UNIVERSITI MALAYSIA SARAWAK
UNIMAS

Faculty of Engineering

Performance Evaluation of Biomass Gasification Systems

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Master of Engineering
(Mechanical)
2009

ACKNOWLEDGEMENTS

First of all, I would like to give thanks to God for the opportunity to work on this project. I would like to thank my thesis supervisor, Prof Ir. Dr Law Puong Ling for his unceasing willingness to provide guidance, support and heart felt encouragement. I would also want to thank to my co-supervisor, Ir. Assoc Prof Dr Andrew Ragai Henry Rigit. Special thanks are extended to Assoc Prof Dr Awangku Abdul Rahman Pgn Hj Yusof and Prof Dr Kopli Bujang for their generosity in giving advice and guidance.

A special thank and appreciation are extended to Mr. Wong Chung Tiew, the Managing Director of Prima Natural Resources and Manufacturing Sdn. Bhd. I sincerely appreciate his technical advice, fabrication and modification of the biomass-to-fuel gas (B2F) and biomass-to-energy (B2E) prototypes, and invaluable insights throughout the entire period of this research. I would like to give thanks to the staff and technicians of Faculty of Engineering and Faculty of Resource Science and Technology of UNIMAS, MARDI (Sarawak) and Saratok Palm Oil Mill Sdn. Bhd. for their sincere help in giving guidance and support while conducting laboratory analysis work.

Finally, gratitude of thanksgiving is extended to my beloved family and friends for their fervent prayer and support during the entire course of this research.

ABSTRACT

This research project was carried out in three phases; Phase I - Determination of biomass moisture content and calorific values, Phase II – Assessment and field tests on existing mini-scaled biomass-to-fuel gas (B2F) conversion system, and Phase III - Performance evaluation of biomass-to-energy (B2E) conversion system. Quantification of moisture content and heating values of various types of locally available biomass included palm oil shell, oil palm empty fruit bunch, paddy straw, sago bark and wood chips in addition to preliminary assessment of the operational parameters of the existing mini-sized B2F conversion system. Moisture content analysis showed that paddy straw contained as high as 97.75%, followed by oil palm empty fruit bunch 95.34%, sago bark 96.05%, palm oil shell 95.28%, and wood chips waste 11.61%. In terms of calorific values, dry state wood chips recorded highest heating value of approximately 22.41 MJ/kg, followed by palm oil shell 21.40 MJ/kg, sago bark 19.56 MJ/kg, palm oil empty fruit bunch 17.82 MJ/kg, and paddy straw 15.33 MJ/kg. Assessment on the operational parameters of the existing mini-sized B2F conversion system included a) operational parameters, b) determination of the compositions of "After Filtered Residual Liquid or AFRL", c) determination of the compositions of raw combustible fuel gases produced using wood chips and coal as feedstock, d) nearby incremental levels of carbon monoxide (CO), combustibles gas, total suspended particulates during operation, and e) strengths and weaknesses of B2F. The B2F and B2E were compared against each other in terms of operational parameters and performances. Some of the key operational parameters had been determined; exergy destroyed ($X_{destroyed}$), overall efficiency of B2E, Second Law Efficiency of B2E, air flow rate, and effects of air flow rate on temperature distribution in combustible fuel gas-to-heat energy conversion chamber. Maximum heat generated by wood chips from the combustion chamber was measured 17, 500 kJ/kg. The overall performance of B2E was found to be approximately 90.48%, exergy (useful energy) destroyed at 24.13kJ/s, Second Law Efficiency of 74.78% at air flow rate of 0.0558m^3/s and at average feedstock (palm oil shell) consumption rate of 16 kg/hour, while the ambient air acted as oxidation agent that produced output temperatures of 398°C were observed.

ABSTRAK

Projek penyelidikan ini telah dijalankan dalam tiga fasa; Fasa I- Menentukan kelembapan biomas dan nilai kalorinya, Fasa II – Penilaian dan tapak pengajian terhadap mini saiz penukar biomas-kepada-pembakaran gas (B2F), dan Fasa III - Penilaian prestasi terhadap penukar biomas-kepada-tenaga (B2E). Kuantifikasi terhadap kandungan lembapan dan nilai-nilai pemanasan juga dilaksanakan terhadap pelbagai biomas seperti kulit minyak sawit, tandan kosong kelapa sawit, jerami padi, kulit kayu sagu dan cip kayu, selain daripada penilaian awal parameter operasi mini saiz penukar biomas-kepada-pembakaran gas (B2F). Keputusan menunjukkan jerami padi mengandungi kandungan kelembapan yang tertinggi, iaitu 97.75%, sambut tanda kosong kelapa sawit 95.34%, kulit kayu sagu 96.05%, kulit minyak sawit 95.28%, manakala cip kayu bahan buangan 11.61%. Dalam nilai kalori, cip kayu kering mencatatkan nilai yang tertinggi, iaitu kira-kira 22.41 MJ/kg, diikuti oleh kulit minyak minyak sawit 21.40 MJ/kg, kulit kayu sagu 19.56 MJ/kg, tandan kosong minyak sawit 17.82 MJ/kg, dan jerami padi 15.33 MJ/kg. Penilaian parameter operasi terhadap mini saiz penukar biomas-kepada-pembakaran gas (B2F) merangkumi a) parameter operasi, b) menentukan komposisi “Cecair yang ditapiskan atau ABRL”, c) menentukan komposisi bahan api mudah terbakar yang mentah yang dihasilkan dengan menggunakan cip kayu dan arang batu sebagai stok suapan, d) menentukan tahap peringkat terhadap CO yang berdekatan, gas bahan api, jumlah particulates berapung semasa operasi, dan e) perbandingan. B2F dan B2E penukaran sistem dibandingkan dalam aspek operasi parameter. Operasi parameter telah ditentukan termasuk; exergy yang dirosakkan ($X_{destroyed}$), prestasi keseluruhan bagi B2E penukaran sistem, hukum kedua kecekapan bagi B2E penukaran sistem, kadar aliran udara, dan kesan kadar aliran udara terhadap suhu taburan di bilik penukaran bahan api kepada tenaga haba. Prestasi keseluruhan bagi B2E penukaran system merekodkan kira-kira 90.48%, disertai dengan exergy yang dirosakkan sebanyak 24.13kJ/s, hukum kedua kecekapan dengan 74.78% pada kadar aliran 0.0558m^3/s, purata sebanyak 16 kg/jam untuk pembakaran bahan kulit minyak sawit, dengan udara sebagai agen untuk oksidasion pada suhu 398°C.

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C - Specific heat, kJ/Kg.K

d - Diameter, m

f - Formation of the compound form

G - Total Gibbs function, H – TS, kJ

g - Gravitational, m/s^2

H - Total enthalpy, U + PV, kJ

HHV - Higher heating value, kJ/kmol fuel

h - Specific enthalpy, u + Pv, kJ/kg

h_o - Specific enthalpy at the dead state, kJ/kg

I - Irreversibility

i - Specific irreversibility, kJ/kg

k_e - Specific kinetic energy, kJ/kg

LVH - Low heating value, kJ/kmol fuel

m - Mass, kg

P - Pressure, kPa

P_o - Surroundings pressure, kPa

pe - Specific potential energy, kJ/kg

Q - Total heat transfer, kJ

$\dot{Q}$ - Heat transfer rate, kW

Q_k - Heat transfer through the boundary at temperature T_k at Location k

S - Total entropy, kJ/K

S_o - Specific entropy at dead state, kJ/K.kg

T - Temperature, ^{o}C or K

T_k - Temperature at location k

T_o - Surroundings temperature, ^{o}C or K

t - Time, s

X_{ke} - Exergy of kinetic energy, kJ/kg

X_{pe} - Exergy of potential energy, kJ/kg

U - Total internal energy, kJ

U_o - Specific internal energy at the dead state, kJ/kg

u - Specific internal energy, kJ/kg

V - Velocity, m/s^{1}

V_o - Specific volume at the dead state, m^{3}/kg

v - Specific volume, m^{3}/kg

W - Total work, kJ

$\dot{W}$ - Power, kW

$W_{rev,\ in}$ - Reversible work input, kJ

$W_{rev,\ out}$ - Reversible work output, kJ

W_{surr} - Surroundings work, kJ

W_u - Useful work, kJ

$W_{u,\ in}$ - Useful work input, kJ

$W_{u,\ out}$ - Useful work output, kJ

X_{heat} - Exergy transfer by heat, kJ

$\dot{X}_{mass}$ - Exergy transfer by mass flowrate, kJ/kg.s

X_{pv} - Exergy of flow work, kJ/kg

z - Elevation of the system relative to a reference level in the environment

Greek Letters

Δ - Finite change in quantity

φ - Stream availability, kJ/kg

η_{II} - Second law efficiency, %

Subscripts

ch - Chemical

el - Elements in the compound

gen - Generation

in - Input

out - Output

ph - Physical

rev - Reversible

surr - Surroundings

sys - System

0 - Dead state

1 - Initial or inlet state

2, 3 - Final or exit state

Superscripts

$\dot{}$ (dot) - Quantity per unit time

$\bar{}$ (bar) - Quantity per unit mole

^{o} (circle) - Standard reference state

CHAPTER 1

INTRODUCTION

1.1 Potential Renewable Energy from Biomass in Malaysia

For the past 40 years or so, Malaysia palm oil industry had grown tremendously and today Malaysia is the world's largest producer and exporter of palm oil and its products. In 2004 alone, there were 380 palm oil mills processing approximately 70 million tons of fresh fruit bunch (FFB) producing 13.98 million tons of crude palm oil (CPO) and 3.7 million tons of palm kernel (Ma & Yusof, 2005). In the first quarter of 2006, CPO production had reached 3.2 million tons, which exceeded the forecast by approximately 4% (MPOB, 2006). It was also forecasted that the total CPO production in 2006 would reach 15.1 million tons, which would generate an income of RM21.5 billion (based on an annual average local price of RM1,423/ton in Peninsular Malaysia (Ma & Yusof, 2005).

This inadvertently means an increase in the co-products or biomass of the palm oil industry. These co-products constitute fronds, trunks, empty fruit bunch (EFB), palm fiber and shell which are not fully utilized and commercially exploited. According to Ma and Yusof (2005), currently the most exploited co-products are the fibers and shells which are used as boiler fuels to produce steam and electricity for palm oil and kernel production (MPOB, 2004). However, EFB constitutes the largest biomass (approximately 20% of the total) generated by this industry, contributing to about 16.1 million tons in 2004, which had only been utilized to a very limited extent (Ma & Yusof, 2005). Based on preliminary study, those bio-wastes can be converted to energy by simple gasification process, i.e. to produce combustible gases (SIRIM, 2004 & 2006). Assuming a conversion efficiency of 50% of the EFB total mass to fuel gas using gasification technology, this means 8.05 million tons of EFB can be converted to fuel or combustible gases. If the calorific value of dry EFB is 18,883kJ/kg, this means that the total heat energy obtainable from EFB in 2004 would be 152×10^{12} kJ. This could save palm oil industry hundreds of millions of Ringgit per annum on diesel expenses to produce the same amount of heat for palm oil processing.

One of the most important cash crops in South East Asia is the sago palm. In Malaysia, approximately 90% of the sago starch is produced from the State of Sarawak. Recent development in sago starch research leads to a total of over 60,000 hectares (ha) being cultivated with sago palm. There are over 30 large sago mills operating in the state contributing to an annual export of 61,000 tones of sago starch (DOSM, 2002). Sago palm is well known to generate a total of approximately 25 tons of starch per hectare per year; the highest starch producer in the world (Ishizaki, 1997). Sago logs typically weigh within the range of 100-160 kg per log (standard length of 4 ft or 1.22m), the average being 130 kg per log. The bark constitutes approximately 20% (or 26kg) the weight of each log. At an average consumption rate of 1,000 logs/day, a total of 31.2 tons of bark wastes are produced everyday from each of the sago mills. Daily sago starch production is about 24 tons or equivalent to 20 kg (15%) of starch/log (Bujang *et al.*, 1996). The bark is disposed off by burning, and since up till now, there is no clear new technology that can be adopted for alternative sago bark utilisation.

1.2 Biomass Energy through Gasification

Biomass energy can be categorized as a source of renewable energy which can contribute to long-term energy supply, reduce global atmosphere emissions, meet specific energy service needs, creates employment opportunity and welfare for the local communities. It is estimated that biomass contributes about 14% of the world's energy (Wereko-Brobby CY & Hagan EB, 1996).

To date, various types of biomass gasifiers are available commercially such as updraft, downdraft, cross-draft, fluidized-bed design features and others (FAO, 1986). The specific design of a biomass gasifier can be affected by the properties of the specific biomass feedstock such as energy contents, moisture contents, ash contents, chemical composition, size distribution, bulk density, charring properties, and volatile matters (FAO, 1986). Generally, biomass gasifiers have four main applications; 1) power generation, 2) heat production, 3) chemical production, and 4) fuel production.

Biomass gasification technologies had been widely used for transportation and on farm systems during the periods of World War I and World War II. By 1945, it was estimated that all over the world there were around 9,000,000 vehicles running on biomass combustible (fuel) gas produced by biomass gasification process (Breg *et al.*, 1979). Such vehicles included trucks, buses, agricultural and industrial machines. After World

War II, this technology lost it favourite due to the availability of comparatively cheaper fossil fuels (Breg *et al.*, 1979).

1.3 University–Industry Research Collaboration

A Biomass-to-Fuel gas (B2F) conversion system (Figures 1.1 & 1.2) was recently developed by Prima Natural Resources & Manufacturing Sdn. Bhd. (located at 12th Mile, Oya Road, Sibu, Sarawak) and was patented in more than 120 countries (PCT/SG2004/000158). A subsequent *MEMORANDUM OF AGREEMENT (MOA)* was made on the 8th day of May, 2006 between *PRIMA NATURAL RESOURCES AND MANUFACTURING SDN. BHD.* and *UNIVERSITI MALAYSIA SARAWAK (UNIMAS)* with special focus on R&D (quantification and optimization) and commercialization of B2F technology.

1.4 Problem Statement

The B2F conversion system was developed, constructed and tested for drying and heating purposes in several applications including mushroom culture industry, egg tray manufacturing facilities, coconut milk production processes, and paper recycling facilities. In this system, solid feedstock such as wood chips are gasified in the B2F conversion system, and the fuel or combustible gas is produced by high temperature air mixture to maximize the efficiency of gasification process. The fuel gas is purified by filtration process to become a low-to-medium heat value fuel suitable for heating and drying processes.

However, the B2F conversion system encountered some design and technical drawbacks/problems during operation. The MOA made on the 8th May 2006 entrusted UNIMAS to quantify and improve or optimize the performance of the existing B2F gasification technology. Some of the major problems encountered by B2F (as mentioned above) are as follows.

a) Feedstock input by batch process resulted in non-continuity operation;

b) System experienced inconsistent production of combustible gas;

c) Severe emission or leakage of unburnt (raw) combustible fuel gas from the system to nearby surroundings;

d) As high as 1.5% tar and 13% of "After Filtered Residual Liquid or AFRL" (by weight of total biomass feedstock) are produced as by-products; and

e) The B2F experienced overheating and tremendous heat wastage.

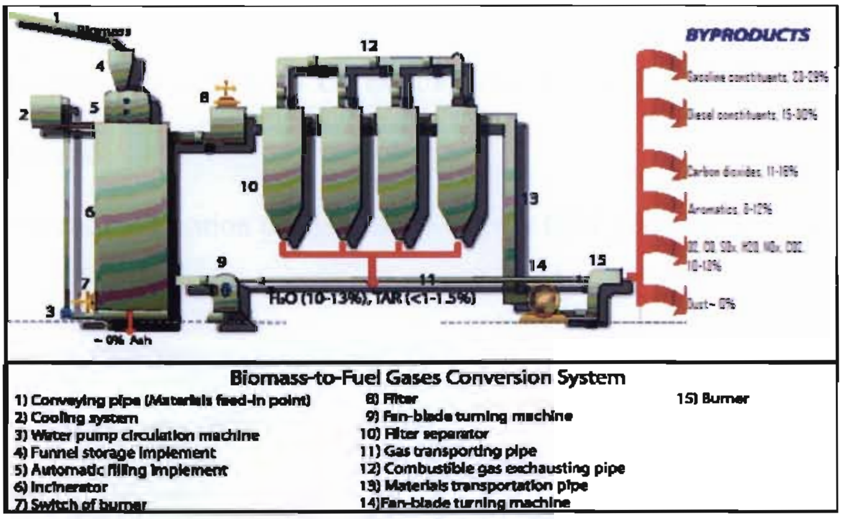


Figure 1.1: Simplified schematic diagram of B2F conversion system

Figure 1.2: Field tests on B2F conversion system

1.5 Research Aims

The specific aims of this research project are as follows:

1) Determination of moisture contents of selected biomass and respective calorific values;
2) Assessment and field tests on existing Biomass-to-Fuel gas (B2F) conversion system; and
3) Performance evaluation of Biomass-to-Energy (B2E) conversion system.

