PERFORMANCE AND AGGLOMERATION STUDY OF OIL PALM EMPTY FRUIT BUNCH IN A BUBBLING FLUIDIZED BED GASIFIER

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In the name of God the most gracious the most merciful

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variables
BM	Bed material
BT	Bed temperature
BTG	Biomass Technology Group
CCD	Central composite design
CT	Combustor temperature
DC	Direct current
DSC	Differential scanning calorimetry
DTG	Derivative thermogravimetric analysis
ECFB	External circulating fluidized bed
EFB	Empty fruit bunch
ER	Equivalence ratio
FC	Fixed carbon
FR	Feeding rate (kg/h)
FV	Fluidization velocity
GA	Gasification agent
GC	gas chromatograph
HHV	Higher heating value (MJ/Nm^3)
IC	Internal combustion
ICFB	Internal circulating fluidized bed
ID	Internal diameter
LHV	Low heating value

LOI	Loss of ignition (%)
LPG	Liquefied petroleum gas
na	Data were not available
RSM	Response surface method
SB	Steam to biomass ratio
SS	Sum of squares
Std. Dev.	Standard deviation
TCD	Thermal conductivity detector
TGA	Thermogravimetric analysis
VM	Volatile matter
XRF	X-Ray Fluorescence

LIST OF SYMBOLS

A	Cross sectional area of the duct (m^2)
a	Time at firing (min)
b	Time at 6/10 from maximum temperature (min)
c	Time to get maximum temperature (min)
C_D	Orifice coefficient
d_0	Diameter of the orifice (m)
$\bar{d}_p$	Mean diameter of the particle size (m)
Cp_w	Specific heat of water (J/kg.K)
g	Acceleration due to gravity (m/s^2)
H	Height of the gasifier (m)
H_b	Heating value of the biomass (MJ/kg)
H_g	Heating value of the producer gas (MJ/Nm^3)
MC	Moisture content (%)
m_{ECW}	Equivalent calorimeter mass of water (kg)
m_s	Mass of sample (kg)
m_{WC}	Mass of water in cylinder (kg)
N	Number of orifices
Q	Air flow (m^3/s)
Q_a	Flow rate of air (Nm^3/h)
r_1	Temperature rate 5 min before firing (min)
r_2	Temperature rate 5 min after maximum temperature (min)
R^2	R-squared

T_a	Temperature at firing (°C)
T_b	Temperature at b time (°C)
T_c	Maximum temperature (°C)
T_{corr}	Correction Temperature (°C)
U	Superficial gas velocity (m/s)
U_0	Velocity of fluid through orifice (m/s)
U_{mf}	Minimum Fluidizing Velocity (m/s)
V	Average air velocity (m/s)
W_0	Weight of dry biomass sample (g)
W_1	Weight of biomass sample after heating at 900 (ºC)
W_2	Weight of biomass sample after heating at 750 (ºC)
W_b	Mass flow rate of biomass (kg/h)
X_{ash}	Ash content in the feed (%)
X_i	Decoded independent process variable
X_j	Decoded independent process variable
Y	Dry gas yield (Nm^3/kg)
Z	Atomic number
β_i	Linear coefficient for the variable
β_{ii}	Quadratic coefficient for the variable
β_{ij}	Linear model coefficient for the interactions between *i* and *j*
ΔP_d	Distributor pressure drop
ΔP_b	Bed pressure drop
ε	Error
η	Cold gas efficiency (%)
η_c	Carbon conversion (%)

λ	Wavelength of the X-ray photons
μ	Dynamic viscosity of the fluid (N.s/m^2)
ρ_f	Density of the fluid (kg/m^3)
ρ_{gor}	Density of the gas passing through (kg/m^3)
ρ_s	Density of the bed (kg/m^3)

KAJIAN PRESTASI DAN PENGELOMPOKAN BAGI TANDAN KOSONG KELAPA SAWIT DALAM PENGEGAS LAPISAN TERBENDALIR BERGELEMBUNG

ABSTRAK

Perkembangan pesat industri moden telah meningkatkan permintaan tenaga dalam beberapa tahun terakhir. Penggunaan biojisim lignoselulosa berterusan telah memenuhi sebahagian daripada peningkatan permintaan di negara maju. Di antara pelbagai teknologi yang diterapkan untuk menukar sisa biojisim, penggasan biojisim telah dibuktikan sebagai strategi yang terjamin untuk menukarkan biojisim kepada biofuel dan bioenergi. Kelapa sawit sebagai penyumbang utama sumber a biojisim di Malaysia telah menarik perhatian dalam memenuhi kedua-dua permintaan tenaga tradisional dan tenaga boleh diperbaharui secara berterusan. Dalam projek ini, penegasan tandan kosong buah kelapa sawit (TKS) diselidiki didalam penggas lapisan terbendalir bergelembung udara dalam skala perintis. Penggas lapisan terbendalir gelembung udara dengan ketinggian 1050 mm dan diameter dalam 150 mm dibina. Pasir silika digunakan sebagai bahan dasa. Keputusan yang diperolehi daripada penggasan TKS dibandingkan dengan habuk kayu sebagai suapan umum untuk penggasan biojisim. Kajian pengaruh suhu bahan dasar (650 kepada 1050 ^{o}C) terhadap prestasi penggasan TKS dan habuk kayu menunjukkan bahawa nilai haba maksimum (HHV) sebanyak 5.37 dan 5.88 (MJ/Nm^3), hasil gas kering pada 1.84 dan 2.0 (Nm^3/kg), penukaran karbon pada 91 dan 85 % dan kecekapan gas sejuk pada 65 dan 72 % diperolehi untuk TKS dan serbuk gergaji masing-masing pada suhu 1050 ^{o}C. Namun, disedari bahawa pengelompokan merupakan isu utama dalam pengegasan TKS pada suhu tinggi kerana kandungan tinggi K_2O dalam TKS. Untuk mengelakkan pengelompokan bahan dasar, penggasan TKS dilakukan pada suhu 770 ± 20 ^{o}C

