CHARACTERIZATION OF A BUBBLING FLUIDIZED BED BIOMASS GASIFIER

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CHARACTERIZATION OF A BUBBLING FLUIDIZED BED BIOMASS GASIFIER

by

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LIST OF SYMBOLS

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MJ/Nm^3	Mega-Joule per nominal m^3, unit for lower calorific value of gas at normal temperature and pressure conditions.	16
P_{in}	Thermal input, kW	32
η	Engine efficiency	32
LCV_{PG}	Lower calorific value of producer gas, MJ/Nm^3	32
Q_{PG}	Volume flow rate of producer gas, Nm^3/hr	32
$P_{in, PG}$	Thermal input from producer gas, kW	32
η_{cold}	Cold gas efficiency	33
$\dot{m}_{biomass}$	Mass flow rate of biomass, kg/hr	33
$LCV_{biomass}$	Lower calorific value of biomass, MJ/kg	33
$\dot{m}_{air}$	Mass flow rate of air, kg/hr	34
T_1	Temperature of bed zone 400mm above air distribution plate, ˚C	36
T_2	Temperature of bed zone 800mm above air distribution plate, ˚C	36
$T_{freeboard}$	Temperature of freeboard zone, ˚C	36
L	Distance of pressure tap from orifice, m	40
D	Pipe diameter, mm	40
Δh	Differential height of water column in manometer, m	40
K	Discharge coefficient	40
ΔP	Pressure drop across orifice, kPa	40
ρ_{air}	Density of air, kg/m^3	40
ρ_{H2O}	Density of water, kg/m^3	40
Q_{air}	Volume flow rate of air, Nm^3/hr	40
R_t	Turndown ratio	42
$P_{max,o}$	Maximum thermal output at maximum cold gas efficiency, kW	42
$P_{min,o}$	Minimum thermal output at maximum cold gas efficiency, kW	42
U_{mf}	Minimum fluidization velocity, m/s	43
d_p	Particle diameter, µm	44

R_a	Aspect Ratio	47
H_s	Static Bed Height, m	48
D_r	Reactor Diameter, m	48
m_{char}	Amount of char collected, kg	55
η_{carbon}	Carbon conversion efficiency	55
$m_{fed\ biomass}$	Amount of biomass fed, kg	56
$\dot{m}_{prim}$	Mass flow rate of condensates from primary condenser, g/min	56
$\dot{m}_{sec}$	Mass flow rate of condensates from secondary condenser, g/min	56
$\dot{m}_{exp}$	Mass flow rate of condensates from expansion tank, g/min	56
$\dot{m}_{cond}$	Total Mass flow rate of condensates, kg/hr	56
T_{outlet}	Temperature of outlet gas from bubbling fluidized bed gasifier, ˚C	56
T_{prim}	Temperature of at inlet of primary condenser, ˚C	56
T_{sec}	Temperature of at inlet secondary condenser, ˚C	56
T_{final}	Temperature of producer gas at stack, ˚C	56
m_{water}	Mass of water, kg	58
ΔH_{H2O}	Specific heat for water, kJ/kg.K	58
m_{sample}	Mass of sample, kg	58
$h_{fg,H2O}$	Latent heat of vaporization for water, kJ/kg	58
A_g	Area under chromatogram for component g	60
$A_{g,I}$	Area under chromatogram for pure component g	60
y_{800}	Point with y=800mm, x=200mm in FLUENT model	64
ΔP_{max}	Maximum pressure drop across BFBG, kPa	83
$\Delta P_{max,\ FLUENT}$	Maximum pressure drop from FLUENT across BFBG, kPa	83
$\Delta T_{1\text{-}2}$	Temperature difference between first and second thermocouple, ˚C	88
P_{char}	Thermal input from char, kW	109
P_{loss}	Thermal energy loss, kW	109
$P_{in,\ diesel}$	Thermal input from diesel, kW	110
H_o	Null hypothesis	114
α	Level of significance	114
$\vec{U}$	Velocity vector, m/s	134

∇	Del operator, m^{-1}	134
e	internal energy per unit mass, kJ/kg	134
f	Field Force per unit mass, N/m	134
τ	shear stress tensor, N/m^2	134
μ'	Bulk Viscosity, Ns/m^2	134
$\overrightarrow{J_e}$	Heat Flux Vector, W/m^3	134
$\overrightarrow{J_q}$	Heat generation term, W/m^2	134
μ	Viscosity, Ns/m^2	134
δ_{ij}	Kronecker delta	134
φ_k	Dissipation function, W/m^3	135
V_k	Volume of phase k, m^3	135
α_k	Volume fraction of phase k	135
K_{sl}	Gidaspow fluid-solid interaction coefficient	135
p_k	Static pressure of phase k, kPa	136
ρ_l	Density of liquid phase, m^3	136
$\overrightarrow{U_s}$	Velocity vector of solid phase, m/s	136
$\overrightarrow{U_l}$	Velocity vector of liquid phase, m/s	136
α_l	Volume fraction of liquid phase	136
α_s	Volume fraction of solid phase	136
μ_l	Viscosity of liquid phase	136
C_D	Drag coefficient	136
Re_s	Reynolds Number of solid phase	136

LIST OF ABBREVIATION

AFR	Air-fuel Ratio
BFBG	Bubbling fluidized bed biomass gasifier
CFBG	Circulating fluidized bed biomass gasifier
CFD	Computational fluid dynamics
CHP	Combined heat and power
ER	Equivalence ratio
ESCO	Energy service companies
ESP	Electrostatic precipitator
GC	Gas chromatograph
HPLC	High performance liquid chromatograph
IC	Internal combustion
IGCC	Integrated gasification combined cycle
IPP	Independent power producer
LCV	Lower calorific value
LPG	Liquid petroleum gas
PG	Producer gas
TCD	Thermal Conductivity detector
TGA	Thermographic analyzer
TNB	Tenaga Nasional Berhad
VSD	Variable speed drive

LIST OF PUBLICATIONS & SEMINARS

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2. Lim M.T., Zainal Z.A. (2006) Experimental Investigation of a Bubbling Fluidized Bed Biomass Gasifier. International Conference on Environment: Knowledge-based Environmental Management and Sustainable Development. Penang, Malaysia.
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PENCIRIAN PENGGAS BIOMASS LAPISAN TERBENDALIR GELEMBUNG

