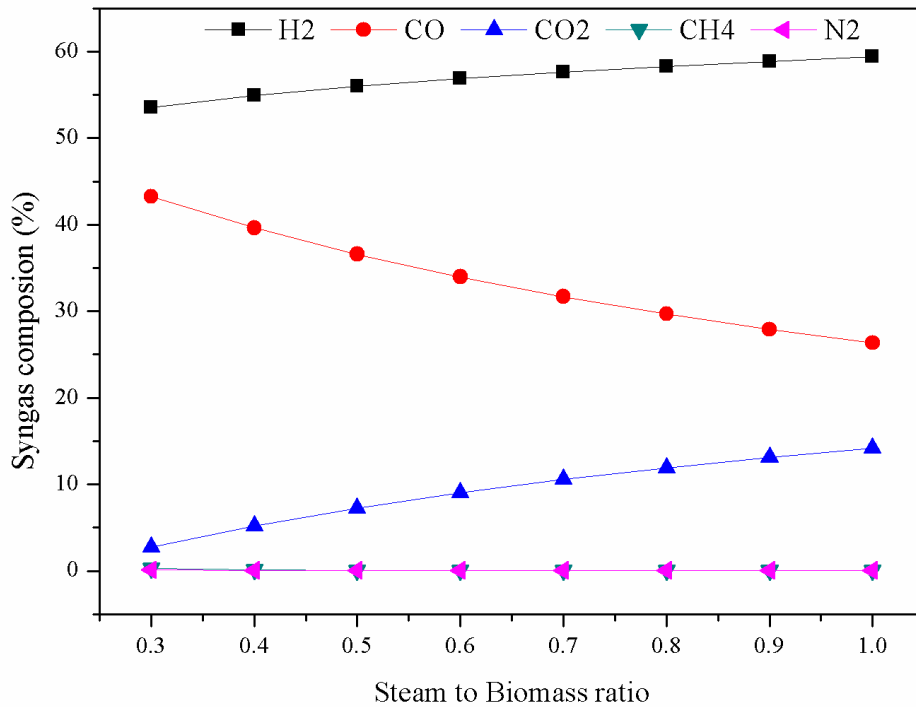


Figure 5-9: Effect of the steam to biomass ratio on the syngas composition.

As the steam to biomass ratio increases from 0.3-1.0, CO drops from 43.25% to 26.33%. Both H₂ and CO₂ increase. H₂ increases from 53.55% to 59.40% and CO₂ from 2.79% to 14.17%. Both CH₄ and N₂ contents are very low. (0.32%-0.02% and 0.08%).

The effect of the steam to biomass ratio on the char split fraction is illustrated in Figure 5-10. With the steam to biomass ratio increases from 0.3-1.0, the char split fraction decreases from 0.122 to 0.136.

The effect of the steam to biomass ratio on the LHV of the syngas is illustrated in Figure 5-11. With the steam to biomass ratio increases from 0.3-1.0, the LHV of the syngas decreases from 11.36 to 9.74 MJ/Nm³.

The effect of the steam to biomass ratio on the gasification efficiency is illustrated on Figure 5-12. When the steam to biomass ratio increases from 0.3-1.0, the gasification efficiency decreases from 83.65% to 71.31%.

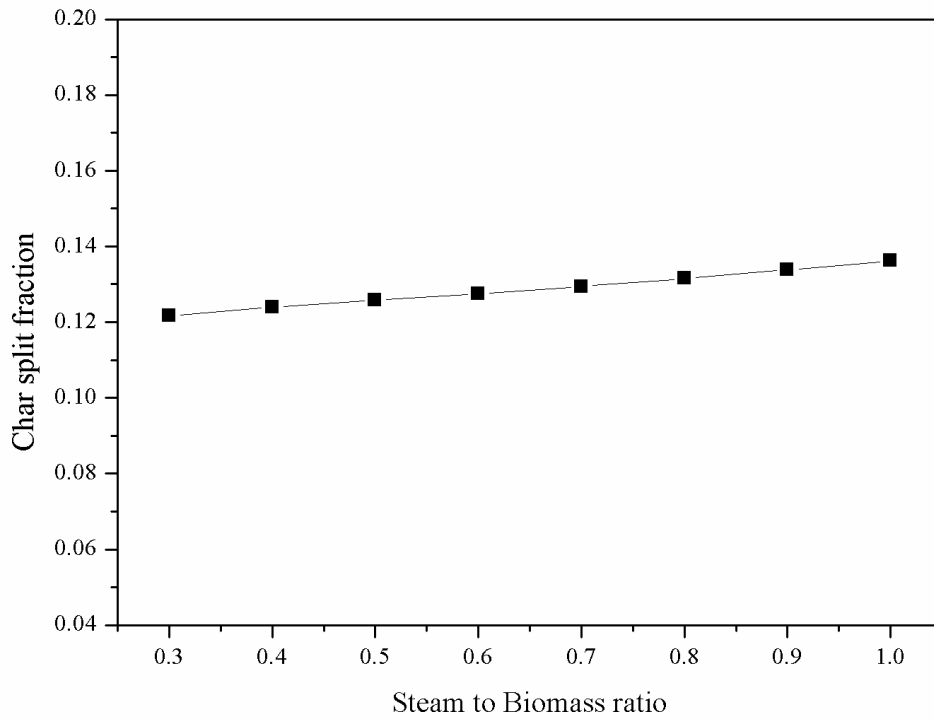


Figure 5-10: Effect of the steam to biomass ratio on the char split fraction.

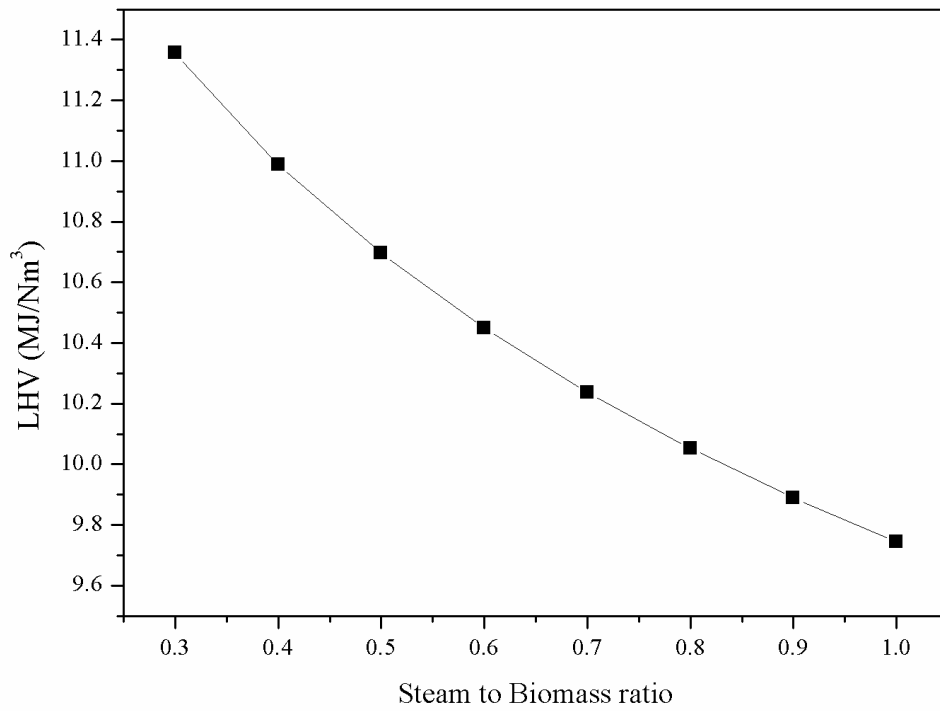


Figure 5-11: Effect of the steam to biomass ratio on the LHV of the syngas.