sementara nisbah kesetaraan udara-bahan bakar (ER) diubah daripada 0.17 kepada 0.32. HHV maksimum sebanyak 4.45 (MJ/m^3) diperoleh pada ER 0.21 di mana tiada pengelompokan ditemui. Sebagai penyelesaian lain untuk mengurangkan kecenderungan pengelompokan bahan dasar, dolomit terikalsin digunakan sebagai alternatif bahan dasar. Kesan dolomit kepada kualiti gas hasilanr dan HHV diperiksa sementara suhu bahan dasar diubah dari 650 kepada 1050 ^oC. Keputusan kajian menunjukkan bahawa pengelompokan bahan dasar masih merupakan pertimbangan utama pada suhu melebihi 850 ^oC. Namun, kualiti gas hasilan dipertingkatkan dengan jelas, terutama dari segi kandungan H_2, apabila dolomite digunakan. HHV maksimum pada 5.55 (MJ/Nm^3), hasil gas kering pada 1.79 (Nm^3/kg), penukaran karbon pada 85 % dan kecekapan gas sejuk sebanyak 65% diperolehi untuk pengegasanTKS. Demi mengoptimumkan pengegasan TKS menggunakan dolomit, satu siri percubaan yang direka oleh rekabentuk komposit berpusat dengan menggunakan metodologi respon permukaan (RSM). Keputusan eksperimen ini adalah munasabah apabila dipadankan pada model statistik yang dibina untuk semua pembolehubah gerak balas. Keadaan operasi optimum dicadangkan oleh perisian adalah suhu bahan dasar pada 850 ^oC dan ER pada 0.22 di mana HHV padai 5.39 (MJ/m^3) boleh dicapai dengan yakin.

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ABSTRACT

Rapid development of modern industry has greatly increased the demand for energy in recent years. Use of lignocellulosic biomass has fulfilled part of this growing demand in developed countries. Biomass gasification is proved to be a promising strategy to convert biomass into biofuel and bioenergy. Oil palm as the main contributor to biomass resources in Malaysia has attracted considerable attention to fulfill the both traditional and renewable energy demands in a sustainable manner. In this project, gasification of oil palm empty fruit bunch (EFB) was investigated in a pilot scale air-blown bubbling fluidized bed. An atmospheric air-blown bubbling fluidized bed gasifier with the height of 1050 mm and internal diameter of 150 mm was developed. Silica sand was used as bed material. The results obtained from gasification of EFB were compared to that of sawdust as a common feedstock. Studying the effect of bed temperature (650 to 1050 ^{o}C) on gasification performance of EFB and sawdust showed that maximum heating value (HHV) of 5.37 and 5.87 (MJ/Nm^3), dry gas yield of 1.84 and 2.0 (Nm^3/kg), carbon conversion of 91 and 86 % and cold gas efficiency of 65 and 72 % were obtained for EFB and sawdust respectively at the temperature of 1050 ^{o}C. However, it was realized that agglomeration was the major issue in EFB gasification at high temperatures due to the high K_2O content of EFB. To prevent the bed agglomeration, EFB gasification was performed at temperature of 770±20 ^{o}C while the air-fuel equivalence ratio (ER) was varied from 0.17 to 0.32. The maximum HHV of 4.45 (MJ/Nm^3) was obtained at ER of 0.21 where no agglomeration was observed. As another solution to reduce the agglomeration tendency of the bed, calcined dolomite was used as an alternative bed

material. The effect of dolomite on the quality of the producer gas and HHV was examined while the bed temperature was varied from 650 to 1050 ^{o}C. The results indicated that bed agglomeration was still the main concern at temperatures above 850 ^{o}C. However, the quality of the producer gas was significantly improved, especially in terms of H_2 content, while using dolomite. The maximum HHV of 5.55 (MJ/Nm^3), dry gas yield of 1.79 (Nm^3/kg), carbon conversion of 85 % and cold gas efficiency of 65 % were obtained for EFB gasification. In order to optimize the EFB gasification using dolomite, a set of experiments was designed by central composite design (CCD) using response surface methodology (RSM). The experimental results were reasonably fitted to the developed statistical model for all the response variables. The optimum operating conditions suggested by the software were the bed temperature of 850 ^{o}C and ER of 0.22 at which the HHV of 5.39 (MJ/m^3) could be confidently attainable.

CHAPTER ONE - INTRODUCTION

1.1. Introduction

Rapid development of technology and industrialization has faced mankind with two major concerns: depletion of fossil energy resources and deterioration of the environment. Fossil fuels are the most common energy sources used in the world. It has been reported that over 80 % of the energy consumption counts for fossil fuels (Escobar et al., 2009). However, there are some crucial problems associated with such fuel sources. Fossil fuels emit significant amount of pollutants such as CO_2, NO_x and SO_x into the atmosphere (Demirbas, 2007). Combustion of fossil fuels produces large amount of CO_2 which is considered for its greenhouse effect and promotion of global warming (Escobar et al., 2009). Besides, energy consumption has increased 17 fold in the last century and with the present rate of energy consumption, it is estimated that the world's oil reservoir will be diminished by 2050. Meanwhile, the cost of fossil fuel is globally increasing (Demirbas, 2007; Saxena et al., 2009). These issues remind us the need to find alternative fuel resources which are renewable, sustainable and count for eco-friendly fuels.

Amongst all of the renewable resources, biomass is the only renewable source of carbon which can be converted to solid, liquid and gaseous product through various conversion processes (Demirbas, 2008). Currently, biomass is the fourth largest source of energy in the world after coal, petroleum and natural gas and provides about 14 % of the world's energy consumption (Saxena et al., 2009). Biomass wastes are mostly burnt in open air or dumped which generate pollutants including dust, acid rain gases such as NO_x and SO_x and large amount of methane which is a more potent greenhouse gas than CO_2. Therefore, in developed countries

there is a growing trend towards the use of biomass-based energies (Escobar et al., 2009). These technologies which use waste or plant matter to produce energy, emit less greenhouse gas than fossil fuels and are cost wise competitive with conventional energy resources.

One of the promising technologies which utilize the biomass wastes is biomass gasification. Gasification of lignocellulosic biomass has attracted considerable attention among various thermo-chemical conversion technologies as it offers high conversion efficiency (Devi et al., 2003). It is one of the strategies for exploitation of renewable fuels and power generation. Biomass gasification also assists the bioremediation plans as it converts the biomass wastes into clean fuel gases and biofuels.