ABSTRAK

Kenaikan harga minyak dan pencemaran alam sekitar yang semakin memudaratkan telah menonjolkan tenaga biomass sebagai satu alternatif yang baik. Sebuah penggas lapisan terbendalir gelembung telah direka disebabkan oleh keupayaannya untuk mengeluarkan haba yang lebih tinggi dan menerima pelbagai jenis dan qualiti bahan api. Penggas lapisan terbendalir gelembung ini mempunyai diameter dalaman 400mm dan disambungkan kepada satu sistem penyejukan dan pembersihan yang mengeluarkan partikel dan kondensasi daripada gas keluaran. Penggas lapisan terbendalir gelembung ini mempunyai pasir sebagai bahan lapisan dan mempunyai diameter partikel sebesar 425 sehingga 600μm, dengan ketumpatan 1520kg/m^3, dan mewakili kumpulan B Geldart. Biomass yang digunakan ialah kepingan kayu yang diperolehi daripada sebuah kilang perabot. Lapisan terbendalir mula bergelembung apabila aliran udara melebihi 150kg/hr dan lapisan terbendalir mula terperangkap dalam gas keluaran bila aliran udara melebihi 220kg/hr. Komposisi gas, nilai kalorific rendah, LCV_{PG} dan kecekapan sejuk, η_{cold} ditentukan untuk ketinggian lapisan static, H_s 500mm dan 600mm dengan variasi nisbah penyamaan (ER). Didapati bahawa untuk H_s 500mm maximum η_{cold} adalah 71% pada ER 0.25; untuk H_s 600mm maximum η_{cold} adalah 81%. LCV_{PG} semakin kurang berbanding dengan ER, dan nilai tertinggi ada pada ER rendah. Char mempunyai LCV 21.07MJ/kg, manakala kepingan kayu mempunyai LCV 17.40MJ/kg daripada ujian bomb kalorimeter. Char mempunyai d_p 100μm daripada analisis sieve. Analisis bendalir kondensasi yang dikumpulkan daripada kondenser melalui menunjukkan bahawa phenol adalah komponen utama, yang merupakan satu komponen yang amat cair dalam air, dan boleh meyebabkan pencemaran. Penggunaan satu sistem pembersihan air buangan akan mengurangkan pencemaran. Analisis tenaga

menunjukkan bahawa tenaga yang terbazir adalah 22.98%, dan kebanyakan tenaga ini terkandung dalam kondensasi. Untuk mengurangkan kondensasi dari sistem jumlah biomass yang dibekalkan untuk penggas dihadkan kepada 155kg/hr. Ini mengeluarkan tenaga haba sebanyak 530kW dan daripada ini jumlah tenaga electrik yang dapat dijanakan daripada enjin adalah 172.5kW sahaja. Ini mengakibatkan nisbah belokan turun kepada 1.98 sahaja, berbanding dengan nilai asal iaitu 2.67.

CHARACTERIZATION OF A BUBBLING FLUIDIZED BED BIOMASS GASIFIER

ABSTRACT

The recent increase in fossil fuel prices and worsening effects of global warming has prompted the use of biomass as a source of energy. A bubbling fluidized bed gasifier biomass gasifier (BFBG) was thus selected for energy conversion due to its high thermal output and ability to accept wide variety of fuels. It was designed with an internal diameter of 400mm and has a thermal output of 640kW. It is attached to a gas cleaning and cooling (GCC) that removes particulates and condensates from the system. The BFBG used silica river sand with a mean particle size, of 425 to 600μm and has a density of 1520kg/m^3, which belongs to Geldart group B particles. The biomass used was rubber wood chips, obtained from a saw mill. Bubbling fluidization began once the superficial gas velocity reached 0.24m/s. The gas composition, lower calorific value of producer gas, LCV_{PG} and cold gas efficiency, η_{cold} were then determined for different static bed heights with varying equivalence ratio. It was found that η_{cold} increases with increasing equivalence ratio until an optimum value before decreasing. LCV_{PG} was found to decrease with increasing equivalence ratio. Between equivalence ratios of 0.177 to 0.452, LCV_{PG} was highest at low 0.177, and was lowest at 0.452. Char had a LCV of 23.69MJ/kg, while wood chips had a LCV of 17.40MJ/kg from bomb calorimeter tests. Char had a particle size of 100μm from sieve analysis. The minimum fluidization velocity for char would be six to eight times of sand, thus elutriation of char from BFBG would be unavoidable. This caused the carbon conversion efficiency to be low at 95.40%, with average char collected to be 2.9kg. The average condensates flow rate was found to be of 9.15% of the biomass fed with low biomass feed rate. Analysis of the condensates showed that phenol was the main constituent, which is highly soluble with water and causes pollution. Incorporation of a wastewater treatment plant would be required to reduce contamination. Energy

analysis of the system showed that heat loss was 21.42%. Most of the energy lost was contained in the condensates. To reduce condensate flow rates the maximum biomass feed rate was limited to 155kg/hr, thus the thermal output would be 530kW. From the internal combustion engines the electricity generated would be 172.5kW$_e$. Thus the actual turndown ratio was found to be 1.98, compared to the design case of 2.67.

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The current trend of energy consumption, in which fossil fuel is the main energy provider, has reached a level where other resources must be unearthed to ensure there is a constant supply for utilization. The amount of estimated remaining reserves has led to the urgency of finding a solution. The best example is the sudden increase of economic activity in China, which has raised the nation's energy consumption to a record high. Coal is an abundant source of energy but more efficient energy utilization methods and energy conservation programs should be considered to ensure sustainability. The rise in fuel prices recently has affected economic activity and only worsens the global energy scenario.

With the increasing contribution of fossil fuels to global warming and climate change the Kyoto Protocol that had been introduced in 1997 came into enforcement in 2004. The signing of the Kyoto Protocol by the developed nations forces them to adhere to the low greenhouse gas emission levels, and hopefully curb its effect on global climate. Following this development governments are pursuing more environmental friendly means to produce energy, and in the process lift the heavy dependence on fossil fuel.

Solar, wind and hydropower has long been identified as highly potential alternative and renewable energy resources. Solar energy harnesses the heat from the sun to produce energy and can be generated directly from sun light using a solar cell. Wind energy uses the wind velocity and converts it into electricity by a wind turbine. Such systems are most suitable in areas where the wind speed is high, mostly in

Northern America, Eastern Europe and Africa (Breeze, 2005). Hydropower involves construction of dams to hold large volumes of water with turbines at the discharge to convert the potential energy into electricity.

The last few decades has seen the introduction of waste to generate power, whereby waste is incinerated in a furnace to provide gas to a turbine. These wastes include municipal waste; industrial and chemical products such as car tires, mold runners, plastic products; biomass waste like palm kernel shell, rice husks, wood chips, pellets, etc. The combustion of municipal waste in furnaces to produce steam and generate electricity has reportedly produced pollutants such as dioxins (Breeze, 2005).

These potential environmental impacts makes biomass waste a more preferable option. Klass mentions that the only natural renewable carbon resource that is large enough to be used as a substitute for fossil fuels is biomass. The International Energy Agency (IEA) reports that the energy consumption for renewable energy resources in year 2000 was 13.8% of total energy consumption, of which 79.8% is combustible renewable resource and waste, most of them being biomass. (Klass, 2004)

Advantages of biomass energy utilization include ensuring the sustainability of energy supply in the long term as well as reducing the impact on the environment. Petroleum fuels, natural gas and coal emit carbon dioxide, nitrogen oxides and sulfur dioxides that are classified as greenhouse gases. As biomass energy uses agricultural waste as fuel, it is considered "CO_2 neutral" and emissions of sulfur dioxides and nitrogen oxides are very low, making it a good option as clean fuel for the environment. Converting these waste into energy reduces pollution of the environment, otherwise the biomass waste would be left to rot in a clearing or most of the time subjected to open-burning by farmers to dispose of it. In neighboring Sumatera, Indonesia, large areas of open burning to clear out bushes for development has caused haze hazards in Malaysia, which reached its peak in 2005 with the air pollution index (API) reaching 500. Visibility was very poor while people were having difficulty breathing and some were admitted to hospitals to receive treatment for shortness of breath.