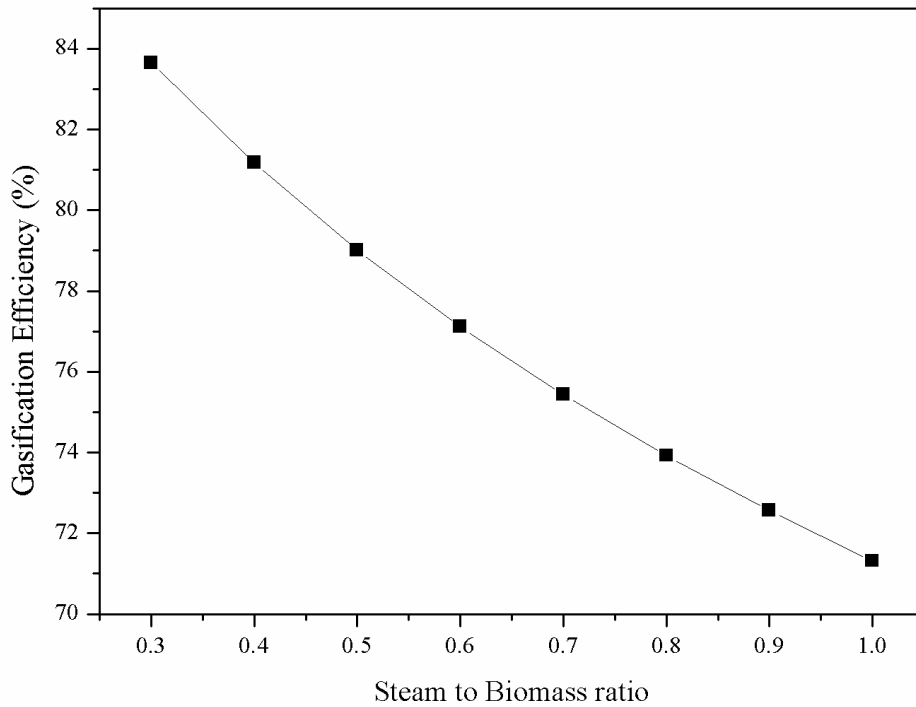


Figure 5-12: Effect of the steam to biomass ratio on the gasification efficiency.

5.4 Sensitivity analysis: Gasification temperature

In this case, gasification temperature was varied from 650-1100 °C while other parameters remained unchanged. The syngas composition, gasification efficiency, char split fraction and the LHV of syngas were studied. Figure 5-13 shows the effect of the steam to biomass ratio on the syngas composition (vol. % dry basis).

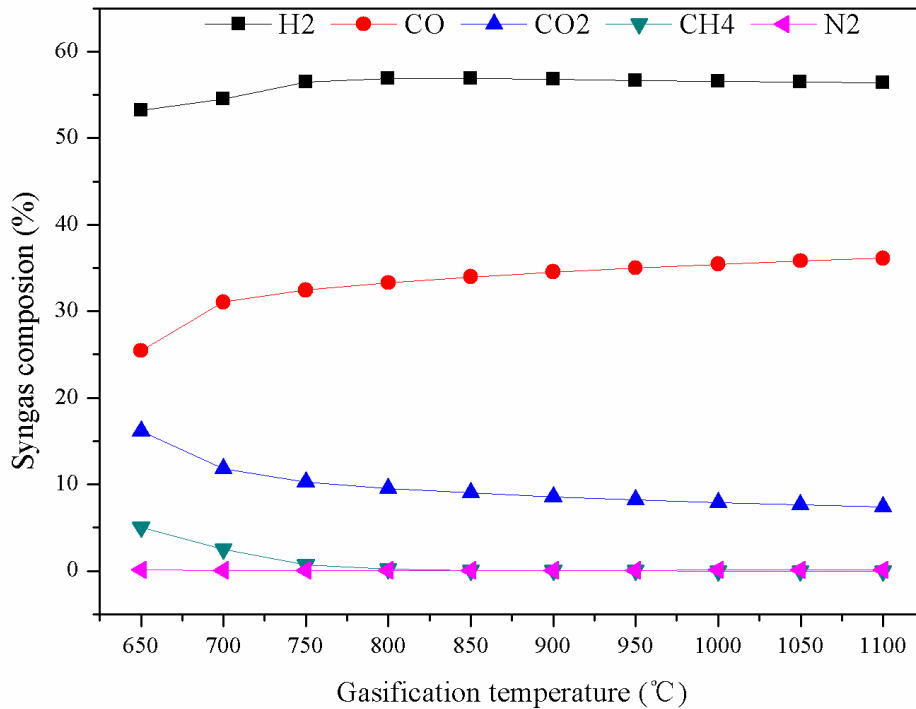


Figure 5-13: Effect of the gasification temperature on the syngas composition.

As the gasification temperature increases from 650-1100 °C, both CH₄ and CO₂ decrease. CO₂ drops from 16.18% to 7.40% and CH₄ from 5.04%-0%. H₂ increases from 53.22% to 54.90% then decreases to 56.39%. CO increases from 25.47% to 36.12%. N₂ content is very low (0.09%).

The effect of the gasification temperature on the char split fraction is illustrated on Figure 5-14. When the gasification temperature increases from 650-1100 °C, the char split fraction increases from 0 to 0.191.

The effect of the gasification temperature on the LHV of the syngas is illustrated on Figure 5-15. When the gasification temperature increases from 650-1100 °C, the LHV of the syngas decreases from 10.77 to 10.41 MJ/Nm³ at 800 °C then increases to 10.65 MJ/Nm³.

The effect of the gasification temperature on the gasification efficiency is illustrated on Figure 5-16. When the gasification temperature increases from 650-1100 °C, the gasification efficiency increases from 66.97% to 78.03% at 700 °C then decreases to 73.29%.

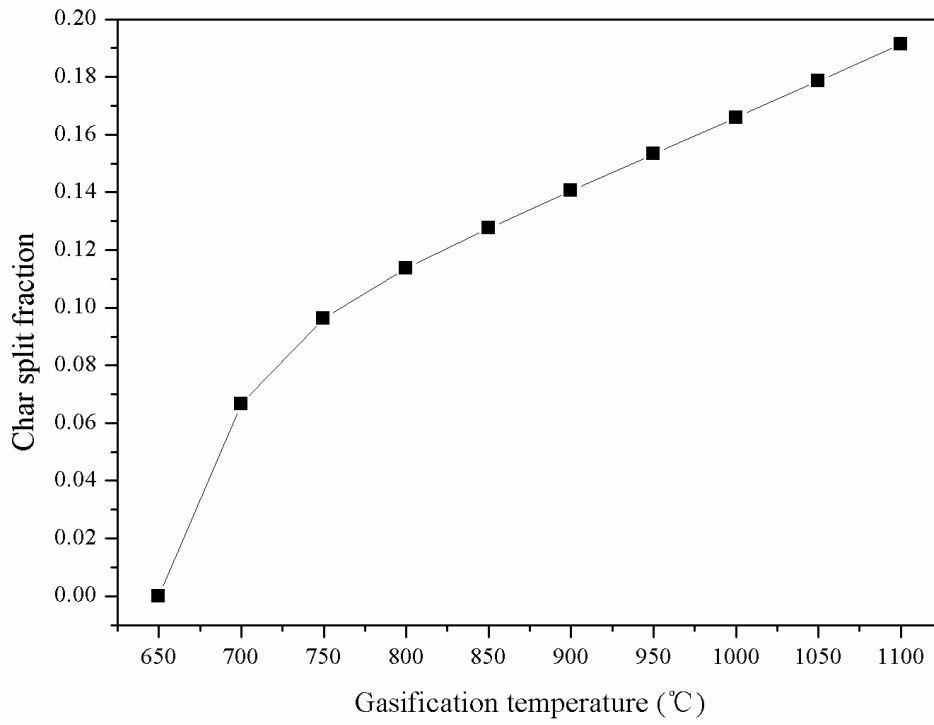


Figure 5-14: Effect of the gasification temperature on the char split fraction.