1.2. Biomass Gasification

Gasification is the partial combustion of hydrocarbons at high temperatures (500 to1400 °C) in atmospheric or pressurized (elevated up to 33 bar) reactors (Basu, 2006). The product of such reaction is called producer gas or syngas mainly consisted of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and minor amounts of water (H_2O), methane (CH_4), higher hydrocarbons (C_2^+) and nitrogen (N_2). Producer gas also contains traces of impurities such as sulfur, mercury, particulates and trace minerals. But, it can be used after adequate clean up and reforming (Devi et al., 2003).

The clean and cooled producer gas is an extremely attractive product that can be used as a fuel for engines and also as a chemical feedstock for industries. It can be

used to run internal combustion engines, substitute furnace oil in direct heat applications and feed high temperature fuel cells. It is also highly desired to convert producer gas to biofuels such as hydrogen, ethanol, methanol and acetate in biological processes (Demirbas, 2007). Besides, gasifiers can be coupled with internal combustion engines, combustion turbines, steam turbines or fuel cells to provide local mechanical or electrical energy requirements. Such plants may be established and operated close to the origin of the biomass wastes providing the requirements of such regions. These units can be operated with fuel of low heating value, typically the producer gas generated from biomass gasification. The coupled systems have high efficiency of internal combustion engines in the low power range and also residual heat flows of such systems can be used for thermal applications (Fauziah et al., 2004).

1.3. Renewable energy development in Malaysia

At present, energy requirements in Malaysia are supplied by four sources: gas (70 %), coal (22 %), hydro power (6 %) and oil (2 %). However, it has been predicted that oil and gas reserves will be depleted in the next 19 and 33 years (Hashim, 2005; Pimentel et al., 2002). Environmental issues associated with industrialization and modernization in one hand and the concern about the depletion of energy resources on the other hand, motivated Malaysian government to reinforce on renewable energy as the fifth reservoir for energy production. The importance of renewable energy development has been fortified in the 10th Malaysian Plan (2010-2015). In this program, production of 985 MW of total energy supply from renewable energy, contributing 5.5 % Malaysia's total electricity generation from renewable resources has been approved. More than 30 % of renewable energy

production, ie., 330 MW is planned to be generated from biomass. The government is committed to encourage the implementation of renewable energy projects (Tenth Malaysia plan).

1.4. Malaysia's biomass-based energy outlook

Biomass resources in Malaysia include a diversity of species. Each biomass resource has its own advantage in clean energy production or disadvantage in greenhouse gas emissions. A scheme of various biomass resources in Malaysia is depicted in Figure 1-1 (Hashim, 2005).

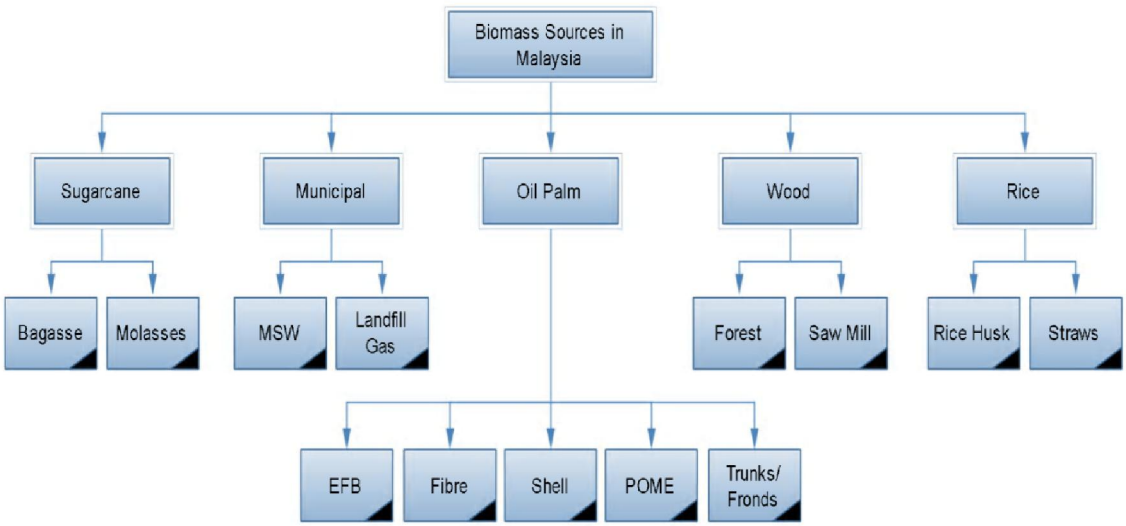

Figure 1-1: Various biomass resources in Malaysia

Malaysia ranks second in the world's palm oil production. However, the waste disposal of almost all the palm bunches from the manufacturing process creates methane which affects adversely to the global warming.

1.5. Oil palm empty fruit bunch in Malaysia

In Malaysia, palm (*Elaeis guineensis Jacq*.) is the dominant agricultural crop. Currently, more than 3.88 million hectares of land in Malaysia are under oil palm cultivation (Idris et al., 2010). Indonesia and Malaysia as the world's leaders in oil palm oil industry provide 86 % of the universal palm oil demand. However, oil palm cultivation is not limited to these countries and its plantation has been established in the world's most diverse tropical regions including Colombia and Brazil (De Souza et al., 2010). Palm as the main contributor to biomass resources in Malaysia has attracted considerable attention to fulfill the both traditional and renewable energy demands in a sustainable manner.

At present, around 368 palm mills are operating in Malaysia that produce significant amount of lignocellulosic biomass including palm empty fruit bunches (53 %), palm mesocarp fibre (32 %) and palm kernel shell (15 %) (Baharaddin et al., 2009). Empty fruit bunch (EFB) which is the empty husks left over after oil extraction from palm fruit, is generated as a waste material from palm oil industries. Although, part of EFB is utilized as solid fuel in the boilers to generate steam and electricity in palm processing mills or used as organic fertilizer (De Souza et al., 2010), however, still large quantities have no specific use. They are burnt in open air which generates pollutants including dust and acid rain gases such as sulfur dioxide and nitrogen oxides or dumped in the plantation. The large amount of EFB generated in Malaysia can be utilized as a potential lignocellulosic biomass source to generate energy and power. Currently, there are some commercial plants to generate power and fuel from EFB in Malaysia. BTG plant (Biomass Technology Group) which deals with pyrolysis of 50 t/day of EFB to produce bio-oil is one of these projects

(chuden website). Chubu Electric Power is another project to generate power from EFB in Malaysia. This power plant has been constructing two small-scale (10,000 kW) power generation facilities that use 240,000 tonnes EFB per year as fuel and currently the first 10,000 kW facility of this project has started its commercial operation (Maeda & Kamada, 2009). Although some industrial plants have been established to convert oil palm lignocellulosic residues into valuable products or energy, so far no commercial gasification plant utilizing biomass has been registered in Malaysia.