1.6 Research Objectives

This research project was carried out in three (3) phases and the primary objectives are summarized in the following paragraphs.

Phase I - Determination of Moisture Contents of Selected Biomass and Respective Calorific Values

i. To determine the moisture contents with respect to calorific values of (1) Paddy straw, (2) EFB, (3) POS, (4) sago bark, and (5) wood chips; and

Phase II – Assessment and Field Tests on Existing B2F conversion system

i. To determine the chemical compositions of AFRL;

ii. To determine the chemical compositions of raw (unburnt) combustible fuel gases generated by wood chips;

iii. To determine the chemical compositions of raw (unburnt) combustible fuel gases generated by Balingian-Mukah Coal;

iv. To assess nearby (<20 meters radius) incremental levels of CO, combustibles gas and total suspended particulate matters; and

v. To identify the operational drawbacks of the existing B2F conversion system.

Phase III – Performance Evaluation of B2E Conversion System

i. To evaluate the performance of B2E conversion system with special focus on overall efficiency of B2E and exhaust gas temperature distribution in combustible fuel gas-to-heat energy conversion chamber;

ii. To assess nearby (<20 meters radius) incremental levels of CO, combustibles gases and total suspended particulate matters during operation;

iii. To evaluate the performance of B2E conversion system with emphasis on the followings:

   a) Exergy destroyed, $X_{destroyed}$,

   b) Overall efficiency of B2E conversion system,

c) Second Law Efficiency of B2E conversion system,

d) Air flow rate, and

e) Effects of air supply on temperature distribution in combustible fuel gas-to-heat energy conversion chamber.

1.7 Thesis Outline

This research focused on the quantification of biomass energy for an array of locally available biomass and performance evaluation of biomass-to-energy (B2E) conversion system. Experimental and performance evaluation works on B2F and B2E were specified in this thesis. The presentation of this thesis is described in the following paragraphs. An introduction to biomass energy together with the problem statement and research objectives are presented in Chapter 1. In Chapter 2, the importance of biomass energy and potential biomass energy resources in Malaysia are presented, and followed by a comprehensive study of the current biomass gasification technologies and exergy analysis. Experimental and performance evaluation works are presented in Chapter 3. Chapter 4 explains the theoretical analysis of biomass energy and performance evaluation of B2E conversion system. Chapter 5 describes and discusses the results and research findings. Finally, the conclusions drawn from the current research work and recommendations for future research are summarized in Chapter 6.

CHAPTER 2

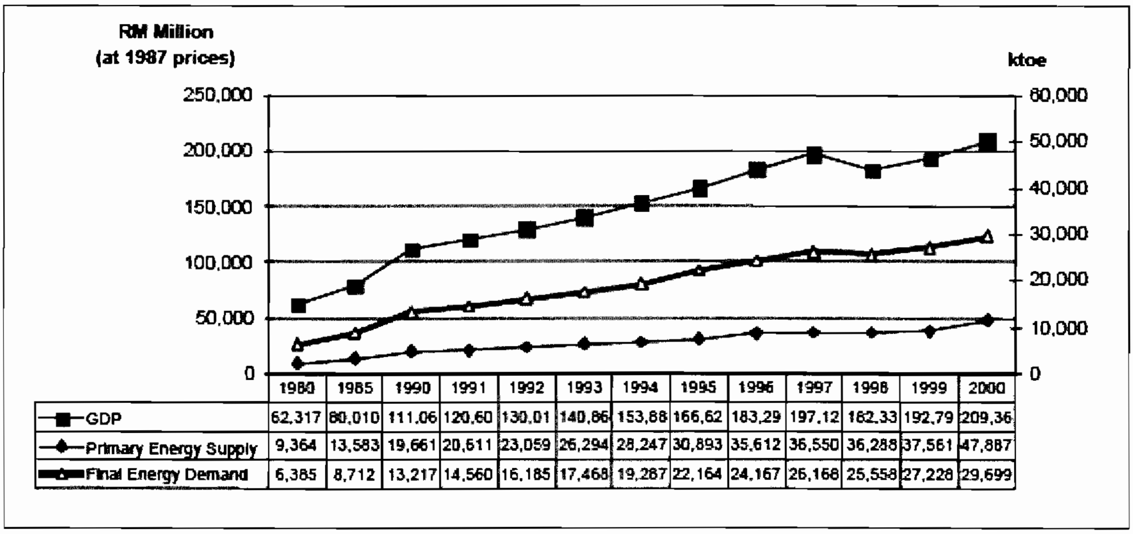
LITERATURE REVIEW

2.1 Overview

Energy plays an important role in daily life especially in the forms of electrical energy, fuel energy and chemical energy. In Malaysia, biomass energy has been showing a trend of increase as compared to other types of energy such as wind, fossil and hydraulic energy. Biomass that has a relatively higher potential to be used to produce useful energy includes palm oil waste, paddy waste, and wood waste. Biomass gasification technology is a technology converts biomass energy to useful energy such as to generate power, heat, chemical production and fuels. In this research, a special emphasis on exergy analysis had been included in the literature review section because it was deemed as a useful tool for determination of the types and true magnitudes of waste and losses of a system.

2.2 Energy Demand and Supply in Malaysia

Figure 2.1 shows the trends in gross domestic product (GDP), primary energy supply and demand in Malaysia from years 1980 to 2000. The major sectors that contributed the highest growth were manufacturing industrial and transport sectors. In the 7th Malaysia Plan, the commercial energy demand had grown by 4.7%; from 928.2 petajoules (PJ) in 1995 to 1,167.1 PJ in 2000 (Table 2.1). In the 8th Malaysia Plan, the average annual growth rate was 7.8%, i.e. from 1,167.1 PJ to 1,699.8 PJ. Table 2.2 indicates the increase in per capita energy consumption from 44.3 GJ in 1995 to 50.1 GJ in 2000, at a rate of 2.5% growth annually. In 2000, the industrial and transport sectors were the major energy consumers in Malaysia that accounted for 73.3% (EC, 2003). Industries that contributed to the increase included food, rubber, glass and wood processing. Undoubtedly, energy demand continues to grow during the 9th Malaysia plan and is projected a 6.7% growth for manufacturing sector as shown in Table 2.3 (EPU, 2006).



	1980	1985	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
■ GDP	62,317	80,010	111,06	120,60	130,01	140,86	153,88	166,62	183,29	197,12	182,33	192,79	209,36
◆ Primary Energy Supply	9,364	13,583	19,661	20,611	23,059	26,294	28,247	30,893	35,612	36,550	36,288	37,561	47,887
△ Final Energy Demand	6,385	8,712	13,217	14,560	16,185	17,468	19,287	22,164	24,167	26,168	25,558	27,228	29,699

Figure 2.1: Trends in GDP, primary energy supply and energy demand in Malaysia (adapted from EcoSecurities Ltd., 2006)

Table 2.1: Commercial energy demands by sector, 1995-2005

Sector	**1995**		**2000**		**2005**		**Average annual growth rate (%)**	
	PJ	**%**	**PJ**	**%**	**PJ**	**%**	**7MP**	**8MP**
Industrial	337.5	36.4	432.9	37.1	650.0	38.2	5.1	8.5
Transport	327.8	35.3	422.8	36.2	642.5	37.8	5.2	8.7
Residential and commercial	118.8	12.8	147.8	12.7	213.2	12.5	4.5	7.6
Non-energy	125.4	13.5	142.8	12.2	165.2	9.7	2.6	3.0
Agriculture and forestry	18.7	2.0	20.8	1.8	28.8	1.8	2.2	6.8
Total	928.2	100.0	1167.1	100.0	1699.8	100.0	4.7	7.8

(adapted from EC, 2003)

Table 2.2: Commercial energy demands by source, 1995-2005

Source	**1995**		**2000**		**2005**		**Average annual growth rate (%)**	
	PJ	**%**	**PJ**	**%**	**PJ**	**%**	**7MP**	**8MP**
Petroleum product	676.0	72.8	804.3	68.9	1139.1	67.0	3.5	7.2
Natural gas	81.1	8.8	120.0	10.3	184.8	10.9	8.2	9.0
Electricity	141.6	15.2	205.0	17.6	320.0	18.8	7.7	9.3
Coal and coke	29.8	3.2	37.8	3.2	55.9	3.3	4.9	8.1
Total	928.2	100.0	1167.1	100	1699.8	100.0	4.7	7.8
Per capital consumption (GJ)	44.3		50.1		66.4		2.5	5.8

(adapted from EC, 2003)

Table 2.3: Major indicators of the manufacturing sector under 9MP, 2000-2010

Indicator	**2000**	**2005**	**2010**	**8MP**	**9MP**
Manufacturing value added (RM million in 1987 prices)	67250	82394	113717	361816	497716
Annual growth rate (%)	18.3	4.9	7.5	4.1	6.7
Share to GDP (%)	31.9	31.4	32.4	30.8	31.8
Share to total exports (%)	85.2	80.5	83.4	82.4	82.5
Share to total employment (%)	27.7	28.7	30.0	27.6	29.4

(adapted from EPU, 2006)

2.3 Energy Policy in the 8th Malaysia Plan

According to the goals of the 8th Malaysia Plan, new sources of energy such as renewable energy will be encouraged to supplement the conventional supply energy. Originally, the four fuel diversification policy which focused on oil, gas, coal and hydro will be extended to include renewable energy as the fifth fuel, particularly biomass, biogas, municipal waste, solar and mini-hydro (EPU, 2001).

2.4 Definition of Biomass

Biomass is the term that has been used to name any materials that are derived from plants and animal (Figure 2.2) (Howstuffwork, 2008). Plants derived from biomass mainly compose of approximately carbon (50%), oxygen (43%), hydrogen (6%) and traces of mineral elements such as nitrogen, potassium, phosphorus, sulfur and some others. The predominant organic compounds are cellulose, hemi-cellulose and lignin. Lignin acts as "glue" to hold the cellulose fibers together. The main advantage of biomass is, they have very low sulfur contents and it is abundantly available in most tropical countries, while fossil fuels need to be imported from a limited number of suppliers.

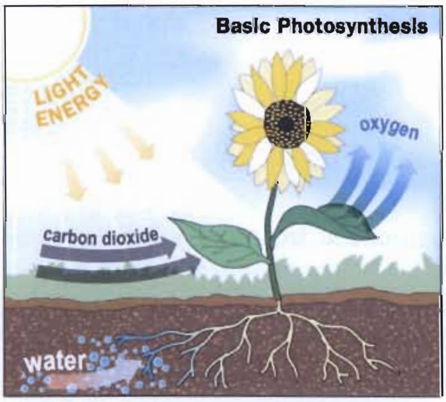


Figure 2.2: Basic fundamentals of biomass (adapted from Howstuffwork, 2008)

Biomass can be converted into biofuel energy. Biofuels differ from fossil fuels in various aspects such as availability, cost, suitability as a gasifier fuel, chemical compositions, heating values, ash and moisture contents. Generally, biomass can be categorized into two groups, that is 'dry' streams including wood, straw, and waste from food industry (e.g. husks from rice, corn, etc.) and 'wet' streams that consist of green waste, manure, and sludge. The dry streams are more suitable for thermal processing technologies, i.e. gasification, combustion, and pyrolysis. Obviously, evaporation of moisture in a thermal processing can result in significant reduction in energy efficiency, in addition to more heating energy needed to dry out the moisture contents.

2.5 Potential Biomass from Agricultural Sector in Malaysia

In Malaysia, biomass contributes around 14%, which is approximately 340 million barrel of oil equivalent (boe) of energy used every year. Five major sectors that contribute waste to the biomass energy in Malaysia are palm oil, forestry product, rubber agriculture, paddy agriculture, animal farming and urban waste. Other minor contributors include coconut, cocoa, and sugar cane agriculture (Lim, *et al.*, 1999). Table 2.4 shows the estimated energy productivity, biomass production and utilization from biomass in Malaysia.

In 1999, the amount of energy used for palm oil accounted 37.261 million of boe as compared to the estimated current annual energy for potential of unutilized biomass of 104.977 million of boe. In 2004, there were 380 palm oil mills processing approximately 70 million tons of EFB that produced 13.98 millions tons of CPO and 3.7 million tons of palm kernels. Assuming a conversion efficiency of 50% of the EFB total mass to fuel gas using biomass conversion system technology, this means that approximately 8.05 millions tons of EFB can be converted to these gases. If the calorific value of dry EFB is 18,883kJ/kg, this means that the total heat energy obtainable from EFB in 2004 would be 152×10^{12} kJ.

Table 2.4: Estimation of the energy productivity and biomass production and utilization

Crops/activities	**Energy productivity (boe/ha/yr)**	**Current annual amount used for energy purposes (million boe)**		**Current annual energy potential of unutilized biomass (million boe)**	
Oil palms	88.70	Fruit shells	23.609	Pruned fronds	77.665
		Fruit fibers	13.630	EFB	11.444
		Effluents	0.022	Effluents	2.928
				Replanting waste	12.94
Rubber trees	29.50	Wood	4.967	Wood	3.707
				Effluents	0.210
Paddy plants	11.54			Rice husks	1.025
				Rice straws	2.541
Coconut trees	28.21	Fronds	1.578	Fronds	0.164
		Shells	0.785		
Cocoa trees	80.33			Pruning wastes	16.850
				Pod husks	0.085
				Replanting wastes	0.630
Sugar cane	54.90	Bagasse	0.421	Leaves and tops	0.298
Logging	-	-		Residues	19.060
Timber processing	-	Sawdust and waste	3.733	Tree bark and sawdust	1.000

(adapted from Lim, *et al.*, 1999)

2.5.1 Palm Oil

According to Malaysia Palm Oil Board (MPOB), in year 2003 Malaysia was the largest producer and exporter of palm oil in the world. In 2003, the cultivation for palm oil was more than 3.75 millions hectare (MPOB, 2003). The production of CPO in 2003 was 13.35 millions tonnes whereby 12.25 millions tonnes was exported that earned RM 26.15

billion (MPOB, 2003). An illustration of fresh oil palm fruit is shown in Figure 2.3, and plots of palm oil residues versus potential power generation (MW) are shown in Figure 2.4 (Biomass Resource Inventory Report, 2003). Table 2.5 shows the residue product ratio versus potential power generation from palm oil residues (MPOB, 2002).

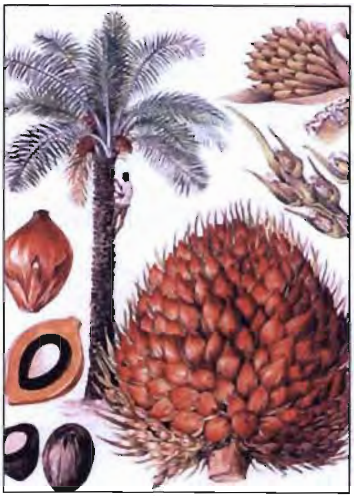


Figure 2.3: Palm oil

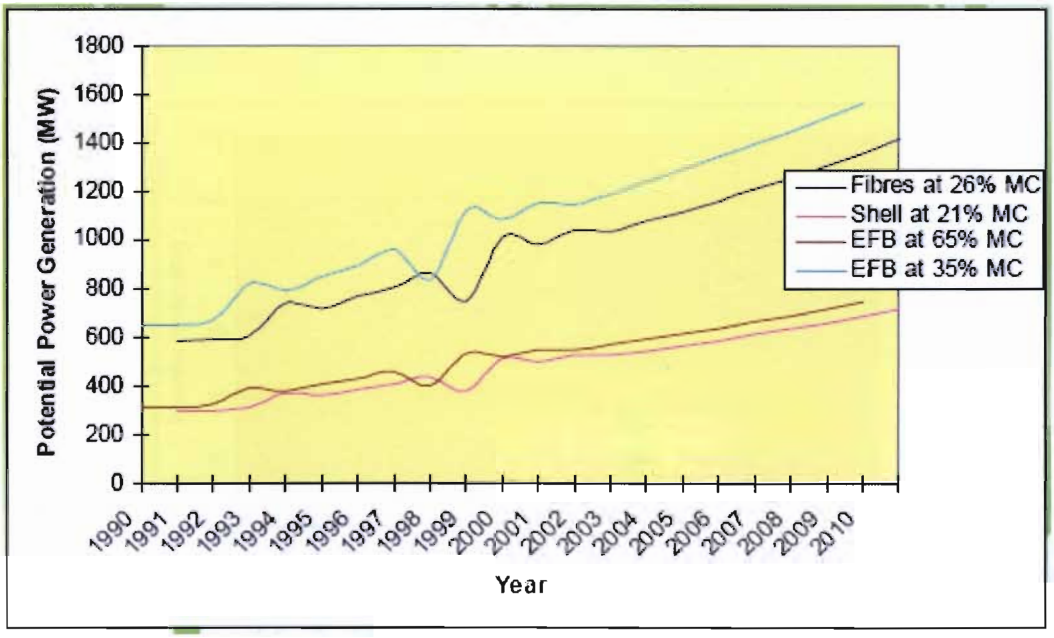


Figure 2.4: Palm oil residues versus potential power generation (MW)
(adapted from Biomass Resource Inventory Report, BioGen Project PTM, 2003)

Table 2.5: Residue product ratio versus potential power generation from palm oil residues

Type of industry	Production (Thousand tonne)	Residue	Residue product ratio (%)	Residue generated (Thousand tonne)	Potential energy (PJ)	Potential electricity generation (MW)
Palm oil	59800	EFB at 65% MC	21.14	12641.7	57	521
		Fiber	12.72	7606.6	108	1032
		Shell	5.67	3390.7	55	545
	Total solid			16670.6	220	2098
	POME ($3.5m^3$ per ton of CPO/65% of FFB)			38870		320

(adapted from Malaysian Oil Palm Statistics 2002, 22nd edition, MPOB)

2.5.2 Paddy

Plots of paddy residues versus potential power generation are illustrated in Figure 2.5. Table 2.6 shows the residue product ratio and potential power generation from paddy residue, while Table 2.7 shows the moisture contents and calorific values of paddy residues.