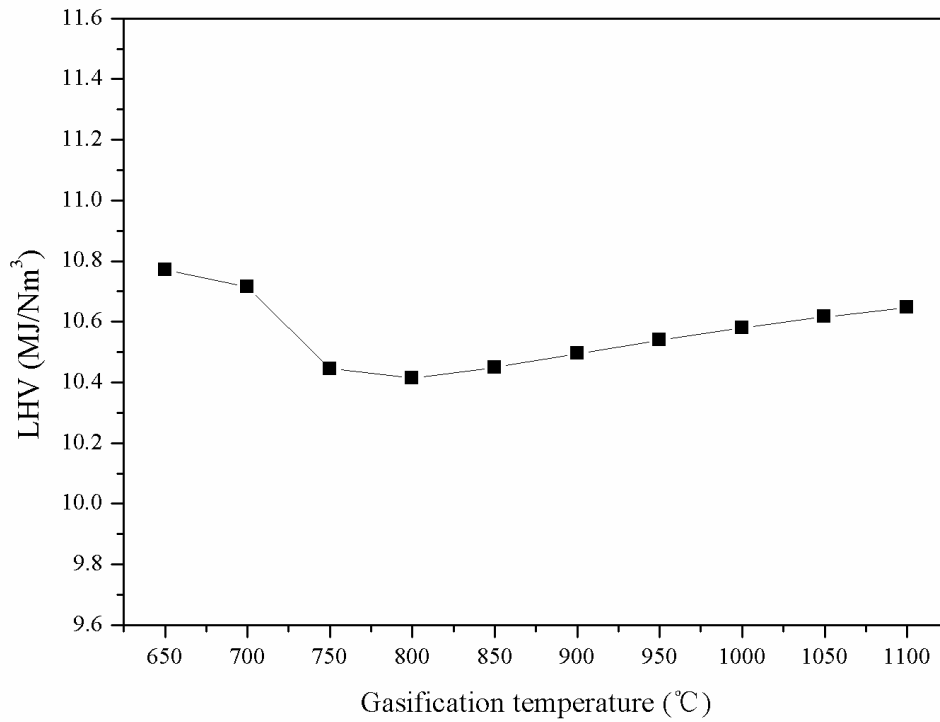


Figure 5-15: Effect of the gasification temperature on the LHV of the syngas.

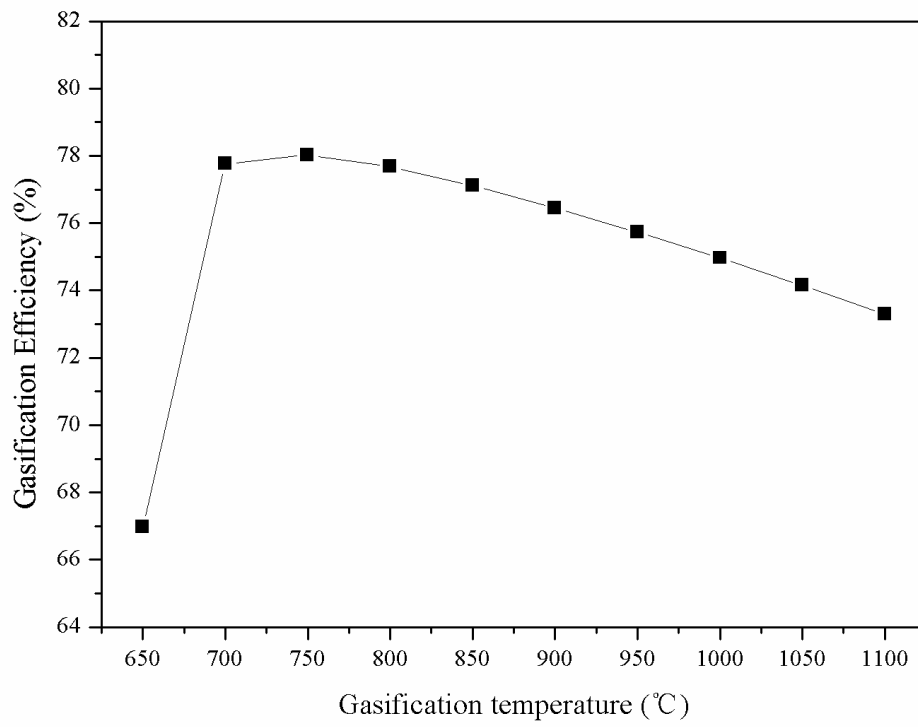


Figure 5-16: Effect of the gasification temperature on the gasification efficiency.

6 Discussion

The results obtained from the four sensitivity analyses are discussed in this chapter. The effects of different operating variables on the gasification results are analyzed in order to derive the optimized gasification condition.

6.1 Steam temperature

Syngas composition and LHV are almost unchanged with the increase of steam temperature as it is shown in Figure 5-1. Figure 5-2 shows that the increase of the steam temperature reduces the char split fraction from 0.137 to 0.108. This is because the heat required for the gasification is reduced, the reduced heat is provided by the heated steam. Therefore less char is needed for the combustion, which means more char is gasified and more syngas is produced. Figure 5-3 shows the gasification efficiency increases by 2.95%, which is only a little improvement of the gasifier performance. As a result, preheating the steam to a high temperature is not recommended unless excess heat is available.

6.2 Air temperature

Syngas composition and LHV are almost unchanged with the increase of air temperature as it is shown in Figure 5-4. Figure 5-5 shows that the increase air temperature reduces the char split fraction from 0.155 to 0.087. This is because the heated air supplied a part of heat required in the gasifier. Therefore less char is needed for the combustion, which means more char is gasified and more syngas is produced. Figure 5-6 shows the gasification efficiency increases by 6.99%. The results show that preheating air is more effective than preheating steam. Therefore, preheating the air is more recommended than preheating the steam. If excess heat is available, the air should be preheated. The flue gas contains sensible heat that can be used to preheat the air. This can be realized by implement a heat exchanger.

6.3 Effect of steam to biomass ratio and gasification temperature on the gasification results

The results in section 5.3 and section 5.4 showed that the change of steam to biomass ratio and gasification temperature has significant impact on the gasification results. Therefore in the analyses of the LHV of syngas, char split fraction and the gasification efficiency, both S/B and gasification temperature are considered. The range of gasification temperature is changed to 700-1000 °C.

6.3.1 Effect of steam to biomass ratio on the syngas composition

Figure 5-7 shows that the steam to biomass ratio (S/B) has great impact on the syngas composition. Over the S/B range from 0.3 to 1.0, both CO and CO₂ increase while H₂ decrease significantly. H₂ increases by 5.85% and CO₂ increases by 11.38%. CO decreases by 16.92%. Both CH₄ and N₂ contents are very low (0.32%-0.02% and 0.08%). From a thermodynamic point of view, if other reactants are constant, increasing the steam mass flow rate means increasing the concentration of the reactants. This results in the equilibrium point moves forward and more products are generated. In char gasification reaction, steam reforming reaction, and water-gas shift reaction, char, CO and CH₄ are consumed to generate more H₂ and CO₂. From this result, increasing the S/B has a positive effect on obtaining high H₂ syngas. But the heat consumption for the generation of steam should also be considered.

6.3.2 Effect of gasification temperature on the syngas composition

Figure 5-8 shows that the H₂ content increases over the gasification temperature range from 650 to 850 °C and the H₂ increases by 3.68%. The maximum value of the H₂ content is at 800 and 850 °C. After 850 °C, H₂ content has a slightly decrease. Over the gasification temperature range from 650 to 1100 °C, CO increases significantly from 25.47% to 36.12% while both CO₂ and CH₄ decrease. CO₂ decreases by 8.78% and CH₄ decreases by 5.04%. N₂ content is very low (0.09%). The result is because the char gasification reaction and Boundouard reaction are endothermic reactions. Increasing temperature will move the equilibrium point forward, which encourage the consumption of char and CO₂ to generate more CO. Meanwhile, the water-gas shift reaction is exothermic reaction, increasing temperature will move the equilibrium point backward which has the same effect on the CO and CO₂ as the Boundouard reaction. The H₂ yield is dominated by both the char gasification reaction and water-gas shift reaction. The char gasification reaction is endothermic reaction while the water-gas shift reaction is exothermic. Increase of gasification temperature will move the equilibrium point forward in endothermic reaction resulting in the increase of H₂ yield. But for water-gas shift reaction, the equilibrium point will move backward, which resulting in the decrease of H₂ yield. Therefore the H₂ content is almost unchanged. The reduction of the CH₄ is because of both the methane decomposition reaction and the steam reforming reaction are endothermic, increasing temperature will move the equilibrium point forward which leads to the decomposition of CH₄ into C and H₂. That is also the reason why there is an increase of H₂ content at lower temperature.

6.3.3 Effects on the char split fraction

The effect of steam to biomass ration and gasification temperature on the char split fraction is shown in Figure 6-1. The char split fraction varies between 0 and 0.2132.