The high potential of oil palm solid biomass residues to generate fuel and energy boosts the importance of gasification plants establishment in Malaysia. The purpose of the current research is to study the gasification of lignocellulosic biomass in a fluidized bed gasifier to explore the potential of this local biomass waste for future exploitation. Notice of little availability of data in the literature regarding EFB gasification boosts the significance and necessity of such investigation. Gasification was conducted using EFB in a pilot scale air-blown bubbling fluidized bed. The effect of several process parameters and catalytic bed materials on the quality and composition of the producer gas as well as the gasification performance was investigated. However, more research and development of technology should be devoted into this field to enhance the economical feasibility of this process for future exploitations.

1.6. Objectives of the study

- To investigate the effect of process parameters on the producer gas composition and gasification performance using palm empty fruit bunch and wood sawdust
- To evaluate the performance of catalytic bed materials in fluidized bed gasification of EFB

1.7. Scopes and limitations of the study

In this study, EFB was used as a lignocellulosic feedstock to conduct the biomass gasification. To demonstrate the potential of this locally available biomass, the gasification results were compared to that of wood sawdust.

Silica sand and dolomite were used as bed material. In order to generate a producer gas with a reasonable heating value, the effect of the bed temperature, equivalence ratio and bed material type on the quality of the producer gas was examined. The producer gas quality was assessed in terms of gas composition, HHV, carbon conversion, dry gas yield and cold gas efficiency.

To prevent the sever bed material agglomeration observed with silica sand, the bed temperature was reduced or silica sand was replaced with calcined dolomite. The optimum operating condition to prevent any agglomeration was statistically determined using response surface methodology (RSM), while using dolomite as the bed material.

1.8. Organization of the thesis

A brief introduction on alternative energy, biomass gasification process and potential of palm oil empty fruit bunch as a lignocellulosic abundant waste material to carry out the gasification is presented in chapter 1. This chapter also includes the objectives and scope of this research.

Chapter 2 reviews biomass gasification in fluidized beds. Various types of fluidized bed gasifiers are discussed here. A detailed review on the effect of biomass type, catalytic bed material, bed temperature, equivalence ratio and steam to biomass ratio on the gasification process is presented. Also, the bed agglomeration as a crucial phenomenon in fluidized bed is included in this chapter.

Chapter 3 covers the research methodology. Preparation of the experimental set-up, elemental and proximate analysis of the biomass, the bed materials and ash analysis, operating of the gasifier considering influential process parameters, producer gas collection and analysis are presented.

The obtained experimental results and data are presented in chapter 4. The biomass and bed material analysis results, producer gas composition and gasification performance are presented. Bed agglomeration as the major concern in EFB gasification is discussed and some conditions have been implemented to avoid the agglomeration. Optimization of the catalytic EFB gasification process has been performed based on the statistical method.

Chapter 5 includes concluding remarks regarding the effect of operational parameters and bed material type on the gasification performance and agglomeration. Some recommendations for future studies based on the experimental results are presented in this chapter. A guideline is given for further studies and possible expansion and development of the system.

The temperature profiles, GC monograms of some producer gas samples and 2-Dimentional CAD drawing of some compartments of the operated gasifier are presented in Appendix.

CHAPTER TWO - LITERATURE REVIEW

2.1. Introduction

Gasification is one of the thermal procceses which converts the lignin component of biomass along with the cellulose and hemicellulose into synthesis gas. The gaseous product obtained from the gasification can be eventually used after cleaning up to run internal combustion engines or producing a large variety of biofuels including synthetic diesel and ethanol through Fischer–Tropsch conversion. Thus, the purity and high quality of the producer gas is of utmost importance for its consequent applications. In traditional gasifications, high percentage of undesired products and tar were generated during the gasification process. Long time application resulted in damages such as corrosion and blockage in the system, besides reduction in the overall efficiency of the system.

Gasifiers are categorized into four main types of fixed bed, moving bed, fluidized bed and entrained flow (Zhou et al., 2009a). There are some disadvantages associated with both fixed bed and moving bed gasifiers due to the generation of large quantities of tar and char which are resulted from low and non-uniform heat and mass transfer between solid biomass and gasifying agent within the reactor (Warnecke, 2000; Xu et al., 2009). In contrast, fluidized bed gasifiers provide excellent mixing and gas-solid contact which enhances the reaction rate and conversion efficiencies. Besides, use of bed material as heat transfer medium and catalyst reduces the tar content of producer gas and improves its quality (Schuster et al., 2001).

The purpose of current chapter is to present a detailed review on gasification of lignocellulosic biomass in various fluidized bed gasifiers. The effect of several process parameters on the quality and composition of the producer gas are reviewed. Biomass gasification process in various types of fluidized bed reactors is discussed and the collected results from the literature are reported.

2.1. Important process parameters in fluidized beds

Design and operation of a gasifier requires understanding of the effect of various types of biomass and operation parameters on the performance of the system. Lignocellulosic biomass differ greatly in their physical, chemical and morphological properties which affect the characteristics of the gasification process (Moilanen et al., 2009). Also, the choice of a biomass is significantly depended on its heating value (Nemtsov & Zabaniotou, 2008). Biomass wastes with high heating value contribute to more energy recovery and better system performance in terms of efficiency and economy. However, effective heat and mass transfer properties of fluidized beds provides the possibility of using various types of biomass wastes with different compositions and heating values (Yassin et al., 2009). Various lignocellulosic biomass of cedar wood (Asadullah et al., 2004a), olive oil residue (Arvelakis et al., 2003), sugar-cane bagasse and jute stick (Asadullah et al., 2004b), rice straw (Li et al., 2009), pine sawdust (Lv et al., 2004), rice husk and coffee husk (Vélez et al., 2009), spruce wood pellet (Miccio et al., 2009), coffee ground (Murakami et al., 2007), larch wood (Weerachanchai et al., 2009), corn cob (Lu et al., 2008), peach stone (Arvelakis et al., 2005), wheat straw (Oesch et al., 1996), and beech wood (Radmanesh et al., 2006) have been successfully implemented to conduct the

biomass gasification in fluidized beds. Table 2-1 summarizes the ultimate and proximate analysis of various biomass feedstocks used for gasification.