Unlike other renewable energy sources that require costly technology, biomass can generate electricity with the same type of equipment and power plants that now burn fossil fuels (Yan et al, 1997). However low thermal efficiencies have hindered its development and the main challenge now is to develop low cost high efficiency systems.

1.2 Malaysia's Biomass Energy Outlook

In Malaysia a large of portion of biomass utilization is focused on oil palm waste. It is estimated that contribution from biomass to national energy is 90PJ ($90x10^{15}$J) (Koh and Hoi, 2002). The contribution from palm oil waste is 80% while the use of other wastes is rather inefficient. However the biomass energy potential is around 130PJ, which is 5% of the national energy requirement (Koh and Hoi, 2002). Petroleum consists of 93% of the national energy source, and only 0.3% comes from fuel wood (Koh and Hoi, 2003).

Presently there are not much government policies regarding the development and use of biomass resources for power generation and combined heat and power (CHP). The most notable progress came with the Fifth Fuel Policy conceived under the Eight Malaysian Plan in 1998. It enlists renewable energy as the fifth fuel and under this policy it was targeted that renewable energy would supply 5% of the national electricity demand by the year 2005 (Mohamed and Lee, 2006). In 2006 the government has announced the usage of bio-fuels which is a blend of 5% palm oil and 95% diesel fuel in certain vehicles belonging to the ministry (MIDA, 2006).

Despite this development and the potential of biomass energy there are several barriers that limit its commercialization and application in the industry. Financially, as biomass energy projects are capital-intensive, it is difficult to obtain loans from banks as there are no records of experience to rely upon. Bank loan officers also do not have the experience to evaluate the loan for the projects which are backed by performance guarantees. This might be the reason why Energy Service Companies (ESCOs), which are supposedly companies which develop energy projects, have not been successful. Independent Power Producers (IPPs) have set up numerous power plants in the country but no information is available regarding their activities in biomass utilization. The IPPs mainly rely on natural gas fired power plant technologies (M. Zamzam Jaafar et al, 2003).

However the onus is still with the major player of the Malaysian energy market. Currently the power market is monopolized by Tenaga Nasional Berhad (TNB). The company does not promote biomass as fuel in its power plants and there is no indication of it doing so. However, the electricity supply market is in the process of restructuring, and the Ministry of Energy, Communications and Multimedia is responsible for ensuring a level playing field for renewable energy when the need arises (Poh and Kong, 2002).

Overall biomass energy utilization is still in its infant stage in Malaysia although there are abundant potential resources in the country as shown in Table 1.1. It is still undergoing development towards the goal of technology commercialization. Cooperation and commitment from parties involved are needed in other to realize the implementation of biomass energy as a supplementary energy source on national scale.

Table 1.1: Recent renewable energy potential in Malaysia

Renewable Energy Resource	Annual Energy Value (RM Million)
Forest residues	11984
Palm oil biomass	6379
Solar thermal	3023
Mill residues	836
Hydro	506
Solar PV	378
Municipal waste	190
Rice husk	77
Landfill gas	4

Source: Ministry of Energy, Communications, and Multimedia, 2006

The above factors prompted Visdamax Sdn. Bhd., a boiler and kiln dryer manufacturer based in Kulim, to take up the biomass energy project funded by the Malaysian Technology Development Center (MTDC). Universiti Sains Malaysia was engaged in a research capacity to help develop the system, in hope that the demonstration efforts and results pave the way for more experimental work regarding biomass energy.

1.3 Development of Biomass Energy

Many nations have developed biomass energy conversion technologies to provide power. Dooley mentioned that in Japan the government has implemented the New Sun Shine Program, which funds diverse biomass energy projects, from technologies designed for more efficient use of current biomass resources, to basic research designed to genetically engineer microorganisms and new plant species for advanced biomass production. The Japanese government is also funding research for technologies pertaining conversion of biomass into gaseous and liquid fuels and also on biomass combustion technologies. There is also sponsor for research on direct catalytic decomposition of biomass to produce hydrogen (Dooley, 1999).This shows the increase in interest of Japan in utilization of biomass as a renewable energy source. Finland has also utilized biomass gasification to produce electricity in large scale applications. The Lahti power plant is rated to generate 1700GWh of energy (Foster Wheeler, 2005; Nieminen and Kivela, 1998). Mory and Zotter also presented a case study on the Zeltweg power plant in Austria which used circulating fluidized bed gasification (Mory and Zotter, 1998; Granastein, 2002)

1.4 Objective of Project

A bubbling fluidized bed biomass gasifier (BFBG) system was constructed for energy conversion purposes. The objectives of the project would be to:

1. Design a bubbling fluidized bed biomass gasifier
2. Characterize the performance and process of a BFBG system
3. Provide clean producer gas for utilization in an engine.

1.5 Scope of Work

The mass flow rate of air and biomass waste will be measured, varied and monitored to determine the effect it has on the performance of the bubbling fluidized bed gasifier. The resulting air-fuel ratio and equivalence ratio will be determined and compared with results from other researchers. The lower calorific value of the producer gas will be measured to determine the cold gas efficiency of the gasifier. The effect of the equivalence ratio on the lower calorific value, the cold gas efficiency and the gas composition can then be investigated and compared to literature.

The bed height will be varied in order to investigate the effect it has on the performance of the BFBG. Fluidization dynamics is investigated through computational fluid dynamics (CFD) analysis for better understanding of the internal working conditions of the BFBG and will be compared to available literatures regarding fluidization dynamics for relevance.

A mass balance of the system will also be made to check for tar-moisture condensate in the producer gas and the amount of char collected from the cyclone. Analysis on the condensates using high performance liquid chromatograph will be done. An energy analysis of the system will also be carried out.

CHAPTER 2

LITERATURE REVIEW

2.1 Biomass Gasification Process

Agricultural or biomass wastes are leftover organic materials from human activities such as farming, harvesting, foresting or from furniture industries. The chemical composition of the biomass waste varies but basically consists of carbohydrates and lignin. The thermal conversion of biomass waste would eventually produce carbon dioxide and water as the end products. Organic matter then absorbs carbon dioxide from the atmosphere and converts it to carbohydrates through photosynthesis, bringing plants back to soil again. This natural process allows the contribution of carbon dioxide from biomass thermal conversion to be part of the carbon cycle route. The same case does not apply to utilization of fossil fuels, as the carbon does not originate from biomass, the combustion of petroleum products adds more CO_2 to the atmosphere.