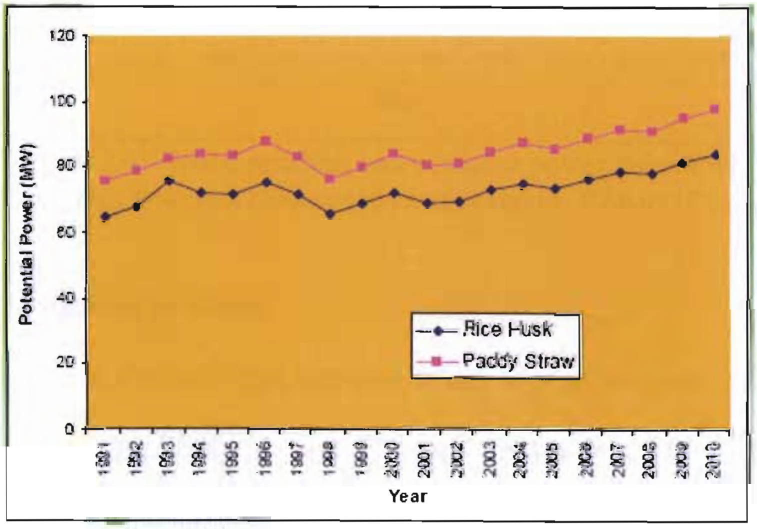


Figure 2.5: Paddy residues and potential power generation
(adapted from Biomass Resource Inventory Report, BioGen Project PTM, 2003)

Table 2.6: Residue product ratio and potential power generation from paddy residues

Type of industry	**Production year 2000 (Thousand tonne)**	**Residue**	**Residue ratio (%)**	**Residue Generated (Thousand tonne)**	**Potential energy (PJ)**	**Potential power (MW)**
Rice	2140	Rice husk	22	471	7536	72.07
		Paddy straw	40	856	8769	83.86
Total	2140			1327	16305	15593

(adapted from Resource: Biomass resource inventory report, BioGen Project PTM, 2003)

2.5.3 Wood

Figure 2.6 illustrates the wood residues and potential power generation.

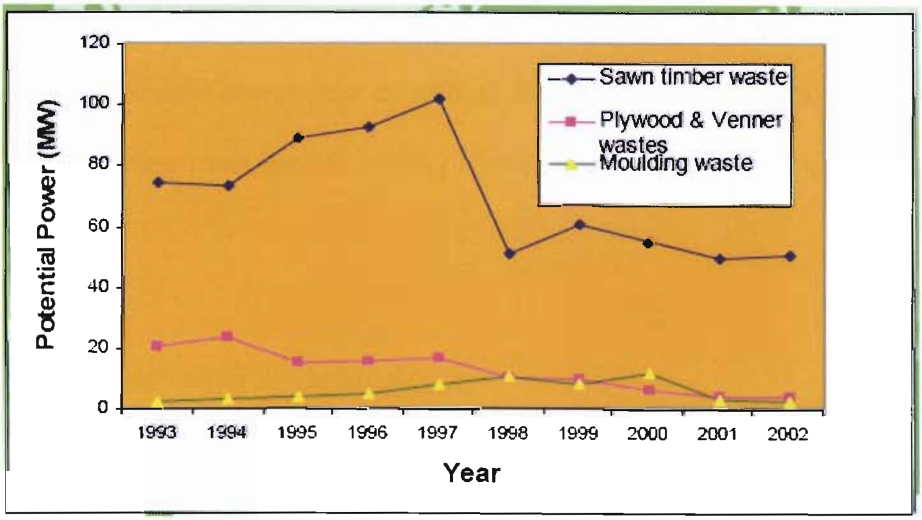


Figure 2.6: Wood residues and potential power generation
(adapted from Resource: Biomass resource inventory report, BioGen Project PTM, 2003)

2.6 Biomass Gasification Systems

Biomass gasification is a process that can convert any type of biomass to run shaft power systems, direct heat applications, and chemical production. Biomass gasification undergoes incomplete combustion process which results in production of combustible gases that consists of polyaromatics, diesel, gasoline constituents, and other byproducts such as heat, H_2O (vapor), tar, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_X), sulfur oxide (SO_x), oxygen (O_2), and suspended particulate matters.

During the periods of World War I and World War II, technologies of biomass gasification were widely used for transportation and on farms. By 1945, it was estimated that there were around 9,000,000 vehicles from all over the world running on producer gas by biomass gasification, such vehicles as power trucks, buses, agricultural and industrial machines (Breg, *et al.*, 1979). After World War II, this technology lost its favourite due to the availability of comparatively cheaper fossil fuels. In view of energy and environment crises, biomass gasification technology had become a favourite technology. Renewable energy can contribute long-term energy supply, reduce global atmosphere emissions, meet specific energy service needs and create employment (VOA, 2008).

2.6.1 Biomass Gasification Technologies

Biomass energy conversion technologies can be divided into three groups; thermo-chemical, bio-chemical, physico-chemical conversion process (Figure 2.7). Thermo-chemical processes include direct combustion, gasification and pyrolysis. The drawback of direct combustion was relatively slower in heat transfer. Gasification technology converts dry biomass into a mixture of fuel gases that can be burnt in internal combustion engines and heating purpose for industrial scale. Pyrolysis is the process of chemical decomposition of organic materials by heating in the absence of oxygen at relatively higher temperature at about 500°C (Vienna University of Technology, 2006). The efficiency of a conventional gasifier is around 80% (BE, 2003).

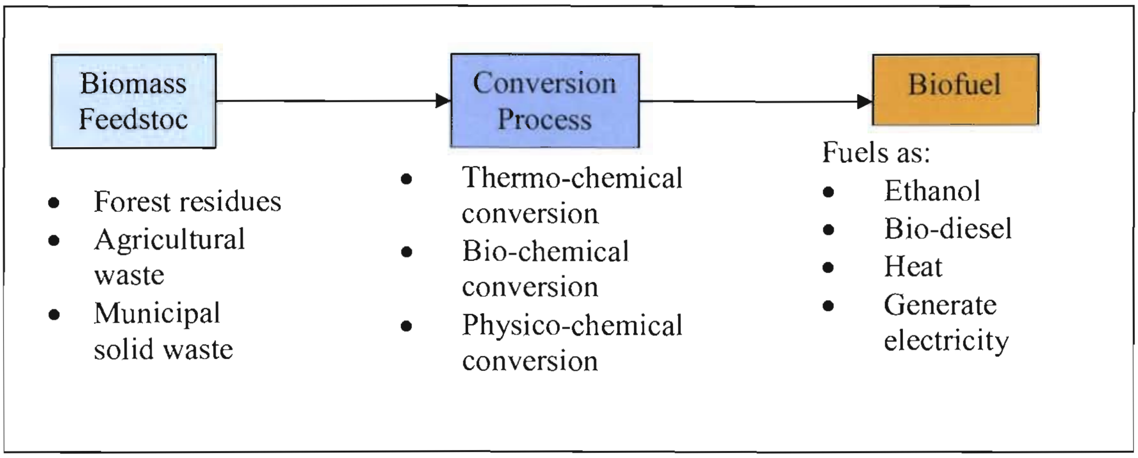


Figure 2.7: Biomass gasification process (adapted from Bain, 2004)

2.6.2 Various Types of Biomass Gasifiers

Biomass gasifiers can be grouped into four major classifications. Table 2.7 shows the differences among those gasifiers.

a) Updraft gasifier,

b) Downdraft gasifier,

c) Bubbling fluidized-bed gasifier, and

d) Circulating fluidized bed gasifier.

Table 2.7: Gasifier types and differences

Gasifier type	Flow direction		Support	Heat source
	Fuel	**Oxidant**		
Updraft gasifier	Down	Up	Grate	Combustion of char
Downdraft gasifier	Down	Down	Grate	Partial combustion of volatiles
Bubbling fluidized bed	Up	Up	None	Partial combustion of volatiles and char
Circulating fluidized bed	Up	Up	None	Partial combustion of volatiles and char

(adapted from DOE, 2002)

a) Updraft Gasifiers

Updraft gasifiers are the oldest and simplest among others gasifiers as shown in Figure 2.8 (SunGrant BioWeb, 2008). First, biomass is introduced to the top of the reactor and a grate at the bottom of the reactor that supports the reacting bed. Air, oxygen or steam are introduced below the grate and diffused up through the bed of biomass and char. At the bottom of the bed, a complete combustion of char takes place liberating carbon dioxide (CO_2) and water (H_2O). These hot gases (~1,000 °C) pass through the bed above are then reduced to hydrogen (H_2) and carbon monoxide (CO) when cooled to below 750°C. In the reactor, the reducing gases (H_2 and CO) pyrolyze the descending dry biomass and finally dry the incoming wet biomass, leaving the reactor at a lower temperature (~500°C) (U.S. Department of Energy, National Energy Technology Laboratory, 2002).

Advantages of updraft gasifier (U.S. Department of Energy, National Energy Technology Laboratory, 2002):

- Small pressure drop,
- Good thermal efficiency, and
- Little tendency towards slag formation.

Disadvantages of updraft gasifier (U.S. Department of Energy, National Energy Technology Laboratory, 2002):

- Great sensitivity to tar and moisture contents of fuel; and
- Low efficiency and relatively longer time is required for initial start up.

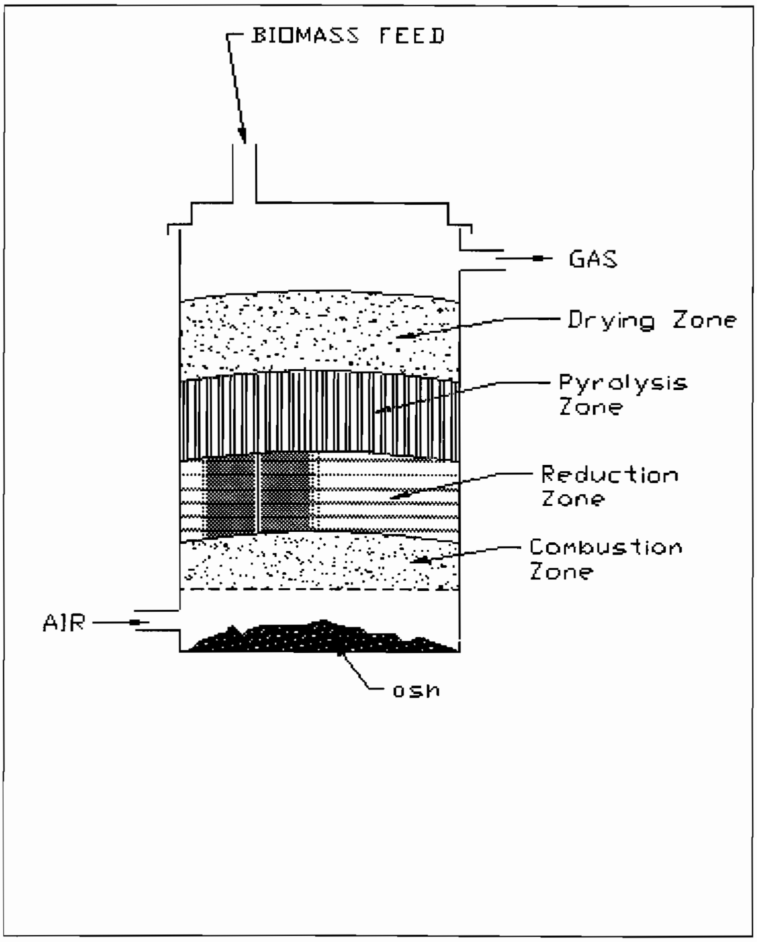


Figure 2.8: Updraft gasifier (adapted from SunGrant BioWeb, 2008)

b) Downdraft Gasifiers

Downdraft gasifiers have the same mechanical configuration as the updraft gasifiers except that the oxidation and product gases flow down in the reactor in the same direction as the biomass feedstock (Figure 2.9) (KP, 2007). The major advantage of this gasifier is that it can combust up to 99.9% of the tars formed. Biomass feedstock and air or oxygen is ignited in the reaction zone at the top of the reactor. The generated gas burns intensely leaving 5 to 15% char and hot combustion gas. These gases will flow downwards and react with the char at 800°C to 1,200°C generating more CO and H_2 when cooled to below 800°C. Finally, unconverted char and ash pass through the bottom of the grate and prior to disposal (U.S. Department of Energy, National Energy Technology Laboratory, 2002).

Advantages of downdraft gasifier (U.S. Department of Energy, National Energy Technology Laboratory, 2002):

- Flexible adaptation of gas production to load; and
- Low sensitivity to charcoal, dust and tar contents of fuel.

Disadvantages of downdraft gasifier (U.S. Department of Energy, National Energy Technology Laboratory, 2002):

- Structure tends to be tall; and
- Not feasible for small scale fuel production.

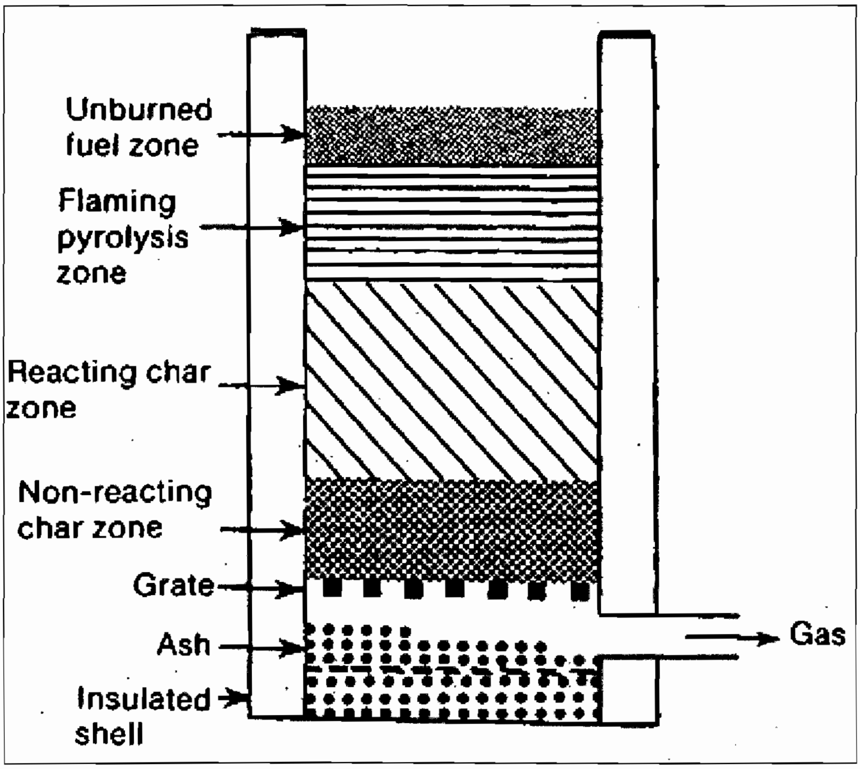


Figure 2.9: Downdraft gasifier (adapted from KP, 2007)

c) Bubbling Fluidized Bed Gasifiers

A bubbling fluidized bed gasifier consists of fine, inert particles of sand or alumina, which have been selected for size, density, and thermal characteristics (Figure 2.10) (Wikipedia, 2008). As gas (oxygen, air or steam) is forced through the inert particles, a point is reached when the frictional force between the particles and the gas counter balances the weight of the solids. At this gas velocity (minimum fluidization), bubbling and channeling of gas through the media occur, such that the particles remain in the reactor and appear to be in a "boiling state". The fluidized particles tend to break up the biomass fed to the bed and ensure good heat transfer throughout the reactor (U.S. Department of Energy, National Energy Technology Laboratory, 2002).