Several researches have been conducted on biomass gasification for improving the producer gas composition (H_2, CO, CO_2, CH_4, and C_nH_m), obtaining a gas with higher heating value, reducing the tar and char content of the effluent stream and enhancing the gas yield, cold gas efficiency and carbon conversion. It should be considered that these gasification performance indexes are in trade-off relationship. For example, increasing the equivalence ratio to reduce the tar concentration will significantly reduce the LHV and cold gas efficiency. Thus, it is impossible to meet all the performance indexes at their desirable values at the same time. Various researchers have put their first priorities on different indexes however; there are some significant operation parameters that should be carefully determined to obtain a gas stream with desirable properties. The main process parameters and their effect on the quality of the effluent stream of the gasifiers are discussed in the following section.

Table 2-1: The ultimate and proximate analysis of various lignocellulosic biomass

Biomass type	Ultimate analysis (db, % w/w)					Proximate analysis (% w/w)				LHV	Ref.
	C	H	O	N	S	Ash	VM	FC	M	(MJ/kg)	
Cedar wood	51.10	5.90	42.50	0.12	0.02	0.3	80-82	18-20	*	19.26	(Asadullah et al., 2004a)
Wood sawdust	46.2	5.1	35.4	1.5	0.06	1.3	70.4	17.9	10.4	18.81	(Cao et al., 2006)
Olive oil residue	50.7	5.89	36.97	1.36	0.3	4.6	76	19.4	9.5	21.2	(Arvelakis et al., 2003)
Rice husk	45.8	6.0	47.9	0.3	-	0.8	73.8	13.1	12.3	13.36	(Vélez et al., 2009)
Rice straw	38.61	4.28	37.16	1.08	0.65	12.64	65.23	16.55	5.58	14.40	(Li et al., 2009)
Pine sawdust	50.54	7.08	41.11	0.15	0.57	0.55	82.29	17.16	*	20.54	(Lv et al., 2004)
Spruce wood pellet	49.3	5.9	44.4	0.1	-	0.3	74.2	17.1	8.4	18.5	(Miccio et al., 2009)
Coffee husk	46.8	4.9	47.1	0.6	0.6	1.0	74.3	14.3	10.4	16.54	(Vélez et al., 2009)
Coffee ground	52.97	6.51	36.62	2.8	0.05	1.0	71.8	16.7	10.5	22.0	(Murakami et al., 2007)
Larch wood	44.18	6.38	49.32	0.12	-	0.12	76.86	14.86	8.16	19.45	(Weerachanchai et al., 2009)
Grapevine pruning waste	46.97	5.8	44.49	0.67	0.01	2.06	78.16	19.78	*	17.91	(Lapuerta et al., 2008)
Jute stick	49.79	6.02	41.37	0.19	0.05	0.62	76-78	21.4-23.4	*	19.66	(Asadullah et al., 2004b)
Sugar-cane bagasse	48.58	5.97	38.94	0.2	0.05	1.26	67-70	28.74-30.74	*	19.05	(Asadullah et al., 2004b)
Corn cob	40.22	4.11	42.56	0.39	0.04	2.97	71.21	16.11	9.71	16.65	(Lu et al., 2008)
Peach stone	51.95	5.76	40.7	0.79	0.01	0.65	81.3	18.1	8.53	21.6	(Arvelakis et al., 2005)
Wheat straw	46.1	5.6	41.7	0.5	0.08	6.1	75.8	18.1	*	17.2	(Oesch et al., 1996)
Cotton stem	42.8	5.3	38.5	1.0	0.2	4.3	72.3	15.5	7.9	15.2	(Guo et al., 2001)
Straw	36.57	4.91	40.70	0.57	0.14	8.61	64.98	17.91	8.5	14.6	(Shen et al., 2008)
Camphor wood	43.43	4.84	38.53	0.32	0.1	0.49	72.47	14.75	12.29	17.48	(Zhou et al., 2009a)
Beech wood	48.27	6.36	45.2	0.14	-	0.8	81	18	*	19.2	(Radmanesh et al., 2006)
Switchgrass	47	5.3	41.4	0.5	0.1	4.6	58.4	17.1	20	18.7	(Jin et al., 2006)

* dry basis, VM: Volatile matter; FC: Fixed carbon; M: Moisture

2.2. Effect of bed materials

Bed materials are of great importance in fluidized bed gasifiers. They act as heat transfer medium but their major role involves in tar cracking which avoids complicated downstream tar removal process (Lu et al., 2008). The presence of catalyst in the bed material during biomass gasification promotes several chemical reactions which influences the composition and heating value of the producer gas. It also reduces the tar yield and prevents solid agglomeration tendency of the bed (Devi et al., 2003).

The catalytic reforming reactions through which tar is converted into useful gaseous compounds are summarized as follow (Narvaez et al., 1996; Wang et al., 2008):

$$C_nH_m\ (tar) + nH_2O \leftrightarrow (n + m/2)\ H_2 + nCO \quad (2.1)$$

$$C_nH_m\ (tar) + nCO_2 \leftrightarrow (m/2)\ H_2 + 2nCO \quad (2.2)$$

$$C_nH_m\ (tar) + (n/2 + m/4)\ O_2 \leftrightarrow (m/2)\ H_2O + nCO \quad (2.3)$$

$$C_nH_m\ (tar) \leftrightarrow (m/2)\ H_2 + nC \quad (2.4)$$

Generally, three main groups of catalysts are implemented to remove tar from the producer gas (Wang et al., 2008; Weerachanchai et al., 2009): (1) natural catalysts such as dolomite and olivine; (2) alkali-based catalysts such as (Li, Na, K, Rb, Cs and Fr) and (3) metal-based catalyst such as nickel catalysts.