Other than combustion, thermal conversion of biomass to generate power can be done through gasification. Gasification produces volatile gases from solid fuels which can be utilized in internal combustion engines or coupled to turbines to generate power. It gives high efficiencies to produce electricity, liquid fuels and chemicals. Integrated gasification combined cycles (IGCC) is by far the most efficient way of generating electricity for both fossil fuels and biomass (Overend, 2000). The implementation of a biomass gasification system can lead to the creation of employment opportunities to local communities where the feedstock is abundant. The inhabitants in these areas, mostly in the country side, would provide the labor supply needed to collect and sort the biomass wastes needed for the gasification system.

Utilizing agricultural waste to generate power via gasification is therefore an alternate option to prevent environmental pollution and replace the over reliance on fossil fuels. Overend stated that gasification provides high efficiency systems, with outstanding environmental performance at reasonable cost (Overend, 2000).

Gasification converts biomass or organic materials to producer gas via partial oxidation. It occurs in three stages and begins with drying, where inherent moisture in the biomass is removed. It is followed by pyrolysis where volatile gases are released. Then finally gasification process takes place, where partial oxidation of residues and volatiles occur.

The producer gas consist mainly of volatiles resulting from pyrolysis, which are carbon monoxide, hydrogen, methane, carbon dioxide, water, nitrogen, some amounts of tar and hydrocarbons. The producer gas can then be used as gaseous fuel in internal combustion engines to generate power, but the inert gases are not reactive, so the benefits of using producer gas is limited to the amount of CO, H_2 and CH_4 that is produced. Producer gas has been reported to have a lower calorific value (LCV) of 4.5-5.0MJ/Nm^3 (Rezaiyan and Cheremisinoff, 2005). Beside from producer gas, a solid by product known as char is produced as well from the gasification process. Char is un-reacted carbon and is high in carbon content.

The various gasifying mediums used are air, oxygen and steam. In some applications a combination of air and steam is used. After initial combustion of the biomass, the flame is shut off with the oxidation medium still flowing through the reactor. This will start a series of chemical reactions that occur in sub-stoichiometric conditions. Basically the chemical reactions that take place in the gasifier are divided into exothermic and endothermic reactions and are listed below (Rezaiyan and Cheremisinoff, 2005).

Exothermic reactions

$C + O_2 \longleftrightarrow CO_2$ (Oxidation)

$2C + O_2 \longleftrightarrow 2CO$ (Partial oxidation)

$C + 2H_2 \longleftrightarrow CH_4$ (Hydro-gasification)

$CO + 3H_2 \longleftrightarrow CH_4 + H_2O$ (CO methanation)

Endothermic reactions

$CO + H_2O \longleftrightarrow CO_2 + H_2$ (water-gas shift)

$C + H_2O \longleftrightarrow CO + H_2$ (water gas reaction)

$C + CO_2 \longleftrightarrow 2CO$ (Boudourd reaction)

The exothermic reactions provide heat to support the endothermic reactions through partial combustion. Eventually a steady state will be reached and the gasifier will maintain its operation at a certain temperature. Researchers have reported varying values of operating temperature, ranging from 600˚C to 900˚C (Gomez et al, 1995) and some up to 1000˚C (Boerirgter et al, 2004).

2.2 Types of Gasifiers

There are basically four major types of gasifiers existing in the industry: downdraft and updraft gasifiers, which are in the fixed bed category; and fluidized bed gasifiers, which consist of bubbling fluidized bed biomass gasifiers (BFBG) and circulating fluidized biomass bed gasifiers (CFBG).

2.2.1 Fixed Bed Gasifiers

Fixed bed gasifiers have a grate at the lower section of the reactor that supports the fuel. Fuel is fed from the top of the reactor and will be stationary on the grate. The grate is movable by an external handle to ensure that the fuel bed is properly reacted. Fixed bed gasifiers are characterized by the direction of flow of the producer gas and can be divided into two categories, the downdraft gasifier and the updraft gasifier. It can be fed with biomass in the form of briquettes or in bulk shapes. However the moisture content needs to be very low in order for the gasification process to occur. A diagram of the downdraft and updraft gasifier is shown in Figure 2.1.

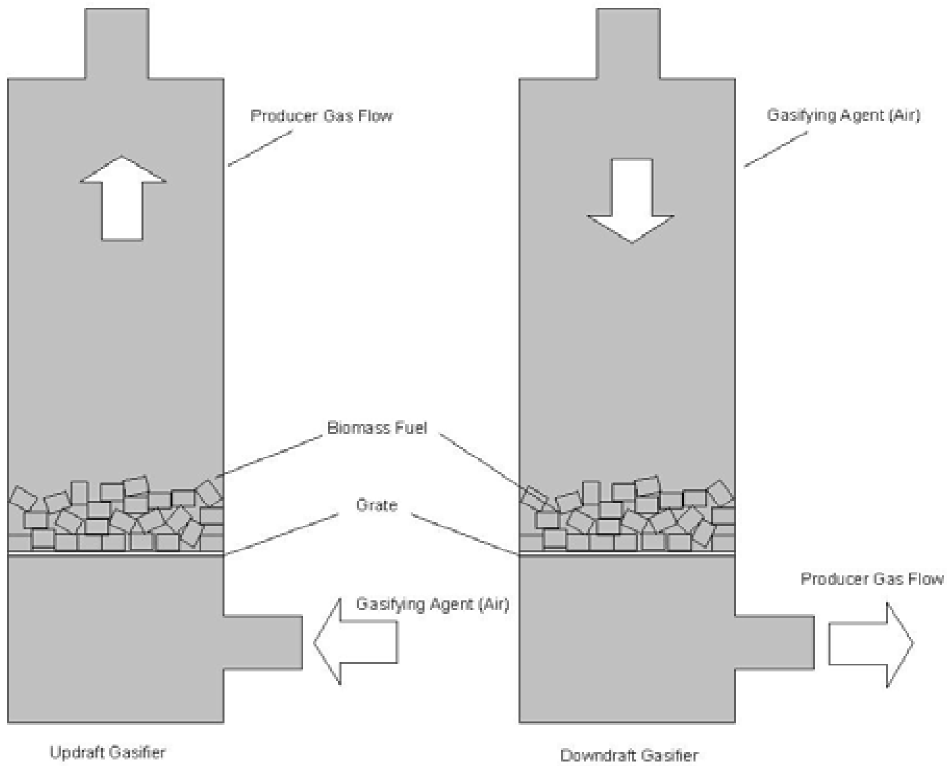

Figure 2.1: Diagram of Updraft and Downdraft Gasifiers

A downdraft gasifier is a co-current flow gasifier, whereby the produced gas flows down the reactor, parallel with the flow of biomass, and exits from the bottom. The gases that flow downward are ignited, leaving charcoal to react with the combustion gases, producing CO and H_2. The advantage of the downdraft gasifier is that it produces low tar content in the producer gas (Rezaiyan and Cheremisinoff, 2005; Warnecke, 2000). In Dasappa’s open top downdraft gasifiers it was found that the tar content in the producer gas was in the range of 50~200mg/Nm^3.(Dasappa et al, 2004). It is suitable for small scale applications. Sridhar et al (2001) have performed experimental work into internal combustion engines running in dual fuel mode with producer gas provided from a downdraft gasifier. An updraft gasifier is a countercurrent flow gasifier where by the producer gas exits at the top of the gasifier. Updraft gasifiers are simple in design and can handle biomass fuels with high ash content.