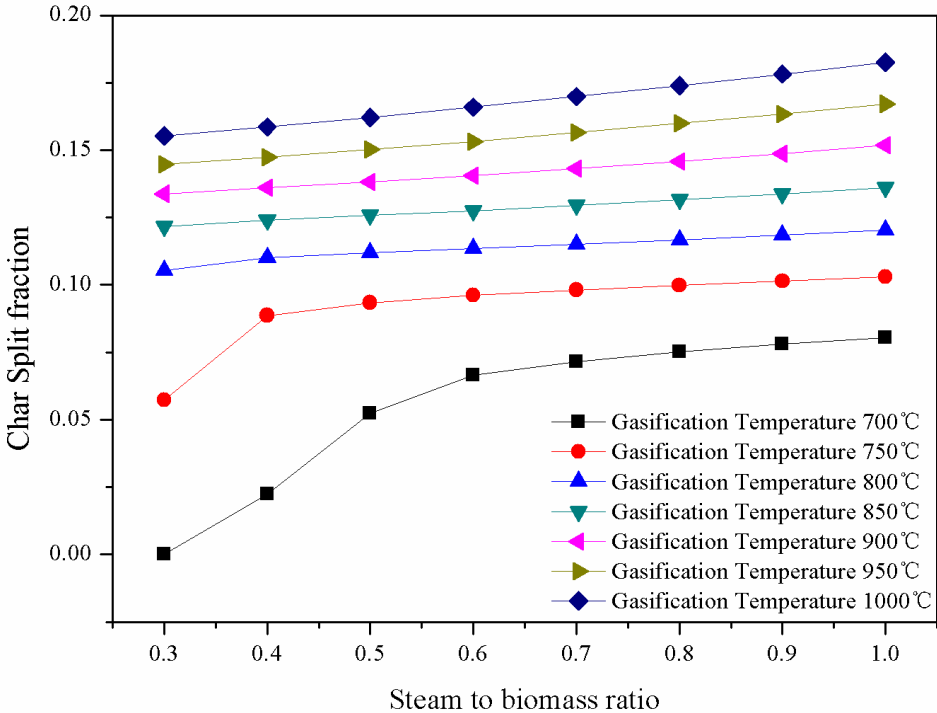


Figure 6-1: Effects of the S/B and gasification temperature on the char split fraction.

From the figure, it is obvious that char split fraction increases with the increase of steam to biomass ratio and the gasification temperature. Because higher gasification temperature requires more heat, the amount of char that goes into the combustor has to increase to provide more heat for the gasifier. Increasing steam to biomass ratio means more steam is fed into the gasifier. To heat up the increased steam to the gasification temperature needs to burn more char to supply enough heat. Therefore the char split fraction increases when the steam to biomass ratio rises up.

6.3.4 Effects on the LHV of the syngas

The influence of steam to biomass ratio and gasification temperature on the LHV of the syngas is shown in Figure 6-2. It can be seen that the LHV varies between 11.51 MJ/Nm³ and 9.58 MJ/Nm³. The LHV decreases with the increase of the steam to biomass ratio when the gasification temperature is kept constant. Referring to Figure 5-13, when the steam to biomass ratio increases, the H₂ content increases by 5.85% while the CO decreases significantly (16.92%). Since the LHV of CO is 12.622 MJ/Nm³ which is higher than the LHV

of H_2 (10.788 MJ/Nm^3 , NREL data), the reduction of CO results in reducing the LHV of the syngas. Therefore the LHV of the syngas decreases with the increase of steam to biomass ratio.

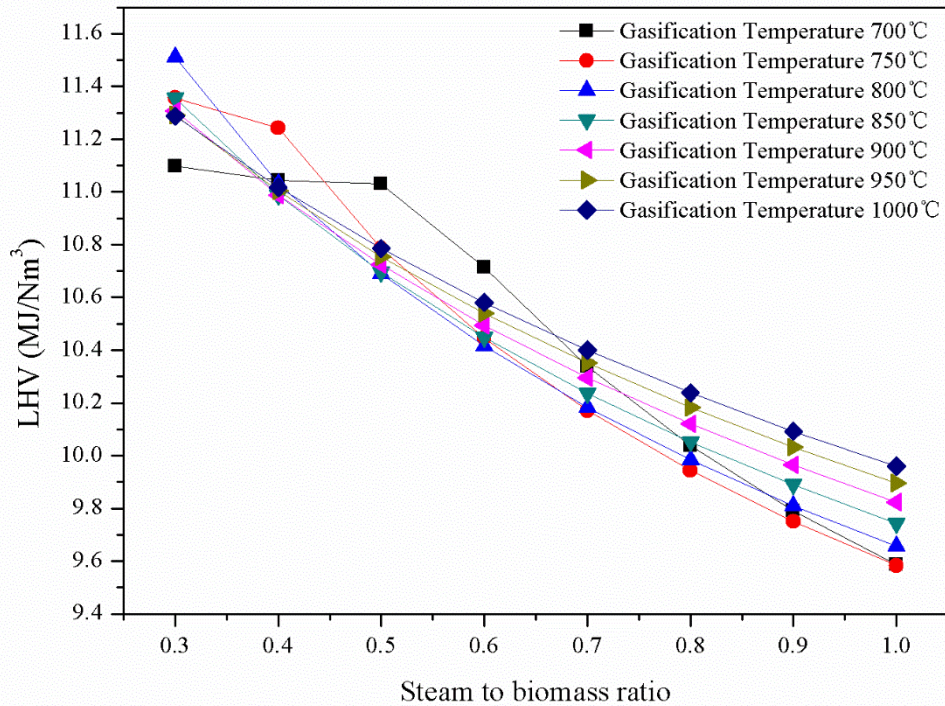


Figure 6-2: Effects of the S/B and gasification temperature on the LHV of the syngas.

Figure 6-2 also shows a general trend of the LHV increases with the increase of the gasification temperature. This is because when the gasification temperature increases, the content of CO increases while there is little change in other combustible gas content, which results in the increase of LHV.

However, under lower temperature ($<800 \text{ }^\circ\text{C}$) and low steam to biomass ratio (<0.5), the trend of the LHV changes with the S/B and gasification temperature is different comparing with the overall trend. This may be because at lower temperature and low steam to biomass ratio conditions, the content of CH_4 is relatively high as it is shown in Figure 6-3. According to the NREL data, the LHV of CH_4 is 35.814 MJ/Nm^3 , which is more than three times as the LHV of H_2 (10.788 MJ/Nm^3). Therefore even a small change of the CH_4 content will have a greater impact on the LHV of the syngas.

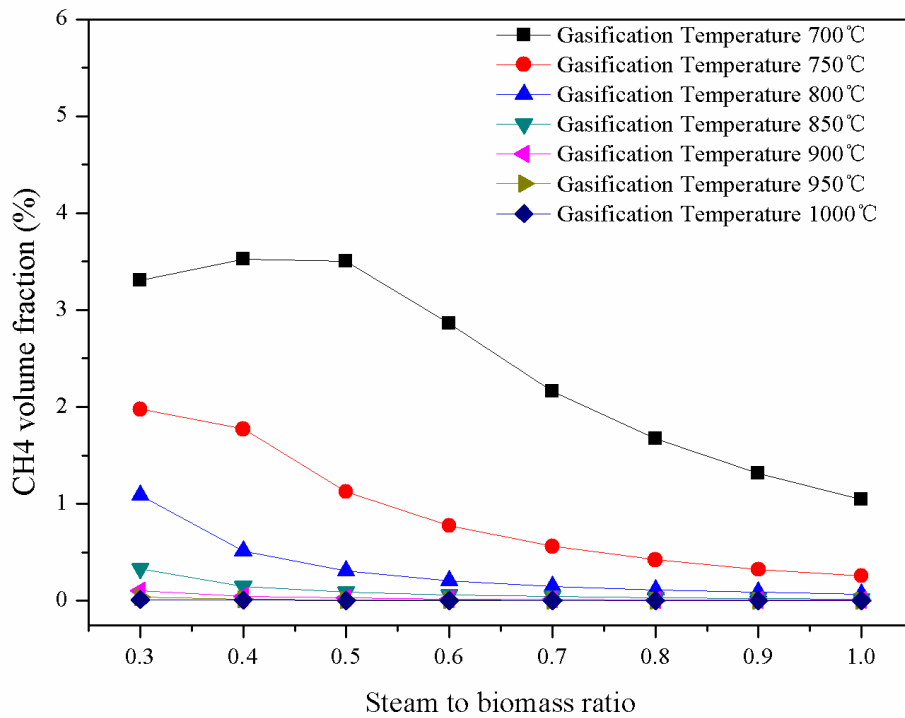


Figure 6-3: Effects of the S/B and gasification temperature on the CH_4 content.