Dolomite is the most commonly used catalyst which effectively removes heavy hydrocarbons from the gas stream (Weerachanchai et al., 2009). It also decreases agglomeration in fluidized bed while using biomass with high alkali

content. But, the undesired property of dolomite is its quick calcination in the gasifier which consequently results in a gas with high particulate (Corella et al., 2004). Olivine is reported to be less effective than dolomite, but its resistance against attrition is more than that of dolomite (Corella et al., 2004; Weerachanchai et al., 2009). Alkali-based catalysts (Li, Na, K, Rb, Cs and Fr) are able to improve the gasification rate and reduce the tar content of the producer gas. However, difficulty in recovery, high cost and agglomeration at high temperatures are some of the disadvantages of the alkali-based catalysts (Weerachanchai et al., 2009). Metal-based catalysts are also highly effective in removing tar and improve the quality of the producer gas. The main problems associated with this type of catalysts are carbon deposition and nickel particle growth, which cause catalyst deactivation (Weerachanchai et al., 2009).

Asadullah et al., (2004a) compared the performance of the heterogeneous catalyst of Rh/ CeO_2/ SiO_2 in a fluidized bed gasification system to that of dolomite, steam reforming catalyst (G-91) and inert bed materials while the ER was set at 0.31 and the bed temperature was in the range of 823 to 973 K. It was observed that the tar content of the producer was completely negligible while using Rh/ CeO_2/ SiO_2 as the bed material. Whereas, the tar concentration of about 30, 113 and 139 g/m^3 was obtained with G-91, dolomite and inert bed materials, respectively. It was also concluded that in the case of Rh/ CeO_2/ SiO_2 catalysts, the efficiency of cold gas was about 71 %, which is more than other cases. Also, little char and coke were observed in the experiments with the Rh/ CeO_2/ SiO_2 as catalysts. In another set of experiments carried out by Miccio et al., (2009), the effect of four different catalysts of quartz, olivine, dolomite and Ni-alumina on tar content of the producer gas was

studied at ER of 0.17 and bed temperature of 870 ^{o}C. In their experiments, tar concentrations of 19.2, 13.2, 11.4 and 9 g/m^3 were obtained for quartz, olivine, dolomite and Ni-alumina, respectively. It was concluded that the presence of catalyst increased the hydrogen concentration in the producer gas and also the total gas yield was slightly improved. In another investigation conducted by Weerachanchai et al., (2009), the performance of three different bed materials of calcined limestone, calcined concrete waste and silica sand was evaluated. It was observed that calcined limestone was the most effective catalyst for tar adsorption at 650 ^{o}C. The obtained results showed that calcined limestone and calcined concrete waste improved the H_2 and CO_2 content of the producer gas, whereas silica sand increased the CO content. Skoulou et al., (2008) used quartz sand and olivine as bed materials in a bubbling fluidized bed gasifier at ER of 0.2-0.4 and bed temperature of 750 to 850 ^{o}C. They concluded that although quartz sand is a cheap and abundant material, it caused severe defluidization due to its tendency to tar formation at temperatures below 800 ^{o}C. They replaced quartz sand with olivine and observed that at low gasification temperature of 750 ^{o}C and ER of 0.2, components of tar were thermally broken down and released H_2 and CO, under the catalytic effect of iron-based olivine. Li et al., (2004) investigated the effect of bed material on tar removal efficiency in a circulating fluidized bed. They used silica sand and a commercial Ni-alumina catalyst as bed material. At the bed temperature of 800 ^{o}C, the amount of tar reduced from 0.4 g/m^3 to 0.15 mg/m^3, as silica sand was replaced with Ni-alumina catalyst.

2.2.1. Dolomite and its catalytic properties

Dolomite [$CaO.MgO(CO_{3)2}$] as a cheap and plentiful catalyst in biomass gasification has been employed by several researchers in power plants (Corella et al.,

2008; Hu et al., 2006; Olivares et al., 1997). Dolomite is an adaptable catalyst with air, steam and a mixture of steam and O_2 as medium gas (Corella et al., 2004; Hu et al., 2006; Narvaez et al., 1996; Olivares et al., 1997). It has also been utilized as a suitable bed material in commercial fluidized bed gasifiers (Salo & Horvath, 2009). Dolomite has proved its ability to avoid or reduce the formation of agglomerates, especially in feedstocks with high alkali content (Gusta et al., 2009). Besides, in-situ catalytic reactions promoted by dolomite positively affects the cracking of tar and enhances the quality of the producer gas (Narvaez et al., 1996; Olivares et al., 1997; Xie et al., 2010). It has been reported that a presence of 20- 30 wt % dolomite in the gasifier bed significantly improves the quality of the producer gas and prevents bed agglomeration (Gil et al., 1999). Corella et al., (2004) studied the effect of various catalytic bed materials on agglomeration with high alkali content biomass feedstocks. They concluded that dolomite and olivine have the ability to avoid bed agglomeration up to 900 °C. Another investigation was carried out by Zevenhoven-Onderwater et al., (2001) in a lab scale pressurized fluidized bed gasifier with reed canary grass as feedstock. Defluidization at 701 ºC in silica sand bed was observed caused by agglomerates formed in the bed, while no agglomeration was observed with dolomite up to 900 ºC.

Dolomite, especially in the calcined state (CaO.MgO) is an active catalyst for tar conversion. Trace elements of potassium and iron oxides found in dolomite, improve the tar conversion ability of dolomite through the steam and dry reforming reactions as well as the steam and thermal cracking reactions. As a result, the level of the combustible gaseous mainly H_2 and CO in the producer gas is improved (Gusta et al., 2009).