Despite the simplicity of design and operation of fixed bed gasifiers, fuel channeling can occur in the reactor, and the temperature distribution is not uniform, resulting in local hot spots (Warnecke, 2000).

2.2.2 Fluidized Bed Gasifiers

Fluidized bed gasifiers originated from the concept of fluidized bed combustion. This technology has inert material in the reactor to promote heat transfer efficiency. The inert material alone will not produce volatile gas and serves as a medium to increase the rate of reaction with biomass fuels through interaction with the fluidizing bed material. Some examples of inert bed material used are sand and alumina. The bed of material is subjected to upward forces of a fluid, normally gases, which will act against its weight and eventually cause the bed particles to have fluid-like motions, moving abruptly due to bubbles formed within the bed.

The fluidized bed gasifier has an air distribution plate and has two functions. It serves as a support to the bed material and also has nozzles or air caps that allow air to flow into the reactor. Below the air distribution plate is the plenum zone where initial combustion is performed for gasifier start-up purposes. The by products of combustion flow through the air distribution plate and into the gasifier, heating up the bed material and the reactor walls until a certain temperature is reached. Fuel feeding will commence once the required temperature is reached and the initial combustion process is halted.

Fluidized bed gasifiers are more flexible in the selection of fuel type. It can gasify various types of biomass without much difficulty and has high carbon conversion rates as well as high heat transfer rates (Gomez et al, 1995; Murphy, 2001; Warnecke, 2000) which enables this system to handle a larger quantity and lower quality of fuels. These gasifiers handle smaller fuel particle size compared to the fixed bed gasifiers. A BFBG utilizes the minimum fluidization velocity of the bed material to achieve fluidization state. Bubbles are formed within the bed and move upwards toward its transport disengaging height. The bubbles carry along with it a small portion of bed material in a portion called 'wake', and when it reaches the maximum or transport disengaging height the bubbles along with the carried material burst through the surface of the bed and falls downward the gasifier by gravity. When it's free fall gravity is balanced by the force of the minimum fluidization velocity, the bed material flow upwards again along with new bubbles formed. This is a cycle that will happen throughout the process, thus increasing the mixing efficiency of the bed material, fuel particles and gasifying agent. This will in turn increase the heat transfer mechanism. Also due to the fluidization the gasifier is in a 'boiling' state, the temperature would be uniform in the reactor (Cuenca and Anthony, 1995; Warnecke, 2000).

A CFBG uses a velocity higher than the minimum fluidization velocity, and requires a cyclone separator to transport the elutriated bed material back to the gasifier. This type of gasifier increases the rate of gasification, has a high conversion rate of tar and is suitable for large scale power generations. A CFBG system consists of a gasifier, a cyclone to separate the circulating bed material from the gas, and a return pipe for circulating the entrained bed material to the bottom part of the gasifier (Manjunath et al, 2004; Warnecke,2000; Peacocke and Bridgwater, 2000). The gas velocity is high enough so that the bed particles are conveyed out from the reactor into the cyclone.

The process control mechanism of CFBG is more complex compared to its bubbling fluidized bed counterpart. However, due to the higher flow rate of air through the CFBG, it is capable of producing higher amounts of energy compared to the bubbling fluidized bed. The bubbling fluidized bed's power output is limited by its minimum fluidization velocity to maintain the bed in a bubbling fluidization state (Maniatis, 2005). Figure 2.2 shows the diagram of the BFBG and CFBG. Table 2.1 shows a comparison of the characteristics the four different gasifiers discussed.

Table 2.1: Comparison of the Four Gasifiers (Warnecke, 2000)

	Downdraft	Updraft	BFBG	CFBG
Thermal Output	Low	Low	High	Higher
Scale-up Potential	Low	Low	High	High
Fluidization Agent Velocity	N.A.	N.A.	Low	High
Quality of Gas	High	Low	Low	Low