6.3.5 Effects on the gasification efficiency

The influence of steam to biomass ratio and gasification temperature on the gasification efficiency is shown in Figure 6-4. The gasification efficiency varies between 84.41% and 63.39%. The maximum gasification efficiency appears at 800 °C with the S/B is 0.3. The figure shows the gasification efficiency has an overall decreasing trend with the increase of the S/B and the gasification temperature. Equation (4.3) indicates the gasification efficiency is determined by the LHV of the syngas and the volume flow rate of the cold gas together. Figure 6-5 shows the effects of the S/B and the gasification temperature on the cold gas volume flow rate. The cold gas volume flow rate is defined as the volume flow rate of the combustible gas produced under standard condition. Figure 6-5 illustrates that above 800 °C, the volume flow rate of the cold gas decreases with both the increase of the S/B and the gasification temperature. Since the char split fraction increases with the gasification temperature and the S/B as it has been discussed in section 6.3.3, the increase of the char split fraction will reduce the char involved in the gasification reactions, resulting in the reduction of the cold gas yield. As it was discussed in the previous section, the LHV of the syngas decreases with the increase of the S/B and decreases with the increase of the gasification temperature, therefore the gasification efficiency reduces with the increase of the steam to biomass ratio. Although the LHV of the syngas increases with the increase of the gasification temperature, the gasification efficiency shows a decreasing trend with the increase of the temperature.

At lower temperature ($\leq 750\text{ }^{\circ}\text{C}$) and lower S/B (< 0.6), the gasification efficiency increases with the increase of the steam to biomass ratio and the gasification temperature. This may be because at lower temperature and lower S/B, there is not enough steam and heat to support the endothermic reactions, which results in the low yield of CO and H₂. Again, the gasification efficiency is determined by the LHV of the syngas and the volume flow rate of the cold gas. As it has been discussed in 6.3.4, at lower temperature and S/B, the changes in CH₄ has a great impact on the LHV. Therefore the gasification efficiency does not follow the overall pattern under these conditions.

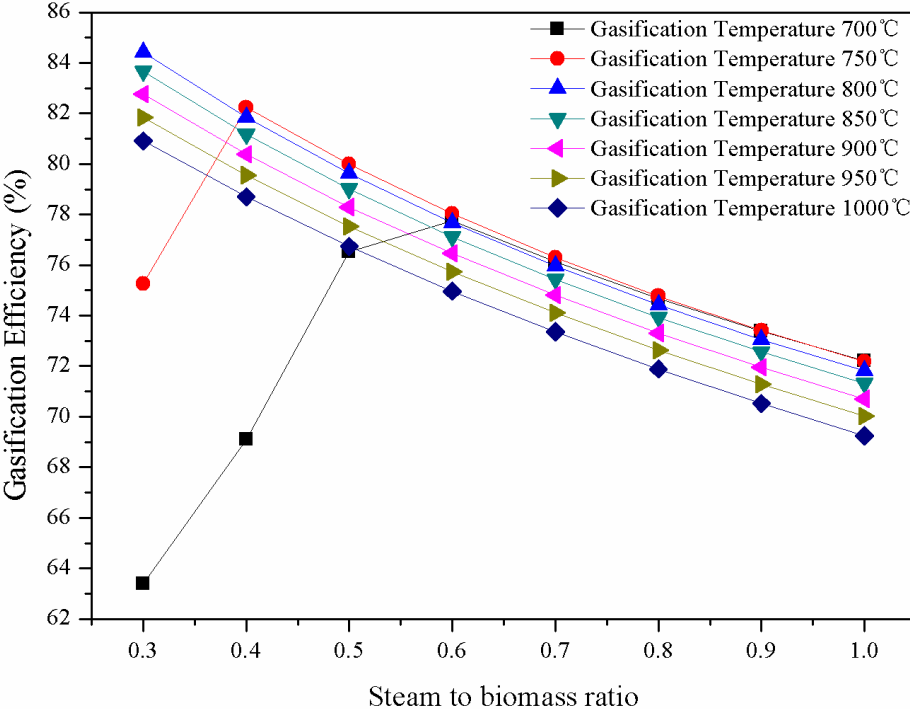


Figure 6-4: Effects of the S/B and gasification temperature on the gasification efficiency.

It is clear that the gasification efficiency can be maximized at the gasification temperature between 750-800 °C and S/B as low as possible.

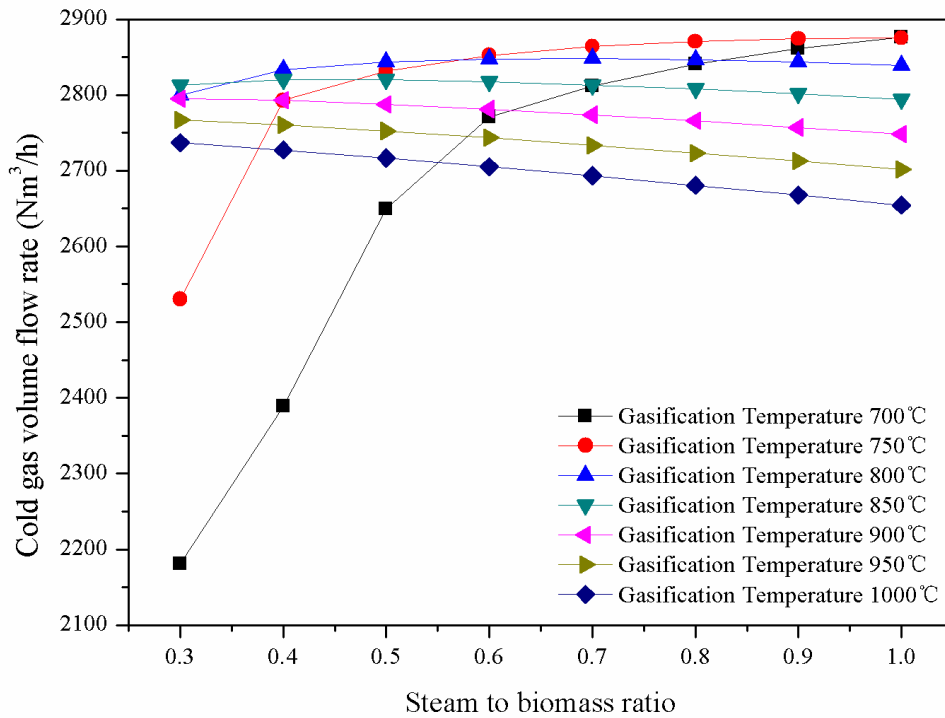


Figure 6-5: Effects of the S/B and gasification temperature on the cold gas volume flow rate.

6.3.6 Effects on the hydrogen yield

The influence of the steam to biomass ratio and gasification temperature on the hydrogen yield is shown in Figure 6-6. The hydrogen volume flow rate varies from 1296 Nm³/h to 2059 Nm³/h. The figure shows that the hydrogen yield increases with increasing the steam to biomass ratio and decreases with increasing the gasification temperature in general. As it has been discussed in section 6.3.1, increasing the S/B will result in the increase of H₂ yield. The H₂ yield is mainly dominated by the water-gas shift reaction and char gasification reaction, increasing the gasification temperature will lead to the increase of H₂ yield in the char gasification reaction and decrease of H₂ yield in the water-gas shift reaction as it has been discussed in the section 6.3.2. Since the two reactions have different reaction rate, it maybe the reaction rate of the water-gas shift reaction is more sensitive to the change of gasification temperature than the char gasification reaction, results in the hydrogen yield decreases with the increase of the gasification temperature. Another explanation might be the char involved in the gasification reaction reduces with the increase of the gasification temperature as it has been discussed in section 6.3.3, which also lead to the reduction of H₂ yield. At lower temperature and S/B, the trend is different. This may be because at lower temperature and S/B, methane does not completely decompose and the char gasification reaction is low at these conditions, which results in the low H₂ yield. When the temperature and S/B increase, the methane

decomposes completely and the condition is suitable for the gasification reaction, therefore the H₂ yield grows faster.