2.3. Effect of bed temperature

Bed temperature is one of the most important operation parameters which affect both the heating value and producer gas composition. Based on Le Chatelier's principle, the effect of temperature on producer gas composition depends on the thermodynamic behavior of the reactions. High temperatures improve product formation in endothermic reactions whereas they favor reactants in exothermic reactions. The main reactions that occur during gasification can be summarized as follow (Li et al., 2009; Weerachanchai et al., 2009):

Oxidation	$C + O_2 \leftrightarrow CO_2$	ΔH= -408.8 kJ/mol	(2.5)
Partial oxidation	$2C + O_2 \leftrightarrow 2CO$	ΔH= -246.4 kJ/mol	(2.6)
Steam reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	ΔH= +206 kJ/mol	(2.7)
	$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$	ΔH= +165 kJ/mol	(2.8)
Water-gas	$C + H_2O \leftrightarrow CO + H_2$	ΔH= +131 kJ/mol	(2.9)
Boudouard	$C + CO_2 \leftrightarrow 2CO$	ΔH= +172 kJ/mol	(2.10)
Water-gas shift reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	ΔH= -41.98 kJ/mol	(2.11)
	$C + 2H_2O \leftrightarrow CO_2 + 2H_2$	ΔH= +100 kJ/mol	(2.12)

In fact, the main objective of the gasification process is to generate a combustible gas enriched in CO, H_2 and CH_4 with medium to high LHV which is suitable for further exploitation in internal combustion engines and turbines (Skoulou et al., 2008). It has been stated that high bed temperatures improve carbon conversion and steam cracking and reforming of tars which result in less char and tar formation and high gas yields (Chaiprasert & Vitidsant, 2009; Pinto et al., 2003).

Lv et al., (2004) studied the effect of bed temperature on carbon conversion, gas yield and LHV of pine sawdust. It was reported while increasing the bed temperature, the carbon conversion efficiency improved from 78.17 to 92.59 % and also the gas yield increased from 1.43 to 2.53 m^3/kg. As the temperature was raised from 700 to 900 ^oC, LHV of the gas reduced from 7.94 to 7.36 kJ/m^3. Narvaez et al., (1996) investigated the effect of bed temperature on composition, tar content and LHV of the producer gas using pine sawdust as biomass feedstock. They reported that in the temperature range (700-850 ^oC), the H_2 content increased from 5 to 10 %, CO increased from 12 to 18 %, CO_2 decreased from 15.7 to 14 % and CH_4 and C_nH_m contents were nearly constant. It was also observed that as the temperature increased, the tar content of the producer gas gradually reduced due to tar cracking and steam reforming reactions at high temperatures. It was also reported that the LHV of the producer gas was slightly increased due to the increase of H_2 and CO content. In another set of experiment conducted by Pinto et al., (2003), co-gasification of coal and biomass (pine) in the bed temperature range of 750 to 890 ^oC was studied. It was observed that increasing the temperature led to an increase of about 70 % in H_2 concentration, whereas a decrease of around 30 % was obtained in CH_4 concentration. It was also reported that the char formation was reduced by 9 % at high temperatures. The reduction in char yield confirmed improved carbon conversion while increasing bed temperature. Wu et al., (2009) investigated rice husk gasification at 700 to 800 ^oC. It was reported that as the temperature was raised from 700 to 800 ^oC, H_2 concentration increase from 5.37 to 7.46 %, CO reduced from 20.62 to 16.53 %, CH_4 concentration varied from 5.79 to 4.79 % and CO_2 increased slightly from 15.52 to 16.08 %. The gas LHV also reduced from 6.47 to 5.54 MJ/m^3 as the temperature was elevated from 700 to 800 ^oC. Kumar et al., (2009) also

studied the effect of gasification temperature of distillers grains in the range of 650 to 850 ^{o}C. They obtained maximum carbon conversion of 82 % and energy efficiency of 96 % at 850 ^{o}C. It was also concluded that increasing the bed temperature from 650 to 850 ^{o}C improved H_2 concentration from 4 to 15 %.

2.4. Effect of gasifying agent

Fluidized biomass gasification has been performed using various gasifying agents such as air, steam, oxygen-steam, air-steam, O_2-enriched air and oxygen-air-steam (Campoy et al., 2009). The technology of biomass air gasification boosts the feasibility of the gasification process and has been developed for industrial application. However, it generates a producer gas highly diluted by nitrogen with LHV of 4-6 MJ/m^3 and H_2 content of 8-16 vol.% which seems to be useful for electricity production or heat generation (Campoy et al., 2009; Gil et al., 1997; Schuster et al., 2001). Biomass O_2-enriched air gasification provides a gas with medium heating value but, it requires oxygen production equipments which increases the cost of gasification process. Biomass steam gasification is capable of producing a fuel gas with heating value of 10-16 MJ/m^3 and H_2 content of 30-60 vol.% (Shen et al., 2008). However, endothermic reactions involved in this process reduce the bed temperature and additional equipments and energy are required to increase the temperature to above 700 ^{o}C (Umeki et al., 2009). In steam-oxygen gasification, the necessary heat is provided through partial oxidation reactions. The produced gas has a high H_2 content and the problem of dilution with nitrogen is avoided but the high cost of pure O_2 makes the process unfavorable for industrial applications (Campoy et al., 2009).

For a defined biomass flow rate, two ratios should be determined for the analysis of the process: Equivalence ratio (ER) in air or oxygen gasification and steam to biomass ratio (SB) in steam gasification process.

2.4.1. Equivalence ratio

Equivalence ratio (ER) is one of the most important operation parameters involved in air biomass gasification. It is defined as the actual air to biomass weight ratio divided by stoichiometric air to biomass weight ratio needed for complete combustion (Narvaez et al., 1996).

High degree of combustion occurs at high ER which supplies more air into the gasifier and improves char burning to produce CO_2 instead of combustible gases such as CO, H_2, CH_4 and C_nH_m. Also, increasing the ER results in a decrease in the LHV of the producer gas because it hinders the production of CH_4 and other light hydrocarbons which have relatively large heating values. Besides, at high ER nitrogen provided by air dilutes the producer gas which in turn results in its low energy content (Mansaray et al., 1999). Studies have shown that too small ER is also unfavorable for biomass gasification as it lowers the reaction temperature (Lv et al., 2004). Therefore, an optimum value for ER in biomass gasification exists in the range of 0.2 to 0.4 which differs according to various operation parameters (Narvaez et al., 1996). Selection of the suitable ER is somehow depended on the producer gas subsequent application. When the raw producer gas is going to be burnt in downstream furnaces, where tar is not a serious issue, the gas should have a high heating value, therefore the gasifier can be operated at the minimum ER of about 0.2.

In the case of temperatures lower than 850 ^{o}C, tar yield is high and ER should be increased to about 0.3-0.4 to compensate such negative effects (Narvaez et al., 1996).