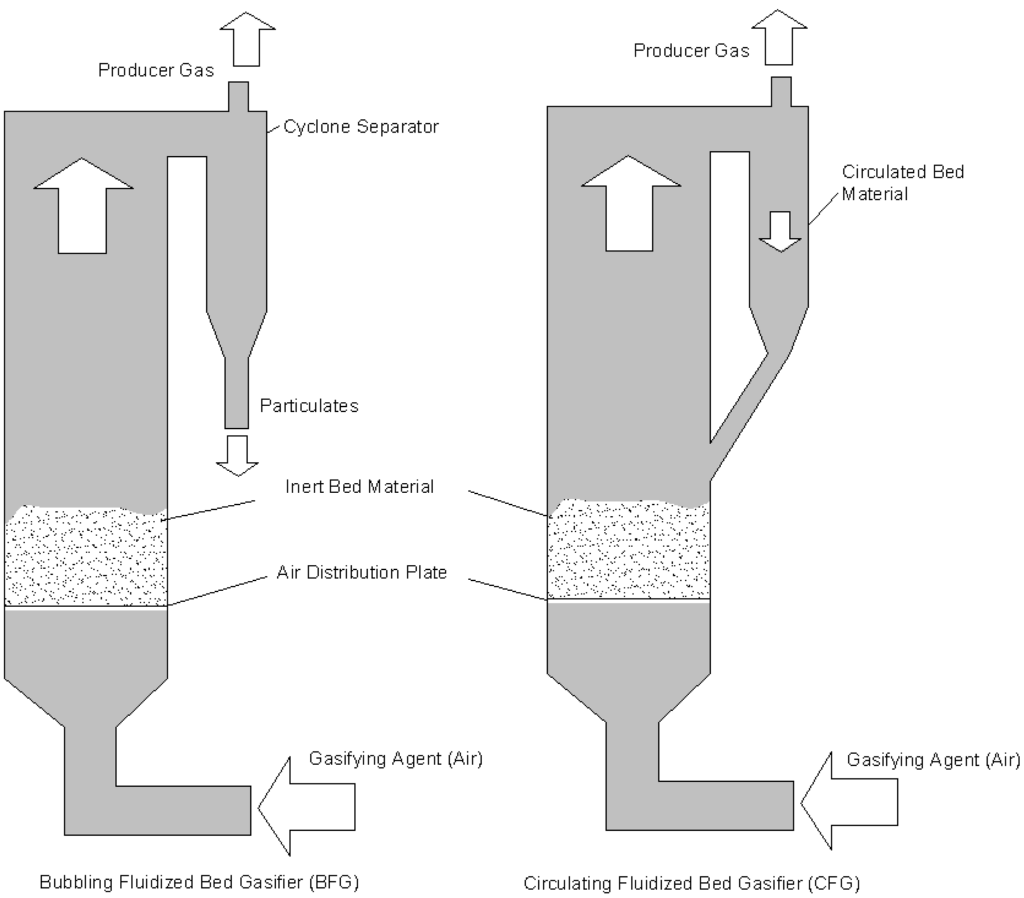

Figure 2.2: Diagram of Bubbling and Circulating Fluidized Bed Gasifiers

2.3 Industrial Applications and Experiences on Fluidized Bed Biomass Gasifiers

Commercial scale fluidized bed biomass gasifiers have been built in Finland by Foster Wheeler. The Lahti power plant built in Finland is an integration of a biomass gasifier to a coal boiler. It has been in operation since March 1998 and has maintained stable operation for the main boiler, gas burner and also the gasifier itself. The maximum power capacity is $167MW_e$ and $240MW_{th}$ for district heat production. The circulating fluidized bed biomass gasifier (CFBG) produces up to 70MWth that is co-fired with coal in the boiler, which gave reduced CO_2, SO_2 and NO_x emissions (Raskin et al, 1998). The heating value of gas produced is very low especially when the moisture content of biomass is high. When the moisture content was 50% the heating value was only 2.2MJ/kg (Nieminen and Kivela, 1998). The energy that the plant has produced up to the year 2002 is 1700GWh. The average operating temperatures were between 800˚C-1000˚C. In this system the gas is used back to preheat the fluidization air to 270°C. The design issues faced by the plant include the fuel feeding method into the gasifier and also the bed material used. Bed materials and additives used were sand and limestone (Raskin et al, 1998; Wilén et al, 2004; Hiltunen, 2005).

The Zeltweg power plant is part of the EU-Demonstration Project, BioCoComb, with a capacity of generating 137MWe stationed in Austria and is surrounded by sawmills (Granastein, 2002). It has a CFBG with fine sand used as bed material. Wood chips and bark sawdust were used as biomass feedstock, and the hydrodynamics of the fluidized bed limits the biomass particles to a maximum size of 30x30x100mm. Although a separator was used it was still unavoidable and oversized particles were fed as well. The CFBG provides low quality gas to be co-fired with coal in a boiler and provides 10MW of thermal input. This replaces 3% of coal utilized for firing the boiler, realizing CO_2 emission reduction. No gas cleaning is required for the gas stream as it is passed to the boiler at high temperatures, 850°C, whereby no hydrocarbons are condensable (Mory and Zotter, 1998). The diagram of the gasifier and its connection to the boiler is shown in Figure 2.3. Handling of bed material during the process was incorporated. The system has a water-cooled screw conveyor at the bottom of the gasifier and was used to handle the discharge of bed and non-combustible materials to avoid large pressure drop in the gasifier. Ash is transported with the gas stream out of the gasifier. Sand was not fed into the bed since the biomass used, bark already contained certain amount of sand.

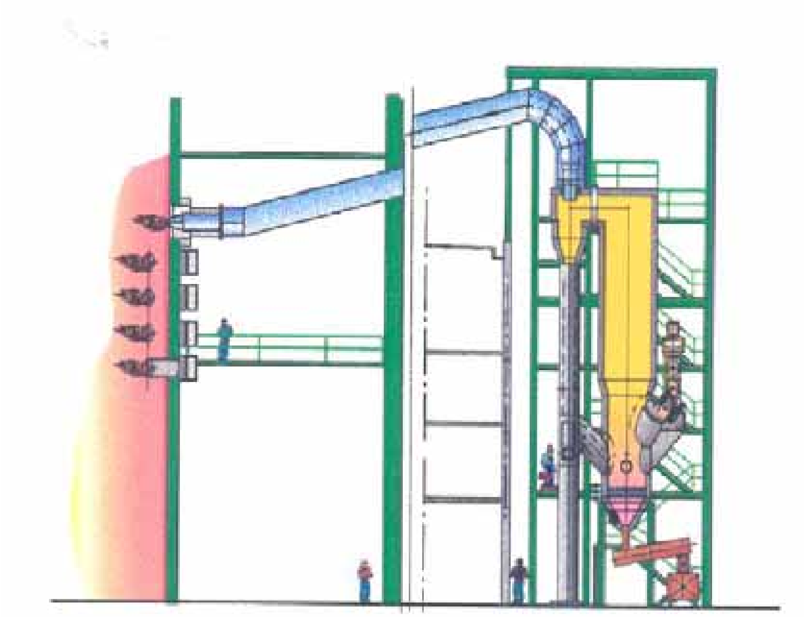

Figure 2.3: BioCoComb Gasifier and its connection to the boiler, Zeltweg, Austria (Granastein, 2002).

Fluidized bed biomass gasification system has been used to cater cooking gas. Such implementation is found in rural areas of China (Smeenk et al, 2005). The fluidized bed gasifier in this project has the blower directly supplying air to the air distributor, and at the bottom there is a slide gate to collect bed material that passed through distribution plate and flow to the bottom. The project was based in Leizhuang village, Henan Province. The schematic of the system is shown in Figure 2.4. The producer gas calorific value was 5MJ/Nm^3, and the reactor is operated one to two hours per day to supply producer gas to 40 households. The gas was stored in a gas holder. It was reported the gas composition changes over time in the gas holder. Gas analysis has reported that carbon monoxide increases while hydrogen decreases.

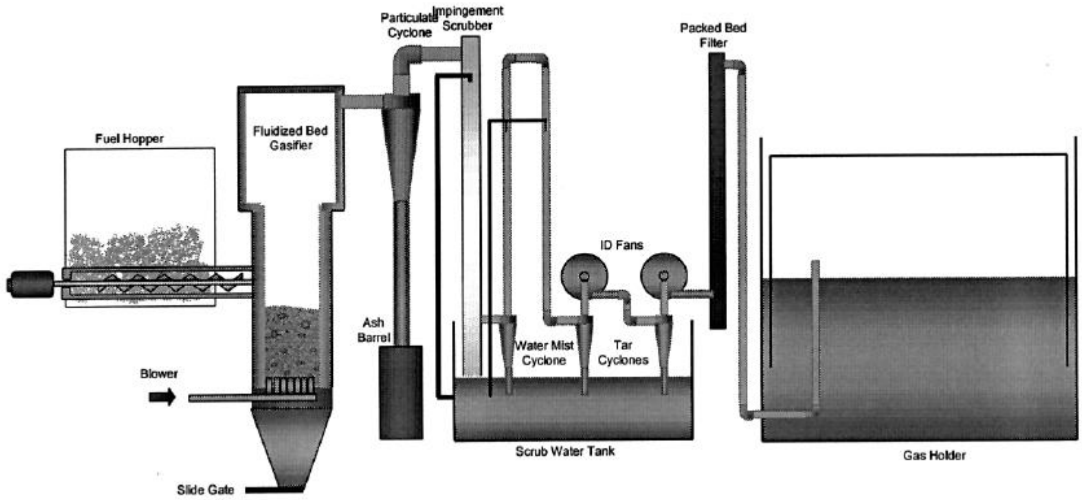

Figure 2.4: Schematic of the gasifier system in the Leizhuang Village (Smeenk et al, 2005)

Pressurized fluidized bed gasifiers can be utilized to drive a gas turbine with woody biomass as fuel (Kawasaki Heavy Industries, 2004). The gasification process occurs at a temperature of 650˚C. The generated gas contains combustible gas and tar and is directed towards a gas turbine combustor while maintaining the temperature and pressure in order to avoid tar troubles that could occur from solidification and liquefaction by cooling.