Advantages of bubbling fluidized bed gasifier:

- Yields a uniform product gas;
- Exhibits a nearly uniform temperature distribution throughout the reactor;
- Able to accept a wide range of fuel particle sizes, including fines;
- Provides high rates of heat transfer between inert material, fuel and gas; and
- High conversion possible with low tar and unconverted carbon.

Disadvantages of bubbling fluidized bed gasifier:

- Large bubble size may result in gas bypass through the bed.

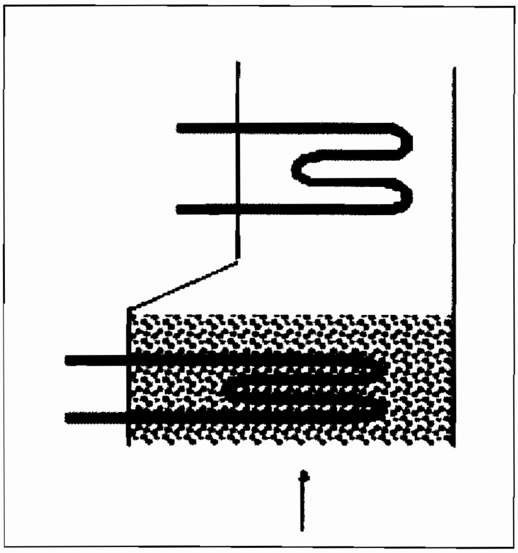


Figure 2.10: Bubbling fluid bed gasifier (adapted from Wikipedia, 2008)

d) Circulating Fluidized Bed Gasifier

Circulating fluidized bed gasifier operates at gas velocity higher than the minimum fluidization point would result in the entrainment of particles in the gas stream (Figure

2.11) (Westinghouse Electric Corporation, 1982). The entrained particles in the gas exit at the top of the reactor are separated in a cyclone and returned to the reactor (U.S. Department of Energy, National Energy Technology Laboratory, 2002).

Advantages of circulating fluidized bed gasifier (U.S. Department of Energy, National Energy Technology Laboratory, 2002):

- Suitable for rapid reactions;
- High heat transport rates due to high heat capacity of bed material; and
- High conversion rates possible with low tar and unconverted carbon.

Disadvantages of circulating fluidized bed gasifier (DOE, 2002):

- Temperature gradients occur in direction of solid flow.

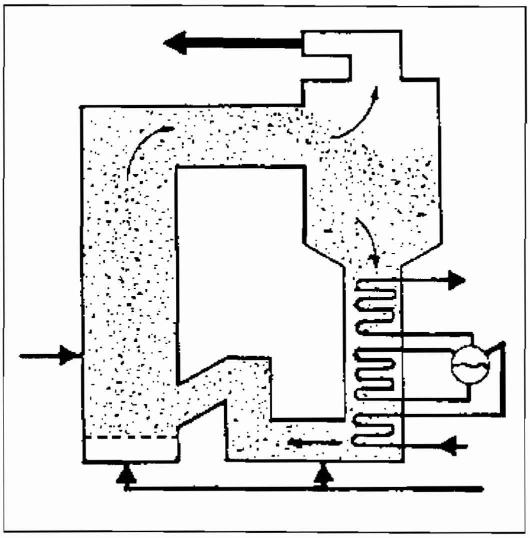


Figure 2.11: Circulating fluidized bed gasifier (Westinghouse Electric Corporation, 1982)

2.6.3 Process Zones in a Gasifier

During the downdraft gasification process, the following 4 phases can take place:

a) Drying process,

b) Pyrolysis / distillation process,

c) Oxidation process, and

d) Reduction process.

a) Drying Zone

In this zone, solid fuel is introduced from the top of the gasifier. As a result of heat transfer from the lower parts of the gasifier, drying of the biomass fuel occurs in the lower section. The water vapor that formed from the biomass will flow downwards and add to the water vapor formed in the oxidation zone. Part of it may be reduced to hydrogen and carbon monoxide (Equation 2.1), and the rest will end up as moisture in the gas.

$$C + H_2O \leftrightarrow H_2 + CO \qquad (2.1)$$

b) Pyrolysis Zone

Pyrolysis process starts when temperature exceeds 250°C. During this process, relatively larger molecules such as cellulose (40-50%), hemi-cellulose (20-30%), and lignin (20-25%) will be broken down into medium-sized molecules and carbon (e.g. char) (FAO, 1986). The products that had been pyrolised would flow downwards into the hotter zones of the gasifier. Some of it will burned in the oxidation zone, the rest will be broken down into smaller molecules such as hydrogen, methane, carbon monoxide, ethane and ethylene, if all those elements remain in the hot zone long enough. Typical chemical reactions in pyrolysis zone can be expressed as follow.

$$\text{(Biomass volatiles/char)} + O_2 \rightarrow CO_2$$

$$C + O_2 + 3.76N_2 \rightarrow 3.76N_2 + CO_2 \tag{2.2}$$

c) Oxidation (Combustion) Zone

A burning (oxidation) zone is formed at the level where oxygen (air) is injected. The reactions with oxygen are highly exothermic and the temperature may rise up to 1,200°C, and even up to 1,500°C. Typical chemical reactions in oxidation zone can be expressed as follow.

$$C + O_2 + 3.76N_2 \rightarrow 3.76N_2 + CO_2 \tag{2.3}$$

The main function of oxidation zone is to provide high temperature and to convert all the condensable products from the pyrolysis zone. The air inlet velocities and the reactor geometry must be well chosen in order to avoid cold spot in the oxidation zone (FAO, 1986). There are two methods to avoid cold spot in this zone:

i. Reduce the cross-sectional area at a certain height of the reactor, and

ii. Spreading the air inlet nozzles over the circumference of the reduced (smaller) cross-sectional area, or use a central air inlet with a spraying device.

d) Reduction Zone

All the reaction products in the oxidation zone will move downward (from oxidation zone to reduction zone). The reduction reactions that typically take place in the reduction zone can be written as follows.

$$C + CO_2 \leftrightarrow 2CO \qquad (2.4)$$

$$C + H_2O \leftrightarrow CO + H_2 \qquad (2.5)$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \qquad (2.6)$$

$$C + 2H_2 \leftrightarrow CH_4 \qquad (2.7)$$

The main reduction reactions are expressed in Equations 2.6 and 2.7 whereby both of these reactions are endothermic that have the capability of reducing gas temperature. Normally, the temperatures in the reduction zone are between 800°C and 1000°C. The lower the temperature in the reduction zone (e.g. ~700-800°C), the lower is the calorific value of the gas (Rajvanshi, 2007). The percentage of the carbon dioxide reduced to carbon monoxide will depend on the temperature in the gasifier. An increase in the gasification temperature causes an increase in the gaseous product yield and a decrease in the tar yield. Previous researches found that the end product of the reduction zone is a combustible gas which can be used as fuel gas in burners and for internal combustion engines after dust removal and cooling (FAO, 1986).

Table 2.8 summarizes the processes zone during a downdraft gasification process whereby main reactions take place during the processes as expressed in Equations 2.3 and 2.4, and high temperatures are required in processes as expressed in Equations 2.5, 2.6 and 2.7.

Table 2.8: Process zones in downdraft gasifier

Reactions	**Exothermic reactions (Heat is generated)**	**Endothermic reactions (Heat is required)**
Combustion: (Biomass volatiles/char) + $O_2 \rightarrow CO_2$ $C + O_2 + 3.76N_2 \rightarrow 3.76N_2 + CO_2$	√	
Boundouard reaction: (Biomass volatiles/char) + $CO_2 \rightarrow 2CO$ $C + CO_2 + 3.76N_2 \rightarrow 3.76N_2 + 2CO$		√
Partial oxidation: (Biomass volatiles/char) + $O_2 \rightarrow CO$ $2C + O_2 + 3.76N_2 \rightarrow 3.76N_2 + 2CO$	√	
Water gas reaction: (Biomass volatiles/char) + $H_2O \rightarrow CO + H_2$ $C + H_2O \leftrightarrow H_2 + CO$		√
Water gas shift: $CO + H_2O \leftrightarrow H_2 + CO_2$	√	
$C + CO_2 \leftrightarrow 2CO$	√	
CO Methanation: $CO + 3H_2 \leftrightarrow CH_4 + H_2O$	√	
Methanation: (Biomass volatiles/char) + $H_2 \rightarrow CH_4$ $C + 2H_2 \leftrightarrow CH_4$		√
Tar + $H_2O \rightarrow H_2 + CO$		
Tar + $H_2 \rightarrow$ light hydrocarbons + gases		

2.6.4 Biofuels from Gasification

Gasification can be classified into two groups; product gas and biosyn gas, whereby both are parts of the reduction zone. Generally, there are two types of biofuels; (1) Product gases and (2) Biosyngas. The types of biofuels are described in the following paragraphs.

(a) Product Gases

Product gases are generally organic materials that are directly used in their natural form. Product gases produced by low temperature gasification, i.e. <1,000°C and contain CO, H_2, CH_4, C_xH_y aliphatic hydrocarbons, benzene, toluene, and tars (apart from CO_2 and H_2O). The syngas components H_2 and CO typically contain approximately 50% of the energy in the gas, while the remainders are CH_4 and higher (aromatic) hydrocarbons. Normally, such fuels have been used for directly combustion such as cooking, heating and electricity production purposes.

(b) Biosyngas

Biosyngas are used in the form of solid, liquid, or gaseous. Biosyngas produced by high temperature above 1,200°C or catalytic gasification. Under these conditions, biomass can be completely converted to H_2 and CO, besides CO_2 and H_2O. Biosyngas also, can be made from product gas by thermal cracking or catalytic reforming. It is used for relatively wider range of application with higher efficiency on average, such as transport and high temperature industrial processes. Generally, the reactions of biomass gasifier are carried out at 1) elevated temperatures between 500°C and 1,400°C, 2) atmospheric or elevated pressures up to 33 bar (480 psia), and 3) oxidant used can be air, pure oxygen, steam or a mixture of these gases.

The production of combustible gas contains variable amount of ash particles, volatile alkali metal, and tar, which is a complex mixture of aromatic that includes a significant fraction of polycyclic aromatic hydrocarbons (Blasiak, 2002). For air-based gasifiers, it typically produces a product gas that contains relatively higher concentration of nitrogen and hydrocarbons with low amount of methane and possessing low heating values between 4 to 6 MJ/m^3 (107-161 Btu/ft^3). For oxygen and steam-based gasifiers, they produce a product gas containing a relatively high concentration of hydrogen and CO with a heating value ranging from 10 to 20 MJ/m^3 (268-537 Btu/ft^3).

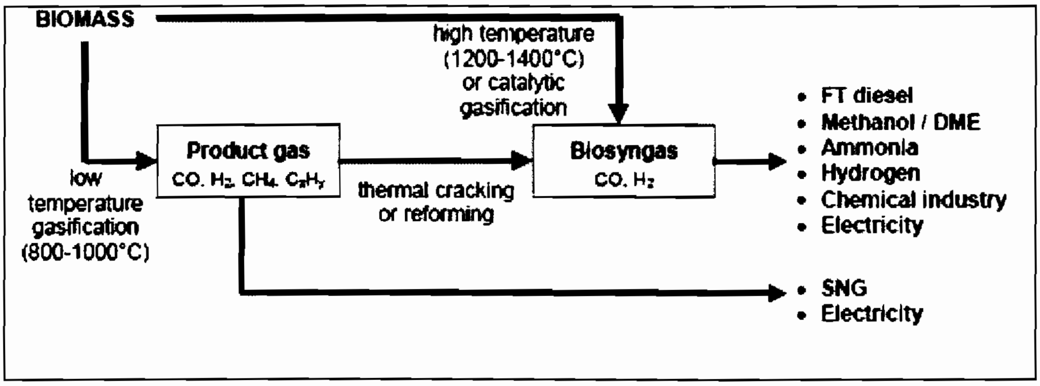


Figure 2.12: Typical applications of 'Biosyngas' and 'Product Gas'

2.6.5 Problems Faced by Gasification Systems and Elimination Methods

In biomass gasification, the gas can contain significant amount of tars. These tars are mainly polyaromatic hydrocarbons (PAHs) (Blasiak, 2002). Table 2.9 summarizes some of the contamination problems faced by current gasification systems (EUBIA, 2007).

Table 2.9: Contamination problems faced by gasification systems

Contaminant	**Example**	**Potential Problem**
Particles	Ash, char, fluid bed material	Erosion
Alkali metals	Sodium and potassium compounds	Hot corrosion, catalyst poisoning
Nitrogen compounds	NH_3 and HCN	Emission
Tars	Refractive aromatics	Clogging of filters
Sulfur, chlorine	H_2S and HCl	Corrosion, emission, catalyst poisoning

(adapted from EUBIA, 2007)

Generally, there are three (3) practical methods that are suggested or available for removal of tars from fuel gas (BTG, 2004). These methods include a) Physical removal of tars, b) Thermal conversion of tars, and c) Catalytic destruction of tars.

a) **Physical Removal of Tars** - Removal of tars via physical processes such as separation process.

b) **Thermal Conversion of Tars** - Thermal conversion, also called "cracking" focuses on the application of extremely high temperatures to disintegrate complex organic compounds into more benign forms.

c) **Catalytic Destruction of Tars** - Catalytic destruction of tars involves the use of catalysis to promote disintegration of tars. Example of catalytic used is nickel-on-alumina commercial steam-reforming.

2.6.6 Techniques to Improve the Efficiency of Gasification System

According to Blasiak (2002), available techniques to improve the efficiency of gasification system include the followings.

- Supply oxygen at 600-700°C accelerates the destruction of primary products, and inhibits the formation of aromatics; however, once benzene, the primary component of aromatic compounds in tar is formed, it cannot be destroyed by oxygen;
- Higher temperature will also result in higher rates of reaction and a reduction of required residence times;
- Steam-biomass reaction rates may be enhanced by increasing the gasifier steam content.

2.7 Comparison of Biomass Gasifier and Diesel-Operated System

Quantitative case studies conducted by previous researchers had shown that gasification systems were far more superior than conventional systems over economic advantages (FRIM, 2005). It was found that a net saving of 32% of the cost of generating electricity for using gasification system as compared to a conventional diesel system on same capacity (FRIM, 2005).

2.8 Energy Conversion Efficiency

Energy conversion efficiency is the ratio between the useful output of an energy conversion machine and the input. The useful output may be electric power, mechanical work, or heat (Wikipedia, 2008).

Overall efficiency is defined as (Yunus, & Michael, 1998),

$$\mathit{Overall\ efficiency} = \left(\frac{\mathrm{HV}_{\text{gaseous products}}}{HV_{Biomass}\ x\ \dot{m}_{fuel}} \right) 100\% \tag{2.8}$$

Where

$HV_{\text{gaseous products}}$ = Heat value of gaseous products

HV_{Biomass} = Heat value of biomass

$\dot{m}_{fuel} = Mass\ flow\ rate\ of\ fuel$

2.9 Concept of Exergy

Exergy is the amount of energy that can be extracted as useful work. Exergy is also called availability or available energy. The rest of the energy will eventually be discarded as waste energy. In an exergy analysis, the initial state is specified, and thus it is not a variable. The work output is maximized when the process between two specified states is executed in a reversible manner. The system must be in the dead state at the end of the process to maximize the work output. A system is said to be in the dead state when it is in the equilibrium with the environment. At the dead state, a system is at the temperature and pressure of its environment (in thermal and mechanical equilibrium); it has no kinetic or potential energy with respect to the environment (zero velocity and zero elevation above a reference level); and it does not react with the environment (chemical inert). A system has zero availability at the dead state. The system will deliver the maximum possible work as it undergoes a reversible process from the specified initial state to the state of its environment, that is, the dead state. Actually exergy is a property of the system-environment combination and not of the system alone. Therefore, altering the environment can be one of the ways to increase exergy (Yunus, & Michael, 1998).