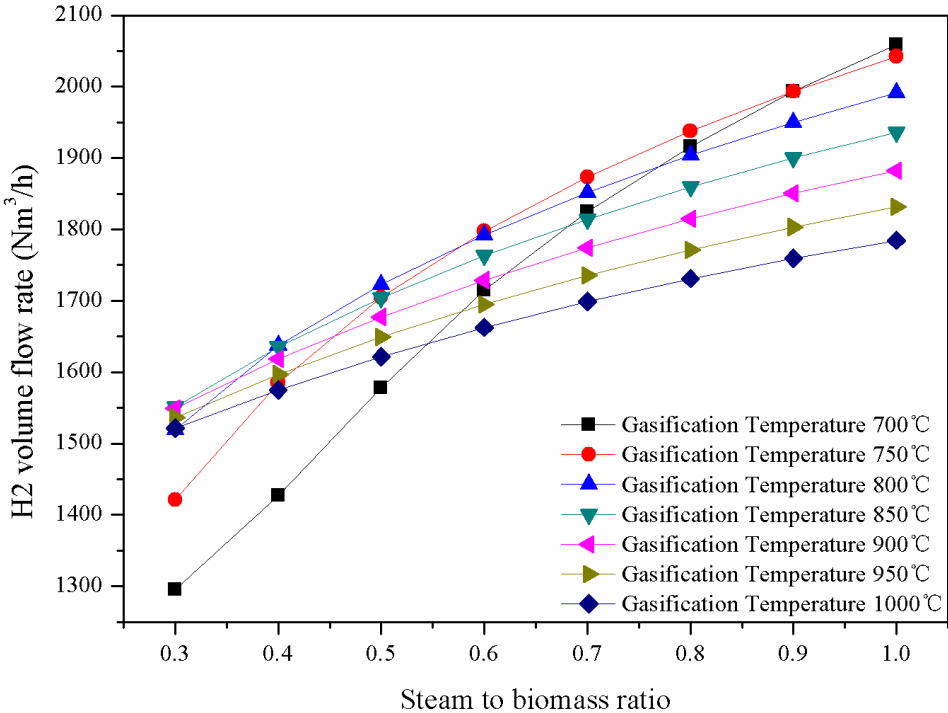


Figure 6-6: Effects of the S/B and gasification temperature on the hydrogen yield.

It is clear that in order to maximize the H₂ production, the steam to biomass ratio should be high and the gasification temperature should be kept low. The heat consumption for the steam generation should also be considered

6.4 Heat requirement for the biomass decomposition

The consumption of the heat for the biomass decomposition is 2.38MW, which is nearly 1/4 of the total heat produced after the gasification process. Therefore the gasification of biomass produces sufficient heat even the decomposition of biomass requires a lot of energy. In a real plant, additional fuel is needed for the combustion part to supply heat for the pyrolysis. Therefore in this simulation, a heat stream was modeled to provide heat for the decomposition of biomass and a design specification block was set to calculate the heat required for the decomposition instead of split more char into the combustor.

6.5 Summary

The optimum operating parameters can be concluded through the above analyses. The gasification condition changes according to the different requirement. For general purpose, the gasification temperature should be kept around 800 °C, the steam to biomass ratio should be kept around 0.5. Considering the complex situation as the plant is in larger scale when commercialized and the equilibrium may not be achieved in a real plant due to the reaction time and reaction kinetics as they were not considered in this simulation. The optimum gasification temperature can be controlled between 800 and 850 °C and the steam to biomass ratio can be controlled between 0.4 and 0.6. If the excess heat is possible, it can be used to heat up the feed air for the maximization of the gasification efficiency.

7 Conclusion

Biomass is a promising energy which is environmental friendly and carbon neutral. Fluidized-bed gasification technology for combined heat and power is particularly suitable for biomass utilization. Among the different types of fluidized bed gasification technologies, the dual fluidized-bed gasification technology developed by the Technology University of Vienna has been commercialized successfully in Güssing, Austria.

The biomass gasification in a dual fluidized-bed gasifier was simulated using Aspen Plus V8. The gasifier is a minimization of Gibbs free energy model. Key operation parameters which are feed steam temperature, feed air temperature, steam to biomass ratio and gasification temperature were varied by implementing sensitivity analysis blocks. The effects of these parameters on the syngas composition, char split fraction, LHV of the syngas and the gasification efficiency were studied.

The simulation result shows that the modeling is successful and qualified for analyzing the effects of the key operation parameters on the gasification results. The sensitivity analyses indicates that preheating the feed air is more effective than preheating the feed steam. Increasing the steam to biomass ratio has positive effect on increasing the hydrogen yield and the proportion of hydrogen content in the syngas. The increase of S/B has negative effects on increasing the LHV of the syngas and the gasification efficiency. Increasing the gasification temperature will result in the decrease of the gasification efficiency and the hydrogen yield while it has positive effects on increasing the LHV of the syngas. The gasification results behave a little different when the steam to biomass ratio and the gasification temperature are low.

In summary, the optimum gasification temperature should be kept around 750-850 °C, the steam to biomass ratio should be kept around 0.4-0.6. If excess heat from the flue gas is available, it should be used to preheat the feed air. Due to the different demand for the product gas, the optimum operation parameters may vary.

7.1 Suggestions for future work

Based on the experience gained from this project, more studies can be carried on using Aspen Plus. Since this simulation was based on the minimization of Gibbs free energy model, the simulation based on the kinetic model can be studied. Simulation of the gasification process with CO₂ capture using CaCO₃ can also be studied. Besides, there is no research on the simulation of the whole CHP plant based on the dual fluidized-bed gasifier, which can be a

good research direction. The CHP plant can be modeled and simulated using Aspen Plus and the behavior of the CHP plant can be studied under different operating parameters.

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Appendices

Appendix 1: Project description

Appendix 2: Sensitivity analysis data for changing steam temperature

Appendix 3: Sensitivity analysis data for changing air temperature

Appendix 4: Sensitivity analysis data for changing steam to biomass ratio and gasification temperature

Appendix 1: Project description



Telemark University College
Faculty of Technology

FMH606 Master's Thesis

Title: Optimization of biomass gasification reactor using Aspen Plus

TUC supervisor: Britt Halvorsen, Rajan Thapa, Marianne Eikeland

Task background:

Continuously increasing price of oil and gas, energy crisis and increased environmental consciousness towards the greenhouse gas emission have opened a new opportunity to the biomass, the oldest source of energy known to the mankind. The energy source neutral to CO₂ needs to be utilized efficiently. One of the options to do so is gasification of biomass for combined heat and power (CHP) production. Biomass such as wood chips is heated in a fluidized bed gasification reactor to produce a mixture of combustible gases such as CH₄, CO and H₂. The combustible gases are further burned in gas engine or gas turbine to produce electricity and heat. Alternatively, the gases can be further processed for conversion of biomass to liquid fuels. The technology based on fluidized bed gasifiers has been used in continuously operating full scale power production plants, where the biomass CHP plant in Gussing, Austria, is one of the examples. The plant is developed by Technical University of Vienna (TUV). The university has more than 15 years of the research experiences within the fluidized bed biomass gasification technology. The ongoing research task is to optimize the gasification reactions in order to increase its efficiency.

Task description:

1. Literature survey on:
 - Thermodynamic properties of different types of biomass.
 - Basic concept of steam gasification and different gasification technology.
 - Reaction kinetics and different parameters of steam gasification
2. Simulation of gasification reactor using simulation software Aspen Plus. The simulation will be performed to study steam gasification of woody biomass and optimized utilization of the product gas.

Address: Kjølnes ring 56, NO-3918 Porsgrunn, Norway. **Phone:** 35 57 50 00. **Fax:** 35 55 75 47.



Student category: (PT, EET)

Practical arrangements:

The work will be mainly carried out at TUC
Short course will be conducted on use of Aspen Plus software.