Lv et al., (2004) studied the effect of ER on gas yield and LHV. They varied the ER from 0.19 to 0.27 and realized that the variation of ER could be divided into two stages of 0.19 to 0.23 and 0.23 to 0.27. In the first stage, the gas yield increased from 2.13 to 2.37 m^3/kg and the gas LHV increased from 8.82 to 8.84 MJ/m^3. It was observed that in the second stage, the LHV and gas yield decreased due to the improvement of the oxidation reactions which also decreased the concentration of CO, CH_4 and C_nH_m and increased the CO_2 concentration. So, the value of 0.23 was selected as the optimum ER. In another set of experiments conducted by Narvaez et al., (1996), ER was varied in the range of 0.25 to 0.45 to find the optimum ER. It was observed that increasing the ER reduced the amount of H_2, CO, CH_4 and C_2H_2. Maximum H_2 concentration of 10 % was obtained at ER of 0.26. They also realized that while the ER was increased the tar content of the producer gas was gradually decreased and at ER of 0.45, minimum tar concentration of 2-7 g/m^3 was achieved. They obtained LHV of 5.2-7 MJ/m^3 and 3.5-4.5 MJ/m^3 at ERs of 0.25 and 0.45, respectively. It was also concluded that the gas yield was in a direct relationship with ER. Similar trends were obtained by Li et al., (2009) who investigated the co-gasification of biomass and coal while the ER was in the range of 0.31 to 0.47. They also explained that as ER increased, more oxygen was introduced into the gasifier which enhanced the combustion and increased the bed temperature from 948 to 1026 ^{o}C. (Skoulou et al., 2008) also studied the effect of ER variation (0.2 to 0.4) as one of the most important operation parameters on the quality of the producer gas. They reported favored concentration of CO at low ER of 0.2 and its hindered production at

ER of 0.4 because of complete oxidation of carbon into CO_2. Also, H_2 production peaked at ER of 0.2. Lower heating value of the producer gas was obtained at high ER which was due to the promotion of the oxidation reaction and dilution of the producer gas with N_2. Mansaray et al., (1999) investigated the effect of ER on the gasifier performance. They concluded that as the ER was increased from 0.25 to 0.35, the concentration of CO_2 and N_2 also increased while the concentration of the combustible gases gradually decreased. They also realized that the gas yield increased from 1.3 to 1.98 m^3/kg as the ER was raised from 0.25 to 0.35 respectivly.

2.4.2. Steam to biomass ratio

Steam to biomass ratio (SB) which is defined as the flow rate of the steam fed into the gasifier divided by the biomass flow rate is one of the important process parameters involved in steam gasification (Campoy et al., 2009).

An experimental study on biomass air-steam gasification was conducted by Lv et al., (2004). They investigated the effect of SB on the quality of the producer gas in the range of 0 to 4.04. It was observed that the introduction of steam to the system improved the gas yield, LHV and carbon conversion efficiency. They reported the SB range of 1.35 to 4.04 as the optimum SB in which the CO, CH_4 and C_2H_2 content of the producer gas decreased, whereas the CO_2 and H_2 concentration gradually increased. It was explained that in this SB range, more steam reforming reactions of CO, CH_4 and C_2H_2 occurred in the presence of steam which resulted in high concentrations of H_2 and CO_2. Over the optimum range a decreasing trend was observed in the gas yield, LHV and carbon conversion efficiency due to the low reaction temperature caused by low temperature steam. Qin et al., (2009)

investigated the effect of SB on tar formation and the corresponding tar properties in wood sawdust gasification. In their experiments, SB was varied in the range of 0.49 to 2.66 at 900 ^{o}C. The results revealed that as the SB was increased, the tar yield gradually decreased from 3.87 to 1.71 %. It was also concluded that high SB values lower the aromacity of the tar. Another set of experiments was conducted by Gil et al., (1997) who studied the effect of steam-oxygen gasification of pine wood chips on product distribution. In their experiments, steam to oxygen and steam-oxygen to biomass ratios were varied in the range of 2-3 mol/mol and 0.6-1.6 kg/kg, respectively. The achieved results revealed that the H_2 content of the producer gas was in the range of 14 to 30 vol.% and decreased as the steam-oxygen to biomass ratio was increased or the steam to oxygen ratio was gradually decreased. As the O_2 introduced into the system was increased, more H_2 was burnt in the gasifier and less was found in the effluent stream. Similar trend was observed for CO while varying the defined ratios and its concentration in the producer gas was obtained in the range of 30 to 50 vol.%. The tar content of the raw gas clearly reduced to less than 10 g/m^3 as the steam-oxygen to biomass ratio was increased to 1.0-1.1 kg/kg. The char yield also decreased to 10 % while the gasifying agent to biomass ratio was increased to the values higher than 1.0.

As mentioned earlier, steam gasification can provide a gas stream with high content of H_2, but the concentration of the undesirable products such as CO_2 is also increased. In order to improve the efficiency of the steam gasification process, considerable efforts have been devoted to the production of producer gas with high yield of H_2 with simultaneous capture of CO_2. For this purpose, Weerachanchai et

al., (2009) used limestone (CaO) as the bed material to capture CO_2 in steam gasification process of larch wood according to the following reaction:

$$CaO + CO_2 \rightarrow CaCO_3 \qquad \Delta H = -170.5 \text{ kJ/ mol} \qquad (2\text{-}13)$$

They obtained a gas product containing 38.71 mmol/g H_2 and 20.21 mmol/g CO_2. They explained that the significant increase in the CO_2 and H_2 concentration was attributed to the char decomposition, steam reforming reactions of hydrocarbons and tars and also water-gas shift reaction. The CO generated through char decomposition and steam reforming reactions was consumed by water-gas shift reaction to yield more CO_2 and H_2.

2.5. Effect of biomass size

It has been accepted that small particle size biomass significantly increases the overall energy efficiency of the gasification process, but it also increases the gasification plant cost. It has been estimated that for a 5-10 MWe gasification plant, about 10 % of the output energy is required for the biomass particle size reduction (Rapagna & Mazziotti di Celso, 2008; Warnecke, 2000). On the other hand, an increase in biomass particle size reduces the pre-treatment costs, but the devolatilization time increases, and thus for a defined throughput the gasifier size increases (Rapagna & Mazziotti di Celso, 2008). Therefore, a balance should be considered while investigating the effect of biomass particle size on the gasification efficiency.