2.9.1 Theoretical Exergy Analysis

Exergy analysis is a method used for conservation of mass and conversion of energy principles together with the Second-Law of Thermodynamics for the analysis, design and improvement of energy availability. An exergy balance applied to a process or a whole plant tells us how much of the usable work potential, or exergy supplied as the input to the system under consideration has been consumed by the process. The loss of exergy, or irreversibility, provides a generally applicable quantitative measure of process inefficiency. In other words, an exergy analysis is similar to an energy analysis, but takes into account the quality of the energy as well as the quantity. Since it considers entropy, exergy analysis allows a system to be analyzed more comprehensively by determining where in the system the exergy is destroyed by internal irreversibilities, and the causes of those irreversibilities. Exergy balance for any system undergoing any process can be expressed as

$$\text{(Total exergy entering) - (Total exergy leaving) – (Total exergy destroyed)}$$
$$= \text{(Change in the total exergy of the system)} \quad (2.9)$$

And the above expression (Equation 2.9) can be simplified as

$$X_{in} - X_{out} - X_{destroyed} = \Delta X_{system} \quad (2.10)$$

2.9.2 Exergy and its Essential Utilization

- Addresses the impact of energy resource utilizations on the environment;

- As an effective method using the conservation of mass and conservation of energy principle together with Second-Law of Thermodynamics for design and analysis of energy systems;
- It is a suitable technique for furthering the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of waste and losses to be determined;
- It is an efficient technique revealing whether or not and by how it is possible to design more efficient energy system by reducing the inefficiencies in existing systems;
- It is the key component in obtaining sustainable development; and
- It has a crucial role in energy policy making activities.

2.9.3 Reversible Work and Irreversibility

Reversible work and irreversibility are the essential tools to evaluate the actual initial and final states. Reversible work, W_{rev} is defined as the maximum amount of useful work that can be produced as a system undergoes a process between the specified initial and final states. The heat transfer between the system and surroundings must take place reversibly, and no irreversibility present within the system during the process. Any difference between the reversible work, W_{rev} and the useful work, W_u is due to the irreversibilities. This difference is called irreversibility, *I*.

$$I = W_{rev,\,out} - W_{u,\,out} \quad \text{or} \quad I = W_{u,\,in} - W_{rev,\,in} \qquad (kJ) \tag{2.11}$$

The useful work W_u is the difference between the actual work W and the surrounding work, W_{surr}.

$$W_u = W - W_{surr} = W - P_o (V_2 - V_1) \quad \text{(kJ)} \tag{2.12}$$

Where

V = Volume of the system

P_o= Atmospheric air

Irreversibility is equal to the exergy destroyed. It represents the energy that could have been converted to work but was not.

2.9.4 Exergy Associated With Kinetic Energy, Potential Energy, Internal Energy, Flow Work and Enthalpy

Exergy associated with kinetic energy, ke

The exergy of the kinetic energy (ke) of a system is equal to the kinetic energy itself regardless of the temperature and pressure of the environment. The exergy of knetic energy, X_{ke} can be expressed as follow.

$$X_{ke} = ke = \frac{v^2}{2} \quad \text{(kJ/kg)} \tag{2.13}$$

Where V = Velocity of the system to the environment

Exergy associated with potential energy, pe

The exergy of the potential energy (pe) of a system is equal to the potential energy itself regardless of the temperature and pressure of the environment. The exergy of potential energy, X_{pe} can be expressed as follow.

$$X_{pe} = pe = gz \quad (kJ/kg) \tag{2.14}$$

Where

g = Gravitational acceleration

z = Elevation of system relative to a reference level in the environment

Exergy associated with internal energy, u

Exergy of internal energy (u) can be expressed on a unit-mass basic as

$$\text{Exergy of internal energy: } X_u = (u - u_o) + P_o(v - v_o) - T_o(s - s_o) \quad (kJ) \tag{2.15}$$

Where

u_o = Internal energy of the system at the dead state

v_o = Volume of the system at the dead state

s_o = Entropy of the system at the dead state

T_o = Ambient temperature

Exergy associated with flow work, Pv

Exergy of flow work (X_{Pv}) can be expressed as:

$$\text{Exergy of flow work: } X_{Pv} = Pv - P_o v = (P - P_o)v \tag{2.16}$$

Exergy (Work Potential) Associated with Enthalpy, h

Exergy content of enthalpy can be determined by following the approach used to determine the exergy content of internal energy by considering a unit mass in a flow stream at a specified state with negligible kinetic and potential energies that undergoes a process to the dead state in a reversible manner. The useful work delivered during this process would be the exergy of the stream as its initial state, which is equivalent to the exergy associated with the enthalpy of the fluid stream. Enthalpy was defined as the sum of the internal and flow energies, $h = u + Pv$

$$X_h = X_u + X_{Pv} \tag{2.17}$$

$$= [(U - U_o) + P_o (V - V_o) - T_o(S - S_o)] + (P - P_o)\, v \tag{2.18}$$

$$= (U + Pv) - (U_o + P_o v_o) - T_o(S - S_o) \tag{2.19}$$

Exergy of enthalpy: $x_h = (h - h_o) - T_o\,(s - s_o)$; (kJ/kg) (2.20)

Where,

h_o = enthalpy of the fluid at the dead state

s_o = entropy of the fluid at the dead state

2.9.5 Exergy Transfer by Heat, Work, and Mass

Exergy can be transferred into three forms: heat, work and mass flow. There are only two forms of exergy interactions associated with a fixed mass or closed systems; heat transfer and work.

Exergy transfer by heat transfer, Q

Heat transfer, Q at a location at absolute temperature (T) is always accompanied by exergy transfer X_{heat} in the amount of

$$X_{heat} = (1 - T_o/T)\, Q \quad \text{(kJ)} \tag{2.21}$$

Where

T_o = Temperature at dead state

T = Absolute temperature

When $T>T_o$, heat transfer to a system would increase the exergy of that system and heat transfer from a system would decrease it. When $T< T_o$, the heat transfer (Q) is the heat rejected to the cold medium (the waste heat). The exergy transferred with heat would be zero when $T = T_o$ at the point of transfer.

When $T > T_o$, the exergy and heat transfer are in the same direction. This means that both the exergy and energy contents of the medium to which heat is transferred shall increase. But, when $T < T_o$ (cold medium), the exergy and the heat transfer are in opposite directions, i.e. the energy of the cold medium increases as a result of heat transfer, while exergy decreases. The exergy of the cold medium eventually becomes zero when its temperature reaches T_o. When the absolute temperature, T at the location where heat transfer is not constant, the exergy transfer accompanying heat transfer is determined by the integration expressed as follow.

$$X_{heat} = \int (1 - T_o/T)\, \Delta q \tag{2.22}$$

Exergy Transfer by Work, W

$$\text{Exergy transfer by work: } X_{work} = \left.\begin{array}{ll} (W - W_{surr}) & \text{(for boundary work)} \\ W & \text{(for other forms of work)} \end{array}\right\} \tag{2.23}$$

Where $W_{surr} = P_o (V_2 - V_1)$, P_o is atmospheric pressure, and V_2 and V_1 are the final and initial volumes of the system. Therefore, the energy transfer with work such as shaft work and electrical work are equal to the work (W) itself.

Exergy Transfer by Mass, m

The exergy, energy and entropy contents of a system are proportional to mass. Also, the rates of exergy, entropy and energy transport into or out of a system are proportional to the mass flow rate. Mass flow is a mechanism to transport exergy, entropy and energy into or out of a system.

Exergy transfer by mass: $X_{mass} = m\psi$ (2.24)

Where,

$$\Psi = (h - h_o) - T_0(s - s_o) + \frac{v^2}{2} + gz = \text{stream availability, kJ/kg}$$

h = Specific enthalpy, kJ/kg

s = Specific entropy, kJ/kg.K

V = Velocity, m/s

g = Gravitational acceleration, m/s^2

When the properties of the fluid change during the process, the exergy transfer by mass flow can be determined by integration of the following expression.

$$X_{mass} = \int \Psi \, \rho V_n dA_c \quad \text{and } X_{mass} = \int \Psi \delta m = \int \dot{X}_{mass} \, dt \qquad (2.25)$$

where,

A_c = Cross-sectional area of the flow

V_n = Local velocity normal to dA_c

ρ = Density, kg/m^3

Equation 2.21 can be applied when the properties of fluid change during a process.

2.9.6 Exergy Balance: Control System

Control volumes involve mass flow across the boundaries. Generally, mass possesses exergy as well as energy and entropy and the amount of the three extensive properties are proportional to the amount of mass (Figure 2.13) (Yunus, & Michael, 1998).

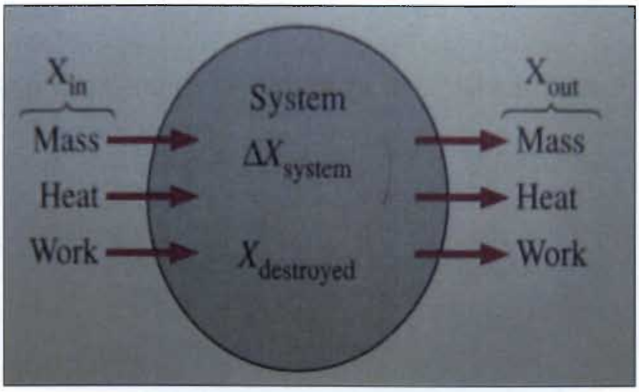


Figure 2.13: Mechanisms of exergy transfer (adapted from Yunus, & Michael, 1998)

Exergy is transferred into or out of a control volume by mass as well as heat and work transfer. The decrease of exergy principle can be expressed as follows.

[Net exergy transferred] - [Exergy destroyed] = [Change in exergy] (2.26)

The above expression (Equation 2.22) can be simplified as

$$[X_{in} - X_{out}] - X_{destroyed} = \Delta X_{system} \tag{2.27}$$

This relation is also referred as exergy balance and can be stated as exergy change of a system, and is equal to the difference between the net exergy transfer through the system boundary and the exergy destroyed within the system boundaries as a result of irreversibilities, or referred as "entropy generation".

$$X_{destroyed} = T_o S_{gen.} \tag{2.28}$$

The above expression (Equation 2.24) can be further elaborated and details are expressed as follows.

$$\sum\left(1-\frac{T_o}{T_k}\right)Q_k - \left[W - P_o\left(V_2 - V_1\right)\right] + \sum m_1\psi_1 - \sum m_2\psi_2 - X_{destroyed} = (X_2 - X_1)_{cv} \tag{2.29}$$

Where

$\left(1-\frac{T_o}{T_k}\right)Q_k$ = Exergy transfer by heat

$\left[W - P_o\left(V_2 - V_1\right)\right]$ = Exergy transfer by work

$m_1\psi_1 - m_2\psi_2$ = Exergy transfer by mass

cv = Control volume

Anything that generates entropy always destroys exergy. The exergy destroyed is proportional to the entropy generated. The more irreversible a process is the larger the exergy destroyed during the process. For instance,

$$X_{destroyed} \begin{cases} > 0 \text{ for Irreversible process} \\ = 0 \text{ for Reversible process} \\ < 0 \text{ for Impossible process} \end{cases}$$

(Yunus, & Michael, 1998)

2.9.7 Second-Law Efficiency, η_{II}

The *thermal efficiency* and the *coefficient of performance* for devices is a measure of their performance. There are defined on the basic of the first-law only, and there are sometimes referred to as the *first-law efficiencies*. The first law efficiency (also known as the *conversion efficiency*), however, make no reference to the best possible performance, and thus it may be misleading.

Consider two heat engines, both having a thermal efficiency of 30 %, as shown in Figure 2.14. Engine A is supplied with heat from a source at 600 K, and engine B from a source at 1000 K. Both engines reject heat to a medium at 300 K. Both engines seem to convert to work the same fraction of heat that they receive; thus they are performing equally well. A close look at these engines in the second law of thermodynamics, it will be a different picture. These engines, can perform as reversible (Carnot) engines, in which case their efficiencies would be

$$\eta_{rev,A} = \left(1 - \frac{T_L}{T_H}\right)_A = 1 - \frac{300\,K}{600\,K} = 50\%$$

$$\eta_{rev,B} = \left(1 - \frac{T_L}{T_H}\right)_B = 1 - \frac{300\,K}{1000\,K} = 70\%$$

It is becoming apparent that engine B has a greater work potential available to it (70% of the heat supplied as compared to 50% for engine A), and thus should do a lot better than engine A. Therefore, engine B is performing poorly relative to engine A even though both have the same thermal efficiency.

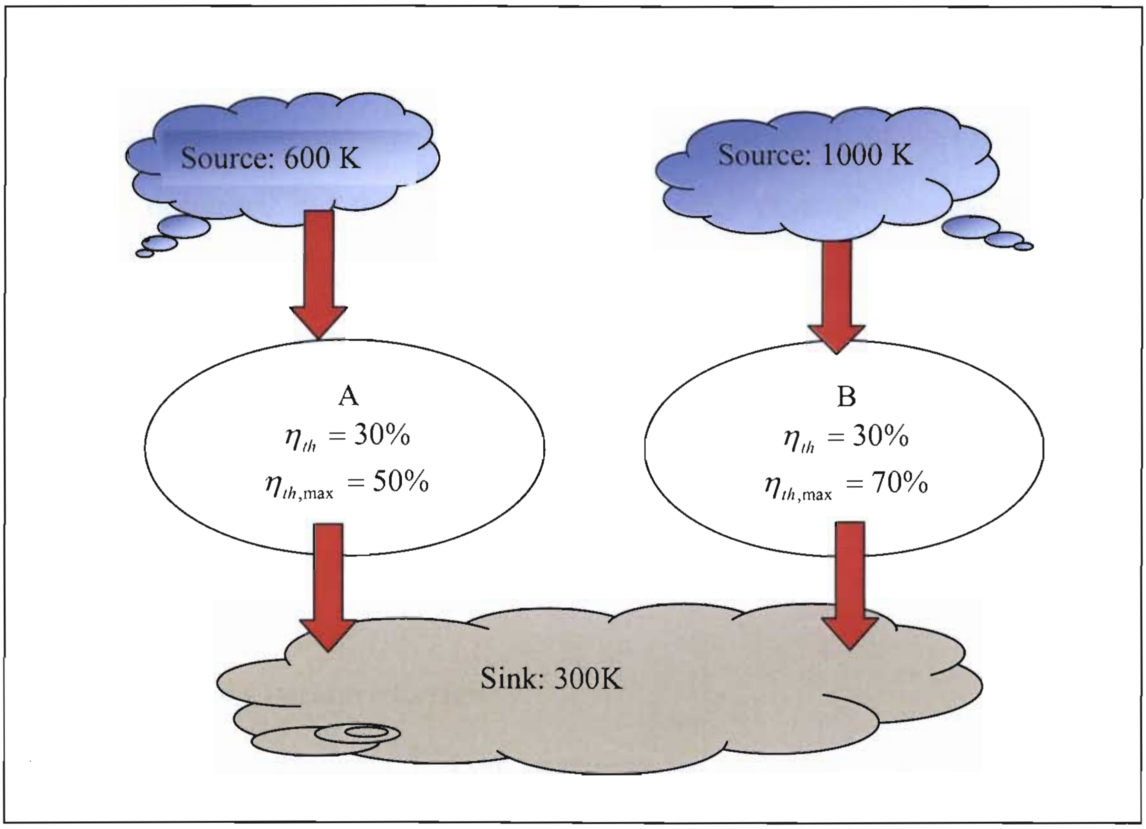


Figure 2.14 Engine A and Engine B

It is obvious that the first-law efficiency alone is not a realistic measure of performance of engineering devices. To overcome this deficiency, we define a **second-law efficiency** η_{II} as the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same condition:

$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}} \ (heat\ engine) \tag{2.30}$$

Based on this definition, the second-law efficiencies of the two heat engines discussed above are

$$\eta_{II,A} = \frac{0.30}{0.50} = 0.60 \qquad \eta_{II,B} = \frac{0.30}{0.70} = 0.43$$

That is, Engine A is converting 60% of the available work potential to useful work. This ratio is only 43 % for Engine B.