Signatures:

Ke Sun 02. Feb. 2014

Student (date and signature):

Birte Halvorsen
Supervisor (date and signature):

Appendix 2: Sensitivity analysis data for changing steam temperature

Volume flow of syngas components and syngas composition at different steam temperature

Steam Temperature (°C)	Volume flow (Nm ³ /h)					Volume fraction				
	H ₂	CO	CO ₂	CH ₄	N ₂	H ₂	CO	CO ₂	CH ₄	N ₂
150	1751.991	1035.524	282.164	1.6330	2.5557	57.00%	33.69%	9.18%	0.05%	0.08%
200	1753.744	1038.291	281.670	1.6459	2.5557	56.98%	33.73%	9.15%	0.05%	0.08%
250	1755.515	1041.098	281.165	1.6589	2.5557	56.96%	33.78%	9.12%	0.05%	0.08%
300	1757.313	1043.947	280.653	1.6724	2.5557	56.94%	33.83%	9.09%	0.05%	0.08%
350	1759.133	1046.841	280.129	1.6859	2.5557	56.92%	33.87%	9.06%	0.05%	0.08%
400	1760.981	1049.781	279.598	1.7001	2.5557	56.90%	33.92%	9.03%	0.05%	0.08%
450	1762.851	1052.770	279.052	1.7143	2.5557	56.89%	33.97%	9.00%	0.06%	0.08%
500	1764.753	1055.807	278.499	1.7292	2.5557	56.87%	34.02%	8.97%	0.06%	0.08%
550	1766.677	1058.896	277.932	1.7440	2.5557	56.85%	34.07%	8.94%	0.06%	0.08%
600	1768.633	1062.036	277.356	1.7596	2.5557	56.83%	34.12%	8.91%	0.06%	0.08%
650	1770.613	1065.229	276.765	1.7753	2.5557	56.81%	34.18%	8.88%	0.06%	0.08%
700	1772.626	1068.474	276.165	1.7916	2.5557	56.79%	34.23%	8.85%	0.06%	0.08%
750	1774.662	1071.774	275.549	1.8080	2.5556	56.76%	34.28%	8.81%	0.06%	0.08%
800	1776.731	1075.125	274.926	1.8252	2.5556	56.74%	34.34%	8.78%	0.06%	0.08%
850	1778.822	1078.531	274.286	1.8424	2.5556	56.72%	34.39%	8.75%	0.06%	0.08%
900	1780.946	1081.988	273.637	1.8604	2.5556	56.70%	34.45%	8.71%	0.06%	0.08%
950	1783.09	1085.499	272.972	1.8784	2.5556	56.68%	34.50%	8.68%	0.06%	0.08%
1000	1785.267	1089.058	272.299	1.8973	2.5556	56.66%	34.56%	8.64%	0.06%	0.08%

Char split fraction, LHV, and gasification efficiency at different steam temperature

Steam Temperature (°C)	Char split fraction	LHV(MJ/Nm ³)	Gasification Efficiency
150	0.137	10.42	76.16%
200	0.135	10.43	76.31%
250	0.134	10.43	76.47%
300	0.132	10.44	76.62%
350	0.131	10.44	76.78%
400	0.129	10.44	76.95%
450	0.128	10.45	77.11%
500	0.126	10.45	77.28%
550	0.124	10.46	77.45%
600	0.123	10.46	77.62%
650	0.121	10.47	77.80%
700	0.119	10.47	77.98%
750	0.117	10.48	78.16%
800	0.116	10.48	78.34%
850	0.114	10.49	78.53%
900	0.112	10.49	78.72%
950	0.110	10.50	78.91%
1000	0.108	10.50	79.11%

Appendix 3: Sensitivity analysis data for changing air temperature

Volume flow of syngas components and syngas composition at different air temperature

Air Temperature (°C)	Volume flow (Nm ³ /h)				Volume fraction					
	H2	CO	CO2	CH4	N2	H2	CO	CO2	CH4	N2
25	1730.613	1002.218	287.980	1.4850	2.5557	57.21%	33.13%	9.52%	0.05%	0.08%
75	1734.349	1007.970	286.997	1.5100	2.5557	57.18%	33.23%	9.46%	0.05%	0.08%
125	1738.073	1013.755	285.991	1.5346	2.5557	57.14%	33.33%	9.40%	0.05%	0.08%
175	1741.822	1019.578	284.980	1.5606	2.5557	57.10%	33.42%	9.34%	0.05%	0.08%
225	1745.579	1025.458	283.945	1.5866	2.5557	57.06%	33.52%	9.28%	0.05%	0.08%
275	1749.371	1031.397	282.898	1.6140	2.5557	57.02%	33.62%	9.22%	0.05%	0.08%
325	1753.185	1037.408	281.827	1.6418	2.5557	56.98%	33.72%	9.16%	0.05%	0.08%
375	1757.029	1043.494	280.735	1.6702	2.5557	56.94%	33.82%	9.10%	0.05%	0.08%
425	1760.904	1049.658	279.620	1.6995	2.5557	56.91%	33.92%	9.04%	0.05%	0.08%
450	1762.853	1052.770	279.053	1.7144	2.5557	56.89%	33.97%	9.00%	0.06%	0.08%
475	1764.811	1055.900	278.482	1.7296	2.5557	56.87%	34.02%	8.97%	0.06%	0.08%
525	1768.748	1062.221	277.322	1.7606	2.5557	56.83%	34.13%	8.91%	0.06%	0.08%
575	1772.716	1068.619	276.138	1.7924	2.5557	56.78%	34.23%	8.85%	0.06%	0.08%
625	1776.710	1075.091	274.932	1.8250	2.5556	56.74%	34.34%	8.78%	0.06%	0.08%
675	1780.730	1081.635	273.704	1.8586	2.5556	56.70%	34.44%	8.72%	0.06%	0.08%
725	1784.772	1088.247	272.453	1.8931	2.5556	56.66%	34.55%	8.65%	0.06%	0.08%
775	1788.836	1094.926	271.181	1.9284	2.5556	56.62%	34.66%	8.58%	0.06%	0.08%
825	1792.917	1101.667	269.887	1.9647	2.5556	56.58%	34.76%	8.52%	0.06%	0.08%
875	1797.015	1108.469	268.573	2.0020	2.5556	56.53%	34.87%	8.45%	0.06%	0.08%
925	1801.127	1115.326	267.238	2.0401	2.5556	56.49%	34.98%	8.38%	0.06%	0.08%
975	1805.250	1122.237	265.883	2.0793	2.5556	56.45%	35.09%	8.31%	0.07%	0.08%
1025	1809.384	1129.200	264.509	2.1194	2.5556	56.41%	35.20%	8.25%	0.07%	0.08%

Char split fraction, LHV, and gasification efficiency at different air temperature

Air Temperature (°C)	Char split fraction	LHV(MJ/Nm ³)	Gasification Efficiency
25	0.155	10.38	74.32%
75	0.152	10.38	74.64%
125	0.149	10.39	74.96%
175	0.145	10.40	75.28%
225	0.142	10.41	75.60%
275	0.139	10.42	75.93%
325	0.136	10.43	76.26%
375	0.133	10.44	76.60%
425	0.129	10.44	76.94%
450	0.128	10.45	77.11%
475	0.126	10.45	77.28%
525	0.122	10.46	77.63%
575	0.119	10.47	77.98%
625	0.116	10.48	78.34%
675	0.112	10.49	78.70%
725	0.108	10.50	79.06%
775	0.105	10.51	79.43%
825	0.101	10.52	79.80%
875	0.098	10.53	80.17%
925	0.094	10.54	80.55%
975	0.090	10.55	80.93%
1025	0.087	10.56	81.31%

Appendix 4: Sensitivity analysis data for changing steam to biomass ratio and gasification temperature

Volume flow of syngas components and syngas composition at different S/B (Gasification temperature is at 850 °C)

S/B	Volume flow (Nm ³ /h)					Volume fraction				
	H ₂	CO	CO ₂	CH ₄	N ₂	H ₂	CO	CO ₂	CH ₄	N ₂
0.3	1550.622	1252.331	80.791	9.3486	2.5557	53.55%	43.25%	2.79%	0.32%	0.09%
0.4	1635.859	1180.321	154.306	4.2391	2.5557	54.94%	39.64%	5.18%	0.14%	0.09%
0.5	1704.173	1113.533	220.161	2.5432	2.5556	56.00%	36.59%	7.24%	0.08%	0.08%
0.6	1762.851	1052.770	279.052	1.7143	2.5557	56.89%	33.97%	9.00%	0.06%	0.08%
0.7	1814.213	997.463	331.904	1.2321	2.5557	57.64%	31.69%	10.55%	0.04%	0.08%
0.8	1859.563	946.957	379.523	0.9226	2.5558	58.30%	29.69%	11.90%	0.03%	0.08%
0.9	1899.813	900.661	422.585	0.7111	2.5559	58.88%	27.92%	13.10%	0.02%	0.08%
1	1935.659	858.069	461.652	0.5599	2.5559	59.40%	26.33%	14.17%	0.02%	0.08%

Volume flow of syngas components and syngas composition at different gasification temperature (Steam to biomass ratio is 0.6)