Madsen and Christensen presented results on the Enviropower Pilot Plant in Tampere, Finland (Madsen and Christensen, 2002) which has a pressurized BFBG with a nominal input of 15MJ/s and operates up 30bar and temperatures up to 1100˚C. Tests with straw were carried out in 1994 using 20tonnes of Danish wheat straw and 120tonnes of Colombian coal. The straw particles size range between 30 to 50mm. A coal-straw ratio of 75/25% was maintained and the bed temperature rose. Bed instability was observed and at an average bed temperature of 975˚C the temperature of the lower part of the bed fell rapidly indicating bed sintering. During operation

Madsen noted that ash sintering occurs for freeboard temperatures above 850˚C, followed by a phenomenon where the lower part of the bed suffers rapid bed temperature decrease. Results have shown that combined straw-coal gasification process reduces tar content compared to straw gasification only.

The VTT plant in Helsinki (Madsen and Christensen, 2002) consists of a fluidized bed gasifier with a capacity of 80kg/hr and operating pressure between 3 to 10bar. It has an inner diameter of 150mm, 250mm inner freeboard diameter, a bed height of 1.2m and a freeboard height of 3.0m. A total of 4600kg of straw and 1350kg of coal were gasified. Aluminum oxide and dolomite were used as bed material. The gasification of straw only in the fluidized-bed gasifier is difficult due to sintering. If the operating temperature were lowered high amounts of tar will be present in the gas. When coal was added there were no sintering problems as in the Tampere plant, gasification could be operated with a straw ratio of 50% weight at 940˚C without sintering. Severe sintering was observed with 25% straw at 30˚C-40˚C higher gasification temperature.

Coal and catalyst such as dolomite are not added in our study. The sintering and bed agglomeration problems would be avoided by maintaining the bed temperature below 900°C.

2.4 Performance Studies of Fluidized Bed Gasifiers

Smeenk and Brown (2005) discussed the results of atmospheric fluidized bed gasification systems using switch grass. The project involved a bubbling fluidized bed reactor with 460mm in diameter and 2440mm high built from mild steel, with one inch of refractory liner that protects the steel and insulates against heat loss. A nominal bed height of 600mm is used. The material feeding system incorporates a screw conveyor and a rotary airlock. It has a purge air at the feed end to prevent backflow of producer gases back into the feeding system. Gas analysis was done using a gas chromatograph (GC) and a Fourier transform infrared spectrometer (FTIR). The obtained calorific value of for producer gas was 5.22MJ/Nm^3.

A study on a fluidized bed in Brazil (Sanchez and Lora, 1994) mentioned the influence of the bed height on the gasification efficiency, whereby a static bed height of 370-480mm corresponds to an expanded bed height of 600-710mm. The outer diameter of the gasifier is 250mm and 200mm for internal diameter, and has a height of 2000mm. The brick lining is 25mm thick. Also it was observed that a bed temperature increase from 740°C to 850°C causes a 3 to 5 fold reduction of tar content. However the ash content of some biomass types causes low melting points, and therefore it was necessary to keep the bed temperature between 600°C-800°C to avoid agglomeration and defluidization. Fine fuel particles are unsuitable for fluidized bed gasifiers as well. Fine granulometry biomass, such as bagasse, lead to low efficiency values of the gasifier. This is caused by intensive elutriation and can be mitigated by increasing the bed height. Also the inconsistency of the fibrous biomass feeder flow capacity affects the performance of the gasifier adversely.

Performance of fluidized bed gasifiers can be controlled by a parameter known as air factor or equivalence ratio (ER). A 280kW$_{th}$ fluidized bed gasifier fueled with bagasse pellets was studied by Gomez et al (Gomez et al, 1999). The gasifier had a diameter of 417mm and a minimum bed height of 686mm. Air and fuel flow rate was 97.44Nm^3/hr and 104.46kg/hr respectively, giving an air-to-fuel ratio of 0.9328. When the ER was increased the bed temperature increases, while gas sensible heat loss and heat loss to the environment also increased. Heat loss due to unconverted carbon or char decreases. Gasifier cold efficiency was highest at 29.2% when the air factor is 0.22. The highest gas to fuel ratio obtained was also at this value of air factor, yielding 1.34kg of gas per kg of fuel showing the highest carbon conversion rate.

Another study on fluidized bed gasifiers (Cao et al, 2006) showed that the maximum cold gas efficiency was obtained at an air-to-wood ratio of 2.557Nm^3/kg. The heating value of gas was 4.911MJ/Nm^3 giving a cold gas efficiency of 58%, and produced 3.266Nm^3 of gas per kg of wood. When the air-to-wood ratio was increased to 3.155 Nm^3/kg the LCV decreased to 3.072MJ/m^3 with a cold gas efficiency of only 39.1%. The fluidized bed used sand as bed material with an average size of 0.11mm and a density of approximately 1470kg/m^3. Gas compositions and light hydrocarbons were determined through a gas chromatograph with thermocouple detectors (TCD) and flame ionization detectors (FID), using Porapak Q, Porapak R and a 5A molecular sieve column. The maximum concentration of fuel gas was reported to be 9.27%, 9.25%, and 4.21% for H_2, CO and CH_4 respectively, which gave a heating value of 3.67MJ/m^3. The maximum carbon efficiency was 87.1%,

It is apparent from the two studies above that the air flow rate and biomass flow rate determines the performance of the system. The two parameters are presented by the ER and the optimum value differs with different gasifiers. It is the interest of this study to obtain the optimum ER where the gasifier operates at maximum efficiency.

The effect of different types of gasifying agents on the product output of a BFBG was investigated by Gil et al (1999). Air, steam and O_2-steam mixtures were used in the study. It was found that the use of steam increased the production of hydrogen and gave a maximum concentration in the range of 53 to 54%. Oxygen-steam mixture decreased the hydrogen production, but gave maximum concentrations of carbon monoxide, in the range of 43 to 47%. The lower calorific value (LCV) was higher for steam and O_2-steam mixtures, in the range of 12.5 to 13.3MJ/m^3 compared to air gasification, with the values being in the range of 4.5 to 6.5MJ/m^3. However, the usage of steam and oxygen-steam mixtures increased the tar yield. Char yield was also higher compared to air gasification, indicating inefficient conversion of char into producer gas.