The second-law efficiency is intended to serve as a measure of approximation to reversible operation, and thus its value should change from zero in the worst-case (complete destroyed of exergy) to one in the best case (no destroyed of exergy). With this in mind, second-law efficiency of a system during a process is defined as (Yunus, & Michael, 1998).

$$\eta_{II} = \frac{Exergy\ recovered}{Exergy\ \ supplied} = 1 - \frac{Exergy\ destroyed}{Exergy\ supplied} \qquad (2.31)$$

2.10 Summary of Literature Review

Energy demand in Malaysia is ever increasing as the country moves towards as developed nation. Biomass energy in Malaysia has significantly increased in demand among all other resources including oil, gas, and hydro-electric power; i.e. from 7.9% in 2003 to 30.3% in 2005 (EPU, 2001). Five major sectors that possess potential biomass energy are oil palm industry, forestry products, agricultural byproducts (such as paddy residues), animal farming industry and urban wastes (Lim *et.al.,* 1999). Biomass gasification is a system that can convert any type of biomass to run shaft power systems, direct heat applications and chemical production. Biomass gasification technologies can be broadly divided into three groups; thermo-chemical, bio-chemical, and physico-chemical conversion processes. All these technologies are applicable in various types of biomass gasifiers of different designs including updraft, downdraft, bubbling fluidized-bed and circulating fluidized bed gasifiers. The process zones in a gasifier can be classified into four phases; drying process, pyrolysis process, oxidation process and reduction process. Economic analysis showed that gasification systems were for more economic advantage over conventional systems (FRIM, 2005). Exergy analysis is an analytical method used for the conservation of mass and conservation of energy principles together with the Second-Law of Thermodynamic for the analysis, design and improvement of energy.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This research project was carried out in 3 phases.

Phase I - Determination of Moisture Contents with respect to Calorific Values of Selected Biomass

i. To determine the moisture contents with respect to calorific values of (1) Paddy straw, (2) EFB, (3) POS, (4) sago bark, and (5) wood chips.

Phase II – Assessment and Field Tests on Existing B2F Conversion System

i. To determine the chemical compositions of AFRL;
ii. To determine the chemical compositions of raw (unburnt) combustible fuel gases (wood chips as feedstock);
iii. To determine the chemical compositions of raw (unburnt) combustible fuel gases (Balingian-Mukah Coal as feedstock);
iv. To determine nearby (<20 meters radius) ground-level incremental CO, combustibles gas, and total suspended particulate matters during operation; and
v. To identify the operational drawbacks of the existing B2F conversion system.

Phase III –Performance Evaluation of B2E Conversion System

i. To evaluate the performance of B2E conversion system with special focus on exhaust gas temperature distribution at combustible fuel gas-to-heat energy conversion chamber; and

ii. Assessment of nearby (<20 meters radius of B2E) incremental levels of CO, combustibles gas, and total suspended particulate matters during operation; and

iii. To carry out preliminary performance evaluation of B2E conversion system with emphasis on the following items.

   a. Exergy destroyed, $X_{destroyed}$,
   b. Overall efficiency of B2E conversion system,
   c. Second Law efficiency of B2E conversion system,
   d. Air flow rates,
   e. Effects of air flow rate on temperature distribution at combustible fuel gas-to-heat energy conversion chamber.

3.2 Phase I - Determination of Moisture Contents with Respect to Calorific Values of Selected Biomass

i. To determine the moisture contents and calorific values of: (1) paddy straw, (2) EFB, (3) POS, (4) sago bark, and (5) wood chips - using bomb calorimeter.

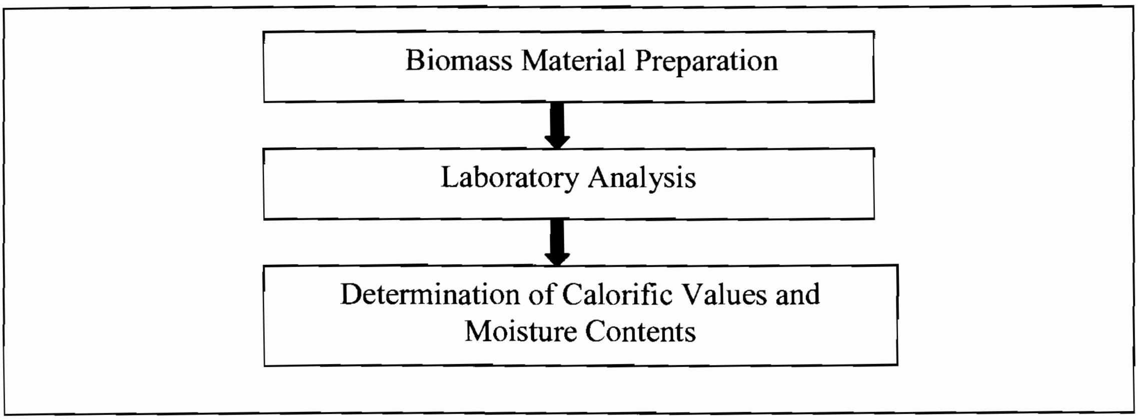


Figure 3.1: Phase I experimental work

3.2.1 Biomass Test Samples Preparation

The Sanyo GALLENKAMP automatic adiabatic bomb calorimeter-autobomb (Figures 3.3 and 3.4) was used to determine the heating values (HV) of solid and liquid fuel samples. The apparatus consists of a bomb calorimeter, i.e. a precision balance scale for weighing fuse and fuse samples. Figure 3.2 illustrates the biomass materials that were being tested for their respective heating values.

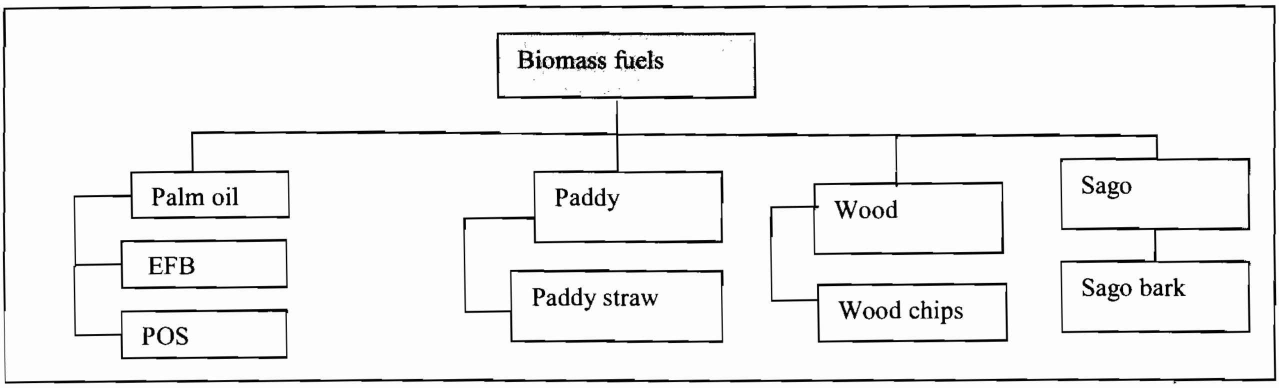


Figure 3.2: Selected biomass materials

Figure 3.3: Bomb calorimeter

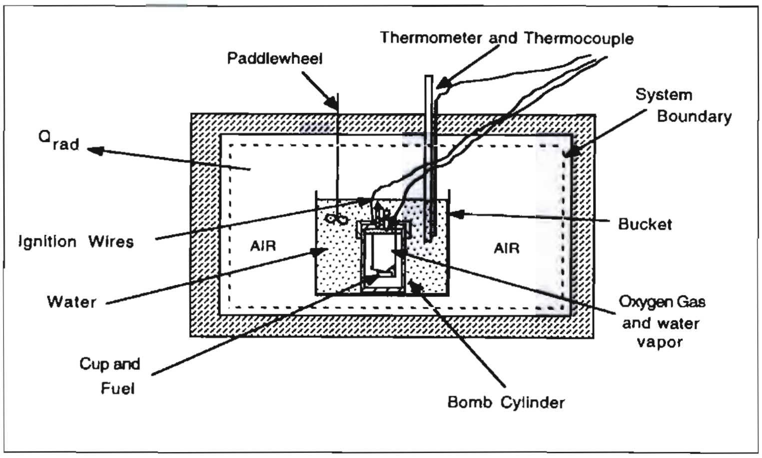


Figure 3.4: Schematic diagram of bomb calorimeter

The operation principle of this device is to burn a fuel sample of biomass and transfer the heat into a known mass of distilled water. The constant volume of distilled water and the constant pressure were controlled during combustion process in order to achieve accurate results. All the samples were blended and weighed to approximately 1.0 gram each. Each of the individual samples were "burnt" in the bomb calorimeter and energy content was subsequently determined.

3.2.2 Experiment Procedures: Biomass Heating Value

- The experimental work employed a bomb calorimeter to determine the calorific values of the selected biomass.
- Samples of paddy straw, EFB, POS, sago bark, and wood chips were cut into small pieces and ground to powder form using blender.
- Powdered samples were compacted into pallets by using Gallenkamp briquette presser (Figure 3.5).

- To determine the moisture contents of biomass, blended samples were dried in an oven at 60°C.
- A dry state of biomass is reached when the sample had attained a constant weight.
- Details of the determination of biomass heating values are shown in Chapter 4.
- Moisture contents of the individual biomass under investigation can be expressed as follow.

$$Moisture\ contents = \left(\frac{Natural\ state - Dry\ state}{Natural\ state} \right) x\,100\% \qquad (3.1)$$

Agricultural bio-waste sample

Sample being blended by using blender

Sample being compacted into pellet by using briquette presser

Figure 3.5: Biomass sample preparation for laboratory testings

3.3 Phase II – Assessment and Field Tests on Existing B2F Conversion System

The primary objective of phase II experimental work was to assess or evaluate the performance of the existing B2F conversion system which was located in 12th mile, Old Oya Road, Sibu. The details are as follows.

i. Determination of the chemical compositions of AFRL (wastewater);

ii. Determination of the chemical compositions of combustible gases (wood chips as feedstock);

iii. Determination of the chemical compositions of combustible gases (Balingian Coal as feedstock);

iv. Determination of nearby (<20 meters radius of emission source) ground-level incremental CO, combustibles gas, and total suspended particulates; and

v. Identification of the operational and environmental drawbacks faced by the existing B2F conversion system during operation.

3.3.1 The Existing Biomass-to-Fuel Gases (B2F) Conversion system

A mini-sized B2F conversion system (Figures 1.1 and 1.2) at 12th Mile Oya Road, Sibu, Sarawak was developed, constructed and tested for drying and heating purposes in commercialized industrial scale applications; mushroom culture industry, egg tray manufacturing facilities, powdered coconut milk production, and paper recycling facilities. For this system, solid feedstocks (mainly biomass as wood chips) are gasified in the updraft B2F conversion system, and the fuel gas or combustible gas is produced by high temperature air mixture to maximize the efficiency of gasification process. The fuel gas is purified by filtration process before being used as low-medium heat value fuel for heating and drying purposes.

3.3.2 B2F: Engineering Functions of the Individual Components

i) An converter with upper receptacle and lower ash collection (Figure 3.6);

ii) A material feed-in opening on top of upper receptacle for introducing biomass into converter;

iii) A lid to cover upper receptacle (Figure 3.7);

iv) A plurality of air inlets at the bottom of upper receptacle to enhance conversion;

v) The B2F conversion system is also equipped with filter connected to the receptacle by a gas conveying pipe (Figures 1.1 and 1.2);

vi) The filters of the B2F conversion system are equipped with the following features (Figures 3.8 and 3.9):

  - An inlet connected with gas conveying pipe;
  - An internal vertical duct at the middle of filter; and
  - An outlet connection at the upper part of internal vertical duct to direct the filtered gas for usage.

vii) The internal vertical duct of the filter is made up of a wider dimensional opening at the bottom end and form a conical shape duct as it moves further up before the vertical duct (Figure 3.9).

viii) There is an external chamber with a tap for removal of overflowed liquid in the filters (Figures 3.6 and 3.7);

ix) The receptacle of the system includes an upper gas storage case for storing combustible gas before sending it to gas conveying pipe;

x) The B2F conversion system is equipped with a receptacle and bottom portion is insulated (made of heat-proof layer as the outer layer) to prevent loss of heat; and

xi) The system's receptacle comprises of a layer of fire-proof brick as the inner wall and a layer of water compartment surrounds.

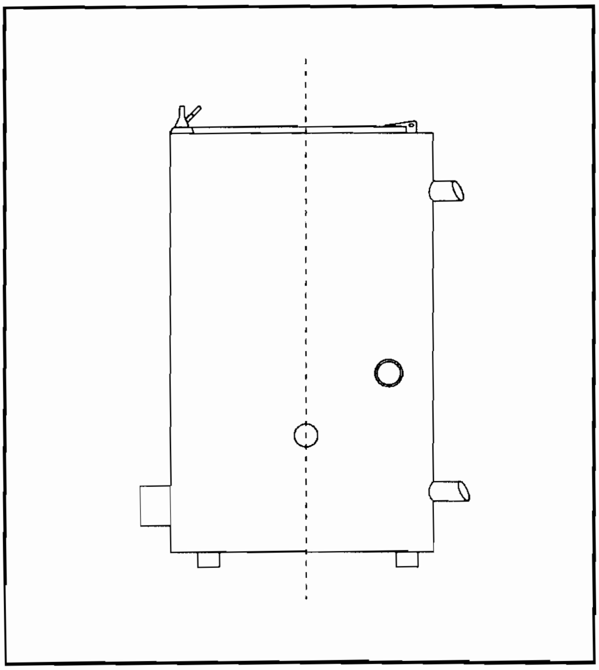


Figure 3.6: Cross-sectional illustration of B2F conversion system

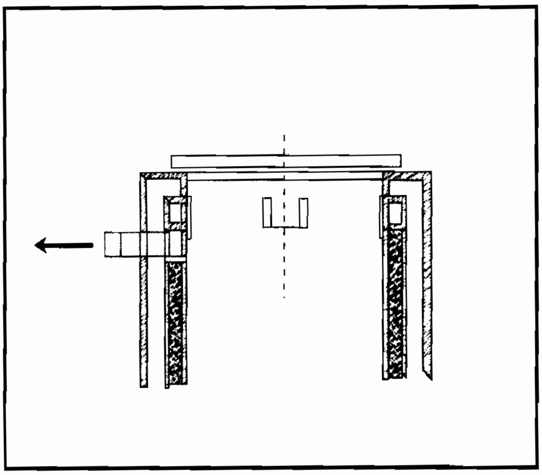


Figure 3.7: Cross-sectional view of the top part of B2F conversion system

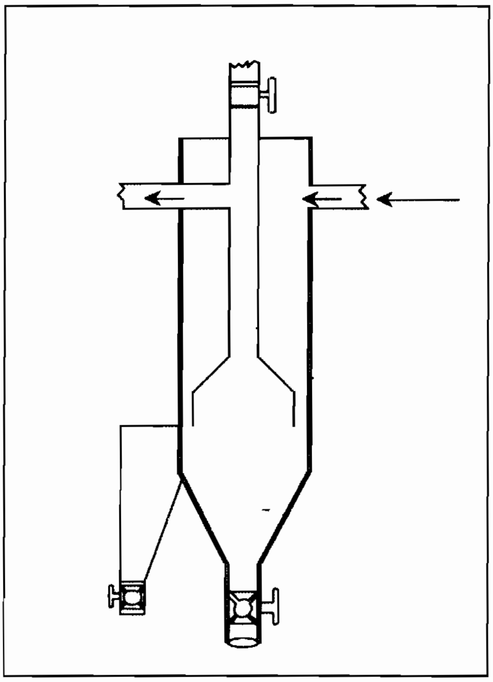


Figure 3.8: Cross-sectional view of filter unit

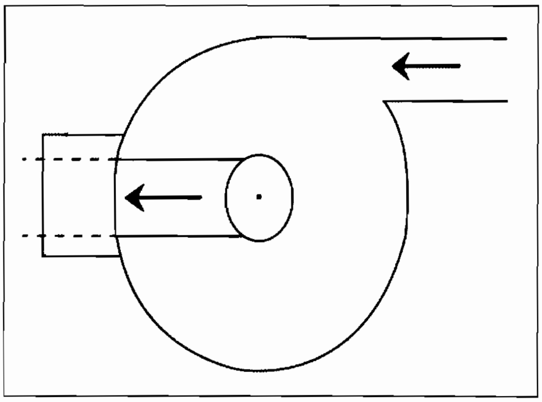


Figure 3.9: Cross-sectional view of filter unit

3.3.3 Equipment Used for Chemical Analysis

Fuel gas and AFRL samples (i.e. condensate collected at the bottom of filters) generated by biomass-to-fuel gas (B2F) were analyzed at Environmental Laboratory, Faculty of Engineering, UNIMAS. Gas chromatography mass spectrometer (GCMS) was used to determine the chemical components of the samples (Figures 3.10 and 3.11). The operation of this equipment consists of a narrow tube known as the "column" in which different kinds of chemical constituents of a sample pass in a gas stream (or carrier gas like hexane) at different rates, depending on their chemical, physical properties and interaction with a specific column filling (stationary phase). As the chemicals exited at the end of the column, they would be detected and identified electronically. The sole function of stationary phase was to separate different chemical components, this would cause different chemical components to exit the column at different times (retention times). The main components of GCMS include the (a) auto sample, (b) inlet (injector), (c) column, and (d) electronic detector (Figures 3.10 and 3.11). The functions of the individual components are described in the following paragraphs.

a) Auto Sampler - The task for auto sampler is to introduce the sample into the inlet.
b) Inlet (Injector) - To introduce a sample into a continuous flow of carrier gas.
c) Column – The column serves as a channel to the detector. Molecular adsorption in the column is very sensitive. For instance, by reducing the temperature can result in greater separation, but can end up in very long elution times.
d) Electronic Detector - To detect the chemical components sent by the column.