Gasification temperature (°C)	Volume flow (Nm ³ /h)					Volume fraction				
	H ₂	CO	CO ₂	CH ₄	N ₂	H ₂	CO	CO ₂	CH ₄	N ₂
650	1508.587	721.990	458.583	142.973	2.5465	53.22%	25.47%	16.18%	5.04%	0.09%
700	1714.853	976.744	370.659	79.297	2.5490	54.54%	31.07%	11.79%	2.52%	0.08%
750	1797.412	1032.515	326.857	22.105	2.5518	56.50%	32.45%	10.27%	0.69%	0.08%
800	1792.192	1049.043	299.814	5.940	2.5540	56.90%	33.31%	9.52%	0.19%	0.08%
850	1762.853	1052.770	279.053	1.714	2.5557	56.89%	33.97%	9.00%	0.06%	0.08%
900	1728.923	1051.677	261.462	0.543	2.5568	56.78%	34.54%	8.59%	0.02%	0.08%
950	1695.172	1047.902	246.118	0.188	2.5576	56.66%	35.02%	8.23%	0.01%	0.09%
1000	1662.652	1042.151	232.615	0.070	2.5582	56.55%	35.45%	7.91%	0.00%	0.09%
1050	1631.508	1034.759	220.696	0.028	2.5586	56.46%	35.81%	7.64%	0.00%	0.09%
1100	1601.641	1025.952	210.149	0.012	2.5590	56.39%	36.12%	7.40%	0.00%	0.09%

Char split fraction, LHV, H₂ flow rate, cold gas flow rate, CH₄ volume fraction, and gasification efficiency at different S/B and gasification temperature

Gasification Temperature (°C)	S/B	Gasification Efficiency	LHV (MJ/Nm ³)	Char Split fraction	H ₂ (Nm ³ /h)	Cold gas flow rate (Nm ³ /h)	CH ₄ volume fraction
650	0.3	64.47%	11.12	0.0000	1307.814	2213.456	3.16%
	0.4	65.20%	10.97	0.0000	1380.330	2269.732	4.08%
	0.5	66.03%	10.85	0.0000	1447.095	2322.737	5.04%
	0.6	66.97%	10.77	0.0000	1508.587	2373.774	6.02%
	0.7	70.59%	10.74	0.0126	1606.287	2510.542	6.44%
	0.8	73.34%	10.55	0.0286	1733.683	2653.944	5.91%
	0.9	72.28%	10.19	0.0352	1847.504	2707.905	4.88%
	1	71.32%	9.89	0.0409	1946.622	2752.788	4.05%
700	0.3	63.39%	11.10	0.0000	1295.667	2181.022	3.30%
	0.4	69.10%	11.04	0.0224	1426.743	2389.199	3.52%
	0.5	76.53%	11.03	0.0524	1577.536	2649.264	3.50%
	0.6	77.77%	10.71	0.0666	1714.852	2771.116	2.86%
	0.7	76.13%	10.34	0.0714	1825.039	2811.456	2.16%
	0.8	74.68%	10.04	0.0751	1916.439	2840.298	1.67%
	0.9	73.38%	9.79	0.0781	1993.479	2861.063	1.31%
	1	72.21%	9.59	0.0806	2059.217	2875.974	1.04%
750	0.3	75.26%	11.36	0.0573	1421.151	2530.231	1.98%
	0.4	82.24%	11.24	0.0887	1585.040	2792.941	1.77%
	0.5	79.99%	10.79	0.0934	1704.853	2831.526	1.12%
	0.6	78.03%	10.44	0.0961	1797.412	2852.257	0.77%
	0.7	76.30%	10.17	0.0981	1873.465	2864.125	0.56%
	0.8	74.77%	9.94	0.0998	1937.951	2870.868	0.42%
	0.9	73.40%	9.75	0.1014	1993.623	2874.320	0.33%
	1	72.17%	9.58	0.1030	2042.234	2875.496	0.26%
800	0.3	84.41%	11.51	0.1053	1519.355	2799.327	1.09%
	0.4	81.85%	11.03	0.1100	1637.495	2832.845	0.51%
	0.5	79.62%	10.69	0.1120	1722.356	2843.652	0.31%
	0.6	77.67%	10.41	0.1136	1792.195	2847.401	0.21%
	0.7	75.96%	10.18	0.1151	1852.072	2847.783	0.15%
	0.8	74.43%	9.98	0.1167	1904.321	2846.151	0.11%
	0.9	73.06%	9.81	0.1184	1950.354	2843.143	0.09%
	1	71.82%	9.66	0.1202	1991.150	2839.113	0.07%
850	0.3	83.65%	11.36	0.1217	1550.622	2812.525	0.33%
	0.4	81.17%	10.99	0.1240	1635.859	2820.642	0.15%
	0.5	79.01%	10.69	0.1257	1704.173	2820.473	0.09%
	0.6	77.11%	10.45	0.1275	1762.851	2817.559	0.06%
	0.7	75.43%	10.24	0.1294	1814.213	2813.132	0.04%
	0.8	73.92%	10.05	0.1315	1859.563	2807.666	0.03%
	0.9	72.56%	9.89	0.1338	1899.813	2801.409	0.03%
	1	71.31%	9.74	0.1362	1935.659	2794.511	0.02%

Continued

Gasification Temperature (°C)	S/B	Gasification Efficiency	LHV (MJ/Nm ³)	Char Split fraction	H ₂ (Nm ³ /h)	Cold gas flow rate (Nm ³ /h)	CH ₄ volume fraction
900	0.3	82.77%	11.31	0.1338	1548.809	2794.750	0.10%
	0.4	80.38%	10.99	0.1360	1618.409	2792.875	0.05%
	0.5	78.30%	10.72	0.1381	1677.408	2787.808	0.03%
	0.6	76.46%	10.50	0.1405	1728.921	2781.364	0.02%
	0.7	74.81%	10.30	0.1431	1774.328	2773.998	0.01%
	0.8	73.32%	10.12	0.1458	1814.564	2765.919	0.01%
	0.9	71.96%	9.96	0.1487	1850.337	2757.255	0.01%
	1	70.71%	9.82	0.1517	1882.214	2748.094	0.01%
950	0.3	81.85%	11.29	0.1447	1536.577	2767.288	0.04%
	0.4	79.56%	11.00	0.1473	1596.992	2760.704	0.02%
	0.5	77.54%	10.76	0.1502	1649.277	2752.549	0.01%
	0.6	75.74%	10.54	0.1532	1695.167	2743.481	0.01%
	0.7	74.11%	10.35	0.1565	1735.690	2733.718	0.00%
	0.8	72.63%	10.18	0.1599	1771.606	2723.382	0.00%
	0.9	71.27%	10.03	0.1635	1803.515	2712.558	0.00%
	1	70.02%	9.90	0.1672	1831.905	2701.311	0.00%
1000	0.3	80.91%	11.29	0.1553	1521.179	2736.836	0.01%
	0.4	78.70%	11.02	0.1586	1574.827	2727.168	0.01%
	0.5	76.73%	10.78	0.1622	1621.574	2716.488	0.00%
	0.6	74.97%	10.58	0.1659	1662.650	2705.095	0.00%
	0.7	73.36%	10.40	0.1699	1698.901	2693.120	0.00%
	0.8	71.88%	10.24	0.1739	1730.983	2680.651	0.00%
	0.9	70.52%	10.09	0.1782	1759.419	2667.756	0.00%
	1	69.25%	9.96	0.1825	1784.640	2654.484	0.00%
1050	0.3	79.97%	11.29	0.1658	1504.753	2705.327	0.01%
	0.4	77.82%	11.03	0.1698	1552.782	2693.109	0.00%
	0.5	75.89%	10.81	0.1741	1594.703	2680.116	0.00%
	0.6	74.15%	10.62	0.1786	1631.506	2666.517	0.00%
	0.7	72.55%	10.44	0.1832	1663.922	2652.409	0.00%
	0.8	71.07%	10.29	0.1880	1692.527	2637.863	0.00%
	0.9	69.70%	10.15	0.1929	1717.786	2622.933	0.00%
	1	68.41%	10.02	0.1979	1740.082	2607.664	0.00%
1100	0.3	79.01%	11.28	0.1763	1487.960	2673.343	0.00%
	0.4	76.91%	11.04	0.1811	1531.081	2658.781	0.00%
	0.5	75.02%	10.83	0.1861	1568.693	2643.571	0.00%
	0.6	73.29%	10.65	0.1913	1601.639	2627.827	0.00%
	0.7	71.69%	10.48	0.1966	1630.564	2611.627	0.00%
	0.8	70.21%	10.33	0.2020	1655.979	2595.032	0.00%
	0.9	68.82%	10.19	0.2075	1678.301	2578.088	0.00%
	1	67.52%	10.07	0.2132	1697.873	2560.834	0.00%