Another study on BFBG was concentrated on generation and conversion of fine carbonaceous particles (Miccio et al, 1999). The fuel or biomass particles are fragmented once it comes in contact with the bed material. Mechanical abrasion and attrition reduces the fragmented particles further. Finally fines are generated through percolative formation, caused by internal porosity of the char particles. In biomass gasification, percolative formation plays an important in fines generation compared to coal as the char porosity is larger than that of coal (Miccio et al, 1999), giving biomass char higher reactivity and a shorter reaction time. The BFBG used had a bed zone ID of 108mm, a freeboard ID of 125mm and a total height of 2.8m. Particles collected from the freeboard section and reactor exit were examined to have large pores and irregular shapes, similar to fibrous structure of biomass fuel. At a reactor height of 1.2m the particles have an average size of 300μm, and it reduces to 200μm above 1.2m. Overall the size of particles decreases with increasing bed height. This showed that carbon conversion efficiencies increased with reactor height and ER, mostly through percolative fragmentation since no bed material is present above the bed section. CO_2, CH_4 and H_2 concentration was found to increase slightly with reactor height, while CO maintain fairly constant.

The influence of operating temperature on the dense phase properties of a bubbling fluidized bed was investigated by Formisani and co workers (2002). It listed the various parameters that were affected by an elevated temperature ranging from 200 to 800˚C. The dense phase voidage which is the void fraction of the solid phase in the bed during operation increases with increasing temperature, while the minimum fluidization velocity decreases till a minimum level before increasing back again. The increase in these two parameters showed that there is an increase in inter-particle forces, which give the solid the ability to form a progressively looser fixed structure. The increase in the minimum fluidization velocity is produced by a variation in dense phase voidage, density and viscosity of the fluidizing gas.

2.5 Process Issues

2.5.1 Tar

Tar is defined as a complex mixture of condensable hydrocarbons by Biomass Technology Group (BTG, 2004), while Dayton (Dayton, 2002) mentioned that tars are condensable fractions of the gasification products and consists mostly of polycyclic aromatic hydrocarbons (PAH), including benzene. Operational issues associated with tar during operation of fluidized bed gasifiers were highlighted as well (Van Paasen et al, 2004). It produced “tar-water mixtures” which were difficult to handle besides causing fouling and plugging in the system. In a separate system developed by Rabou at the Energy Research Centre of Netherlands (Rabou, 2005) such mixtures were collected from an electrostatic precipitator (ESP) and was injected into a screw feeder to recycle the tar back into the CFBG for conversion. The operating temperature of the CFBG was difficult to maintain following this action.

For thermal cracking of tar the residence time of gas in the reactor played an important role in ensuring the tar content was lowered. If the residence time is 1.3s the temperature has to be 900°C; if it is 4s the temperature can be maintained at 850°C (Van Paasen and Kiel, 2004). Rabou however mentioned that the reactivity differs according to the tar composition (Rabou, 2005).

Catalytic cracking showed good tar conversion as reported by Zhang et al (2004) but the cost of replenishing the catalyst, dolomite in the fluidized bed would not be economical and disposal of the spent catalyst presents another issue (Corella et al, 2006). The system in the Battelle Columbus Laboratory (Craig and Mann, 1996) used a fluidized bed reactor with char from the gasifier as bed material operating at a temperature of 900°C to convert the tar and uses steam as gasification agent.

Cao (Cao et al, 2006) demonstrated that injecting secondary air with assisting fuel gas into the freeboard region was able to decompose tar components. The re-circulated fuel gas would be combusted by secondary air to increase the freeboard temperature. Tar content was significantly reduced when freeboard temperature was above 850˚C while the bed temperature was only 650˚C. The injection of secondary air did not introduce additional nitrogen that would dilute the gas and decrease its calorific value, which was reported to be about 5MJ/m^3 at an air-fuel ratio of 2.4Nm^3/kg and assisting fuel gas-biomass ratio of 0.475Nm^3/kg. Injection of steam and carbon dioxide into the freeboard, aimed to promote production of hydrogen and carbon monoxide respectively, caused the temperature to drop as it initiates endothermic reactions. This drop in temperature would increase the tar content and would not be feasible.

A modeling work was done to determine experimental conditions that would yield clean producer gas from fluidized bed gasifiers (Corella et al, 2006). The authors targeted 2g/m^3 as the limit for the tar content of gases, as only below this limit the coke formation on catalysts surface can be removed through gasification. The biomass used was pine wood chips with particle size of 1.0 to 4.0mm. This species of wood contained low potassium and sodium content (Corella et al, 2006). The bed material consists of 80% silica sand and 20% calcined dolomite, a type of catalyst that converts tar. The flow used inside the gasifier was modelled to be piston or slugging flow, as bubbling and channeling flow would cause high tar contents. The parameters varied were secondary air flow rate and the position of injection. When the secondary air flow was 10 to 30% of the total air flow tar content was below 2g/m^3, with the bed temperature at 860-905˚C and the dilute zone at 925-1030˚C. However as the secondary air flow was increased further the primary air flow decreases, causing the bed temperature to decrease and increase the tar content. The tar content increased when the injection point height was increased since there is not enough residence time for the tar to react.

2.5.2 Gas Cleaning Methods

The producer gas from the fluidized bed reactor will be laden with particulates, moisture and tar which needs to be removed for certain applications. Current gas clean-up technologies used such as in coal power plants or cement plants are able to perform this duty. Cyclones are the most common particulate collection devices with removal efficiencies of more than 90% for mean particle sizes of more than 10μm. Fabric filters can be used to remove particles with diameter less than 10μm. Wet ESP have the highest removal efficiencies and can operate at high temperatures of 700°C and are meant to collect aerosols, which has a mean particle size of 0.1 to 1.0μm (Rezaiyan and Cheremisinoff, 2005). An ESP is a device that uses electrical principles to remove particles by charging them when they pass through a corona or a flow region of gaseous ions. The electrical system requires converting industrial alternating currents to pulsating direct currents at high voltages, ranging from 20kV to 100kV as required (Rezaiyan and Cheremisinoff, 2005). This method was not considered for application in this project due to its safety risks.

Some experimental work has been done to cater gas cleaning for application of producer gas in internal combustion (IC) engines. As the producer gas needs to have particle content lower than 50mg/m^3 and tar content lower than 100mg/m^3 for IC engine applications (Hasler and Nusshaumer, 1999; Rezaiyan and Cheremisinoff, 2005), several technologies are available to reduce particle and tar content. High particle removal efficiencies were obtained from wet ESP, rotary atomizers and sand bed filters. Fabric filters did not perform well and actually increased the tar content at of the gas at the outlet, possibly due to adsorption from polymerized tar on the filter. Basically high particle reduction efficiencies utilizing current available technologies could be