Figure 3.10: HP 5890 series II Plus GCMS

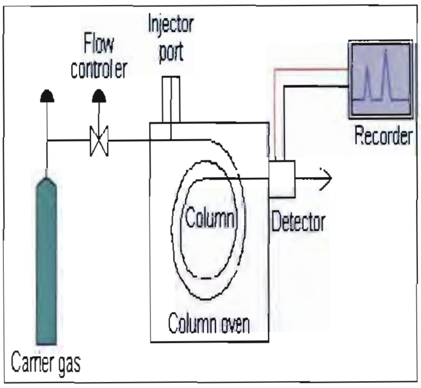


Figure 3.11: Schematic diagram of GCMS

3.3.4 Experimental Procedures

Raw (unburnt) combustible fuel gas samples at pyrolysis chamber generated by the B2F were collected (by Standard Procedure) and analyzed (using Standard Method) by and SIRIM Chemistry Laboratory (Kuala Lumpur). Samples of the condensate AFRL collected from bottom of filters were analyzed at Environmental Laboratory, Faculty of Engineering, UNIMAS. Gas chromatography mass spectrometer (GCMS) was used to determine the chemical components of AFRL samples (Figures 3.10 and 3.11). The chemical compositions of those samples that had been analyzed include the followings.

a) Condensate AFRL collected at bottom of filters,

b) Raw (unburnt) combustible fuel gases generated by pyrolysis of wood and coal, and

c) Assessment of nearby (<20 meters radius) incremental levels of CO, CH_4, combustible gases, and total suspended particulate matters.

a) AFRL Collected At Bottom of Filters

Test Method:

1. Inorganic analysis - Acid digest according to APHA 3030E (Standard Method) and heavy metals (Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mo, Ni, Se, Ag, V, Zn, B and Fe) analysis according to SW 846 610B.
2. Mercury analysis were performed in accordance to APHA 3112B (Standard Method).
3. Analysis of organic compounds.

i. Sample Treatment

A 100 ml of sample was extracted with 300 ml of hexane, the aqueous layer was discarded, and the collected hexane was evaporated to 1 ml by using rotary evaporator. GCMS was used as the primary analytical tool to determine the components contained in the mixture.

ii. Analytical Methods and Procedures

A 1.0 micro-liter (μl) of sample was injected into the gas chromatography (Agilent Technologies 5972 Inert Mass Selective Detector manufactured by Agilent Technologies) with the following preset conditions.

- Column: 30m x 0.25mm I.D x 0.25um film thickness DB5MS phenyl arylene polymer.
- Injector temperature: 250°C.
- Temperature program: 35°C - 250°C @10°C/min.

(b) Analysis of Exhaust Gas and Assessment of Nearby (<20 meters radius) Incremental Levels of CO, CH_4, Volatile Organic Compounds and Total Suspended Particulate Matters During Operation.

In this experimental fieldwork, wood chips and Balingian-Mukah coal had been used as feedstocks. During operation, samples for combustible fuel gas were collected at the exhaust (tail pipe effluent) point of the B2F and at nearby areas (<20 meters radius from emission source) for chemical compounds including CO, CH_4, volatile organic compounds and suspended particulate matters during operation. Details of sample analysis are outlined as follows.

I. Sample treatment: Sample was extracted with 2 ml of Hexane.

II. Analytical method: 1 (μl) of sample injected into Hewlett Packard HP 5890 Series II Plus GCMS and Hewlett Packard 5972 Series Mass Selective Detector with the following instrumental conditions:-

  - Column: 30m x 0.25mm I.D. x 0.25 um film thickness DB5MS phenyl arylene polymer.
  - Injector temperature: 280°C
  - Detector temperature: 280°C
  - Temperature program: 45°C-250°C @ 5°C/min
  - Splitless injection

3.4 Phase III - Performance Evaluation of B2E Conversion System

Phase III research works predominantly focused on the followings.

i. To evaluate the performance of B2E conversion system with special focus on exhaust gas temperature distribution at combustible fuel gas-to-heat energy conversion chamber.

The following parameters were investigated.

a. Exergy destroyed, $X_{destroyed}$ - Determine the loss work potential within the whole B2E conversion system

b. Overall efficiency of B2E conversion system.

c. Second law efficiency of B2E conversion system - Determine the second law efficiency of B2E conversion system.

d. Air flow rate - Determine the volume of air flow rate at different level

e. Effects of the rate of air flow rate on temperature – Determine the performance of B2E conversion system on temperature distribution at combustible fuel gas-to-heat energy conversion chamber with respect to air supply rate.

3.4.1 Experimental Fieldwork

A velocity meter was used to measure the air velocity at combustible fuel gas-to-heat energy conversion chamber. First, the air supply adjustment was regulated to Level 1, and the air or exit velocity was detected. The air or exit velocities for Level 2, 3, and 4 were measured with the same procedure. The temperatures at each chamber were recorded through the temperature indicator as the gasification process was operating, in addition to determination of the exergy destroyed, overall performance of B2E conversion system, and Second law efficiency of B2E conversion system.

CHAPTER 4

Theoretical Analysis

4.1 Theoretical Computations of Potential Energy

The heating value (HV) of fuel is the amount of heat released when a specific amount of fuel is completely burnt and the combustion products are cooled to the room temperature. The heating value can be determined by bomb calorimeter which is the higher heating value (HHV) when the water in the combustion gas is completely condensed. Heating value can be determined by the following expression.

$$\mathrm{HV} = \frac{C_{Apparatus} \quad x \quad (\Delta T)}{M_{Fuel}} \tag{4.1}$$

Where

HV = Calorific value per gram

$C_{Apparatus}$ = Heat capacity of apparatus (J/K). The given value is 9901.48 J/K obtainable during equipment calibration.

ΔT = Temperature rise (K). It is the change in temperature observed before and after operations.

M_{Fuel} = Mass of fuel sample (g)

4.2 Determination of Exergy Destroyed, Overall Efficiency and Second Law Efficiency of B2E Conversion System

a) Exergy Destroyed, $X_{destroyed}$

Control volume:

$$\sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{m}_i \psi_i - \sum \dot{m}_e \psi_e - \dot{X}_{destroyed} = \Delta \dot{X}_{system} \quad \text{(see 2.29)}$$

$_i$ denoted as inlet, $_e$ denoted as outlet.

Flow energy, $\psi = \dot{m}(h - TS)$ (4.2)

Where

T_o = Ambient temperature

T_k = Output temperature of the gasifier (combustible fuel gas-to-heat conversion chamber)

h = Enthalpy

$\dot{m}$ = Mass flow rate of air and biomass

$\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k$ = Exergy transfer by heat

$\dot{W}$ = Exergy transfer by work

$m_i\psi_i - m_e\psi_e$ = Exergy transfer by mass

$$\sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k + \dot{m}_1(h_1 - T_o S_1) - \dot{m}_2(h_2 - T_o S_2) = \dot{X}_{destroyed} \quad \text{(see 2.29)}$$

$$\dot{m}_1 = \dot{m}_2 \quad (4.3)$$

b) Overall Efficiency of B2E Conversion system

The overall efficiency of B2E conversion system defined in energy based, e.g. the heating value of the gaseous products divided by the heating value of the biomass feedstock (Yunus, & Michael, 1998).

$$\mathit{Overall\ efficiency} = \left(\frac{\mathrm{HV}_{\text{gaseous products}}}{HV_{Biomass}\ x\ \dot{m}_{fuel}} \right) 100\% \qquad \text{(see 2.8)}$$

Where

$\mathrm{HV}_{\text{gaseous products}}$ = Heat value of gaseous products

$\mathrm{HV}_{\text{Biomass}}$ = Heat value of biomass

$\dot{m}_{fuel} = mass\ flow\ rate\ of\ biomass$

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Phase I: Determination of Biomass Moisture Contents and Respective Calorific Values

Phase I experimental works focused on (i) determination of moisture contents and respective calorific values of paddy straw, EPB, POS, sago bark and wood chips using bomb calorimeter.

5.1.1 Selected Biomass Samples

The main reason for choosing paddy straw, EFB, POS, sago bark, and wood chips for this study was due to their vast availability in tropical region such as Malaysia.

5.1.2 Moisture Content of Biomass

Biomass moisture content has a strong relationship with calorific value. The higher the moisture content, the lower will be the calorific value. This is due to the evaporation of moisture in thermal processing that would reduce the energy efficiency (TUE, 2005). In this experiment, a temperature of 60°C was applied to all the samples until a dry state was attained.

Figure 5.1: Oven-dried samples

5.1.3 Moisture Content versus Calorific Value

A comparison of moisture content of five different types of biomass investigated is shown in Table 5.1. Figure 5.2 illustrates the plots of paddy straw with moisture content of as high as 97.75%. This was followed by EFB 95.34%, sago bark 96.05%, POS 95.28%, and wood chips 11.61%. The differences in moisture content in various types of locally available biomass understudied could be attributed to their differences in chemical compositions and cell structures.

Table 5.1: Moisture content of selected biomass

Gasification Fuel	**Moisture Content (%)**
Paddy straw	97.75
EFB	95.34
Sago bark	96.05
POS	95.28
Wood chips	11.605

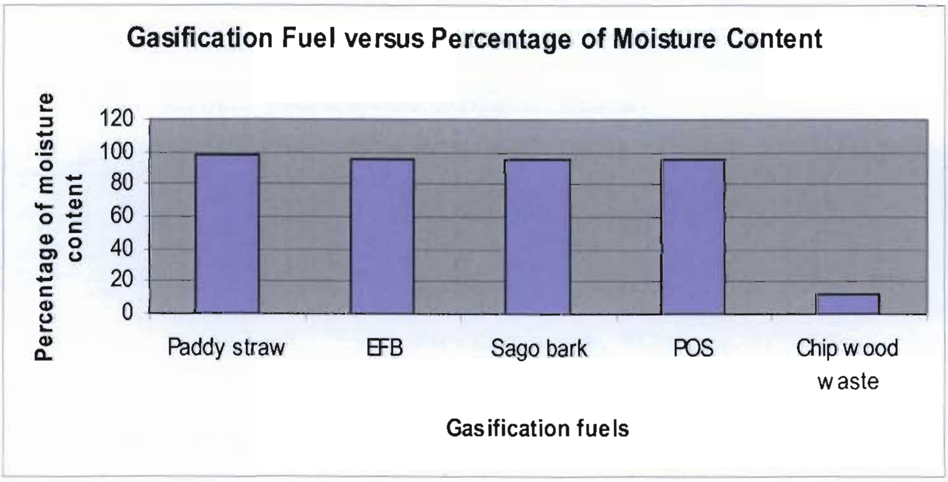


Figure 5.2: Gasification fuel versus moisture content

A total of 60 biomass samples were tested for their respective calorific values. The natural state of the samples were collected from agriculture fields. Detailed experimental results of the individual biomass heating values were determined using bomb calorimeter. The calorific values of paddy straw, EFB, POS, sago bark and wood chips are shown in Table 5.2 and Figure 5.3 while the computational details are attached in Appendix A.

Table 5.2: Calorific values of paddy straw, EFB, POS, sago bark and wood chips

Sample	**Paddy straw**	**EFB**	**Sago bark**	**POS**	**Wood chips**
Natural state	5.43 MJ/kg	10.89 MJ/kg	0.63 MJ/kg	17.13 MJ/kg	18.05 MJ/kg
Dry state	15.33 MJ/kg	17.82 MJ/kg	19.56 MJ/kg	21.40 MJ/kg	22.41 MJ/kg

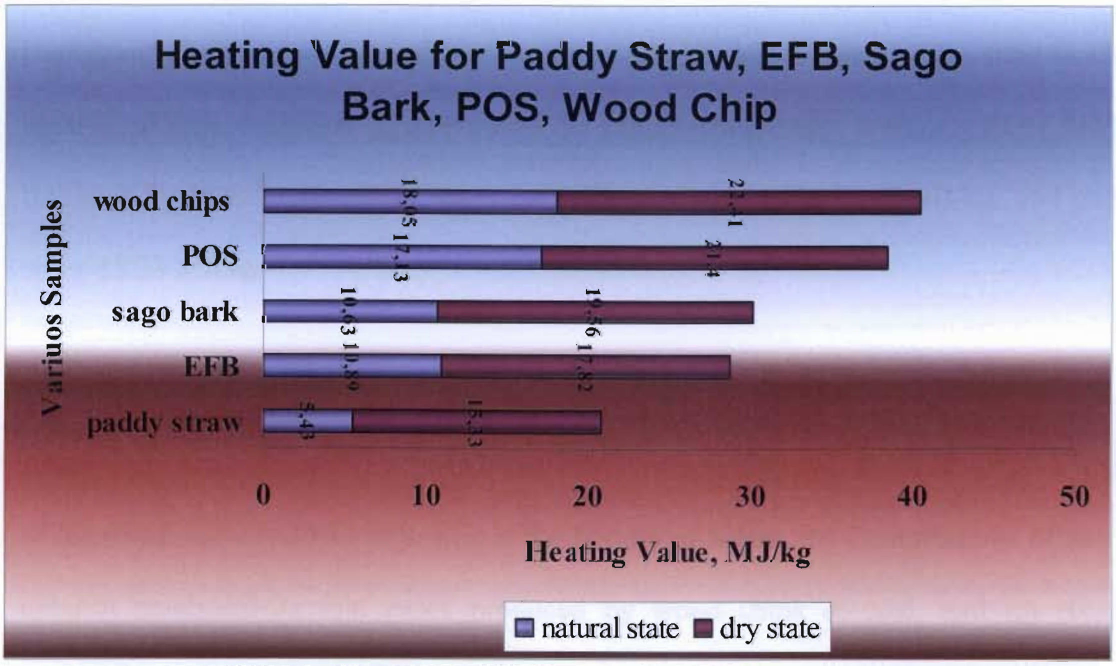


Figure 5.3: Calorific values of paddy straw, EFB, POS, sago bark and wood chips

5.1.4 Effects of Moisture Content on Calorific Value

Experimental results showed that moisture content in biomass could have a strong correlationship with calorific values (Table 5.2). This is due to the amount of energy required to dry the moisture contained in the biomass. Besides moisture content and other properties such as chemical compounds, bulk density and morphological properties could also play an important role in determining biomass calorific values (FOA, 1986). This gasification of biomass involves converting the chemical energy contained in the biomass into chemical energy contained in the gaseous products and sensible energy of the produced gas. According to the first-law of thermodynamics, energy can never be lost. Therefore, it is justifiable to state that energy conversion process does not have energy losses, except for the losses from the process system into the environment (Mark, 2005). As plotted in Figure 5.3, it was shown that the calorific values increased significantly as the moisture content was decreased. Wood chips in dry state had the highest calorific value among others with its value recorded approximately 22.41 MJ/kg, followed by POS 21.40 MJ/kg, sago bark 19.56 MJ/kg, EFB 17.82 MJ/kg, and paddy straw 15.33 MJ/kg.

5.2 Phase II: Assessment and Field Tests on Existing B2F Conversion System

Assessment and evaluation of the existing B2F conversion system focused on the analysis of (a) Condensate (AFBL) collected at the bottom of filters, (b) Compositions of raw or unburnt combustibles fuel gases produced by wood chips & coal, and (c) Nearby incremental levels of CO, CH_4, combustible gases and suspended particulate matters during operation.

The operational drawbacks of B2F conversion system were identified during on-site assessment and tests. The followings are the major shortcomings of B2F conversion system.

i. Level of phenol contained in the AFRL measured as high as 5,310 mg/L, which exceeded the 0.001 mg/L limit and thus does not comply with the Standard A and Standard B established under the Environmental Quality (Sewage and Industrial Effluents) Regulations, 1979;
ii. Approximately 1.5% tars and 13% AFRL were produced as by-products. This amount of organics indicated that the AFRL should not be discharged directly into watercourses without pretreatment;
iii. Feedstock input by batch process led to non-continuity in operation;
iv. System experienced inconsistency in the production of fuel gas;
v. Emissions or leakages and incomplete combustion of combustible fuel gas; and
vi. System tended to get overheated.

a) Characteristics of AFRL Collected at Bottom of Filters

Analysis Assumptions:

(i) Density of hexane extract = 1.0 g/ml
(ii) All phenol derivatives were detected as phenol in the standard method for phenol determination according to APHA 5530D.

As shown in Table 5.3, some of the inorganic and heavy metals contained in the condensate (AFRL) were not in compliance with Standard A and Standard B (parameter limits of effluent set in Environmental Quality (Sewage and Industrial Effluents) regulation, 1979), with the inclusion of cadmium (0.08mg/L), nickel (1.0 mg/L) and lead

(1.73mg/L). AFRL produced by B2F conversion system were analyzed for organic groups, organic compounds and chemical class. Analyses were carried out using GCMS (wood chips had been used as feedstock and analysis by hexane extract) (Table 5.4 and Table 5.5). Example of results obtained from GCMS analysis is illustrated in Figure 5.4.

Table 5.3: Inorganics and heavy metals in AFRL as compared to Standard A and Standard B

Parameter	**Concentration in AFRL (mg/L)**	**Standard A (mg/L)**	**Standard B (mg/L)**
Silver, Ag	0.005	N/A	N/A
Arsenic, As	<0.007	0.05	0.10
Boron, B	119	1.0	4.0
Barium, B	0.29	N/A	N/A
Beryllium, Be	0.0008	N/A	N/A
Cadmium, Cd	0.08	0.01	0.02
Cobalt, Co	0.18	N/A	N/A
Chromium, Cr	0.77	N/A	N/A
Copper, Cu	0.04	0.20	1.0
Iron, Fe	0.375%	1.0	5.0
Molybdenum, Mo	<0.001	N/A	N/A
Mercury, Hg	0.001	0.005	0.05
Nickel, Ni	1.0	0.20	1.0
Lead, Pb	1.73	0.10	0.5
Antimony, Sb	0.11	N/A	N/A
Selenium, Se	0.06	N/A	N/A
Thallium, TI	0.11	N/A	N/A
Vanadium, V	<0.001	N/A	N/A
Zinc, Zn	18	2.0	2.0

Note * Standard A and Standard B refer to the parameter limits of effluent set in Environmental Quality (Sewage and Industrial Effluents) regulation, 1979

Table 5.4: AFRL produced by B2F - organic group/chemical class analysis using GCMS (wood as feedstock and analysis by hexane extract)

Sample code	**Organic group/Chemical class**	**Constituents**	**Area (%)**	**Quality hit list**
Sample	**Hydrocarbon**			
	Alkene	Methyl-cycloheptene	0.07	68
		1,2,3,4 tertramenthyl-cyclobutene	0.18	72
		1-Methoxy-1,3-cyclohexadiene	0.11	64
		2,5-dimethyl-2,4-hexadiene	0.30	74
		2-methyl-1,2,3-hexadiene	0.30	64

		9,10-dihydro-1-methyl-phenanthrene	0.10	72
		9,10-dihydro-1-methyl-phenanthrene	0.10	72
	Alkane	3-methoxy-4-hydroxyphenone propane	0.17	74
	Aromatic	Phenol	1.83	91
		2-methoxyphenol	8.85	97
		2-methoxy-4-methyl phenol	8.80	60
		2-ethyl-phenol	0.25	93
		2,4-dimethyl-phenol	2.66	97
		2,6-dimethyl phenol	0.55	98
		3,5-dimethyl phenol	2.27	90
		2,3-dimethyl-phenol	1.20	87
		3,4-dimethyl phenol	0.78	93
		3,4,5-trimethyl-phenol	0.25	81
		2-ethyl-6-methyl phenol	0.11	91
		4-ethyl-3-methyl phenol	0.32	95
		2,6-dimethoxyl-phenol	0.46	83
		2,4,5-trimethyl-phenol	0.28	93
		2-methoxy-benzeneethanol	2.69	97
		2-methoxy-4-vinylphenol	0.32	90
		2,4,5-trimethyl-phenol	0.42	70
		2,6-dimethoxy-phenol	13.62	91
		2-methoxy-4-propyl-phenol	0.42	94
		2-methoxy-4 (1-propeny)-phenol	0.46	97
		2,6-dimethoxy-4-(2-propenyl)-phenol	0.81	97
		(3S)-2-cholo-1-phenyl-1-penten-3-ol	0.65	74
		2,6-dimethoxy-4-(2-proprnyl)-pehnol	0.30	93
		2,6-dimethoxy-4-(2-propenyl)-phenol	0.57	93
		3-methyl-phenol	7.57	95
		2-etyly-5-methyfuran	0.29	64
		2,4-dimethyl-3-(methoxycarbonyl)-5-ethyfuran	3.74	86
	Benzene derivative	1,2,3-trimethoxybenzene	0.35	95
		1-ethenyl-4-methyl-benzene	0.19	90
		1,2,4-trimethoxybenxene	0.34	86
		1,2,3-trimethoxy-5-methyl-benzene	0.36	98
		5-ethyl-1,2,3-trimethoxybenzene	0.19	86
	Toluene derivative	2,3-dimethoxytoluene	0.47	95
	Halogens			
	Fluoroalkane	3,4-dimethoxyphenylacethydrazide salicylamide	0.14	60
	Oxygen			

	Alcohol	o-cresol	3.55	98
		Bis (2-methylpropyl) ester 1,2-benzenedicarboxykic acid	0.02	72
		Ethyl6,6-di-methyl-2-oxobicyclo [3.1.1] heptane-3-carboxylate	0.10	64
		5-methyl-2-furancarboxaldehyde	1.24	76
		Alpha-phdroxy-4-methoxy-benxeneacetic acid	0.07	60
	Ketone	2-methyl-2-cyclopenten-1-one	0.34	91
		3,4-dimethyl-2cyclopenten-1-one	0.27	90
		2-methylenecyclobutanone	0.05	64
		4,5-dimethyl-2-cyclohexen-1-one	0.13	72
		2,3-dimethyl-2-cyclopen-1-one	2.91	68
		3-ethylcyclopent-2-en-1-one	0.42	93
		6,6-dimethyl-spitol [2,3] hexan-4-one	0.49	68
		3-ethyl-2-hydroxy-2-cyclopenten-1-one	0.59	81
		1-(1-cyclohexen-1-yl) ethanone	0.40	60
		2-hydroxy-3-propyl-2-cyclopenten-1-one	0.27	91
		2,3-dihydro-1H-iden-1-one	0.92	95
		2,3-dihydro-3-methl-1H-iden-1-one	0.18	95
		4-methyl-1-indanone	0.17	96
		3-acetyl-6-methyl-2H-pyran-2,4 (3H)-dione	10.08	72
		1-(4-hydroxy-3methoxyphenyl)-ethanone	0.23	93
		1-(4-hydroxy-3-methoxyphenyl)-2-propanone	0.25	90
		1-(3,4,5-trimethoxypehnyl)-ethanone	0.03	68
	Carboxylic acid	Butanoic acid	0.02	72
		2-methyy-butanoic acid	0.05	64
		4-hydroxy-3-methoxy-methyl ester benzoic acid	0.15	95
	Nitrogen			
	Pyridine derivative	2-methoxy-5-nitro-pyridine	0.06	89
	Amide	1-ethyl-1-phenyl-hydrazine	0.62	90

*Based on chromatogram and quantitative report, the major peaks with hit list quality above 60 were tabulated

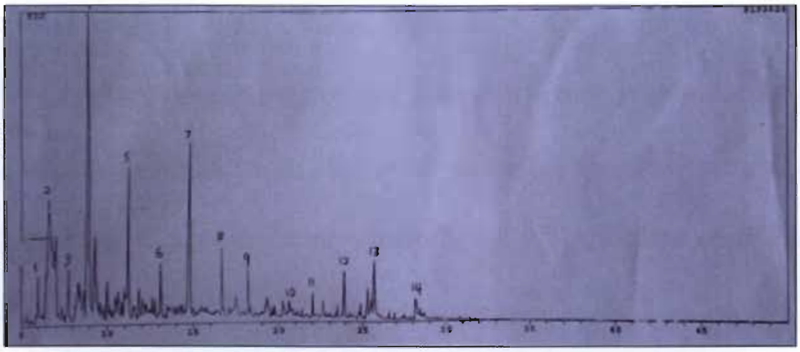


Figure 5.4: Example of results obtained from GCMS analysis

Table 5.5: AFRL produced by B2F – organic compounds analysis (wood as feedstock and analysis using GCMS)

No.	**Retention time**	**Compound Name**	**SI**	**MW**	**MF**
1	5.983	2-Cyclopenten-1-one, 3 methyl	90	96	C_6H_8O
2	6.608	Phenol	90	94	C_6H_6O
3	7.792	2,3-Dimethyl Cyclopent-2en-1-one	92	110	$C_7H_{10}O$
4	8.967	Mequinol	87	124	$C_7H_8O_2$
5	11.275	Phenol,2-memoxy-4-methyl	75	138	$C_8H_{10}O_2$
6	13.133	Benzene, 1,4-dimethoxy-2-methyl	86	152	$C_9H_{12}O_2$
7	14.850	Phenol, 2,6-dimethoxy	93	154	$C_8H_{10}O_3$
8	16.692	1,2,3-Trimethoxybenzene	80	168	$C_9H_{12}O_3$
9	18.217	Benzene, 1,2,3-trimethoxy-5-methyl	79	182	$C_{10}H_{14}O_3$
10	20.608	Methyl-[2-hydoxy-3-ethoxy-benxyl]emer	73	182	$C_{10}H_{14}O_3$
11	22.017	Ethanone, 1-[4-hydroxy-3,5-dimethoxyphenyl]	90	196	$C_{10}H_{12}O_4$
12	23.917	Caffeine	90	194	
13	25.708	Hexadecanoic acid	92	256	$C_{16}H_{32}O_2$
14	28.142	9,12-Octadecadienoic acid	92	280	$C_{18}H_{32}O_2$

b) Analysis of Raw (unburnt) Combustible Fuel Gases Produced by Balingian-Mukah Coal & Wood Chips

Table 5.6 shows the analysis results of raw (unburnt) combustible fuel gas chemical profile (wood chips and Mukah-Balingian coal as feedstock). For comparison purpose, a summary of analysis results of the fuel gases from low grade Balingian-Mukah Coal and wood chips as feedstock and exhaust emissions are summarized in Table 5.7. Compositions of organic compounds of raw (unburnt) combustible fuel gases generated by low grade Balingian-Mukah coal and wood chips (as feedstock) are shown in Table 5.6. It was found that there were approximately 23-29% gasoline constituents, 15-30% diesel constituents, 1-16% CO_2, 10-13% O_2, CO, SO, NO and H_2O, and 46-71% combustible gases.

Table 5.6: Raw (unburnt) combustible fuel gas chemical profile (wood chips and Mukah-Balingian coal as feedstock)

Sample code	**Constituents identified with hit list quality above 80**		**Percentage, %**
Wood chips as feedstock	Ethy-benzene	Constituents of gasoline	1.990
	Propyl-benzene		1.490
	1-ethyl-3-methyl-benzene		3.735
	1,2,5-trimethyl-benzene		3.842
	1-methyl-2-propy-1-benzene		3.342
	2-ethyl-1,4-dimethyl-benzene		2.168
	Undecane		6.424
	5-Udecene		0.677
	Tridecane		1.207
	t-Decene	Constituents of diesel	3.415
	Decane		2.825
	5-Decene		0.895
	Dodecane		4.112
	1-heptyl-2-methyl-cyclopropane		6.395
	1-methyl-2-octyl-cyclopropane		3.434
	Nonyl-cyclopropane		0.801

Sample code	**Constituents identified with hit list quality above 80**		**Percentage, %**
	Ethy-benzene	Constituents of gasoline	10.117
	Nonane		3.854
	Propyl-benzene		1.819
	1-ethyl-2-methyl-benzene		6.293
	Undecane		2.132
	1-Decene		2.423
	Decane		4.042

Coal as feedstock	1-heptyl-2-methyl-cyclopropane	Constituents of diesel	1.626
	Octacosane		4.267
	Docosane		2.231
	11-decyl-docosane		4.490
	7-hexyl-eicosane		3.875
	Octadecane		4.042
	Pentadecane		1.211
	Hencicosane		1.795
	9-octyl-heptadecane		3.962

Table 5.7: Summary of raw (unburnt) combustible fuel gas compositions generated by Balingian-Mukah coal and wood chips

Fuel gases	**Results**
Combustible gas composition	• Approximately 23-29% gasoline constituents • 15-30% diesel constituents • 8-12% poly-aromatics • 1-16% carbon dioxide (CO_2) • 10-13% of O_2, CO, SO, NO & H_2O • 46-71% combustible gases (i.e. gasoline & diesel constituents and poly-aromatics)

c) Nearby Incremental Levels of CO, Combustible Gases and Suspended Particulate Matters during Operation of B2F Conversion System

Table 5.8 shows the analysis results of exhaust gas (burnt), i.e. combustion byproducts of combustible fuel gas. The primary compositions of exhaust gas, i.e. wood chips as feedstock recorded approximately 3.5% O_2, 16.1% CO_2, >10,000 ppm CO, 271 ppm NO_x and 190 ppm SO. However, the key compositions of exhaust gas, i.e. Mukah-Balingian coal as feedstock measured 9.3% O_2, 10.1 CO_2, >10,000 ppm CO, 65 ppm NO_x and 25 ppm SO. It was shown that coal as feedstock of B2F conversion system produced relatively less pollutants in the exhaust gas.

Table 5.8: Analysis of exhaust gas (combustion byproducts of combustible fuel gas)

Fuel (Feedstock)	**Oxygen %**	**CO_2 %**	**CO ppm**	**NO ppm**	**NO_2 ppm**	**NO_X ppm**	**SO ppm**
Wood chips	3.5	16.1	>10,000	271	N.D	271	190
Coal	9.3	10.1	>10,000	65	N.D	65	25

*N.D means Not Detected

During operation, nearby (with 20 meters radius) incremental pollutant levels measured 25-40 ppm CO, 6-10 ppm H_2S, 80-110 $\mu g/m^3$ suspended particulates and <30 $\mu g/m^3$ ash and charcoal (negligible amount), 10-13% H_2O condensate, and 1-2% tars (Table 5.9). The primary functional groups of organic chemical compounds (contained in both raw combustible fuel gas and exhaust gas are summarized in Table 5.10. Other related researches showed that those air pollutants may induce respiratory problems such as asthma, lung cancer cardiovascular issues and premature death. Thus, it is essential to reduce or eliminate them, if possible so as to comply with the standards set by European Union (Wikipedia, 2008).

Table 5.9: Nearby incremental air pollutants during operation

Fuel gases	**Results**
Exhaust emissions	• 25-40 ppm CO • 6-10 ppm H_2S • 80-110 $\mu g/m^3$ total suspended particulates and <30 $\mu g/m^3$ PM_{10} • Negligible ash and charcoal • 10-13% H_2O condensate • 1-2% tars

Table 5.10: Functional group of organic chemical compounds

No.	**Functional group**	**Usage**	**Precaution**
1.	Hydrocarbon	- Combustible fuel sources	- High concentrated CO can lead to significant toxicity of the central nervous system and heart
2.	Halogen	- Used as disinfectants for drinking water, swimming pools	- Can be harmful to biological organisms in sufficient quantities
3.	Oxygen	- Essential purpose of respiration - A notable application of O_2 as a low-pressure breathing gas is in modern space suits - Industrial purpose for smelting of iron	- Oxygen gas (O_2) can be toxic at elevated partial pressures, leading to convulsions and other health problems - Highly-concentrated sources of oxygen promote rapid combustion
4.	Nitrogen	- To preserve the freshness of packaged or bulk foods (by delaying rancidity and other forms of oxidative damage) - In ordinary incandescent light bulbs as an inexpensive alternative to argon	- Rapid release of nitrogen gas into an enclosed space can displace oxygen, and therefore represents an asphyxiation hazard - Causes health issue, such as decompression sickness, severe frostbite

(adapted from Wikipedia, 2008)

5.3 Phase III: Performance Evaluation of B2EConversion System

5.3.1 B2E Conversion System: Engineering Function of Individual Components

The B2E conversion system aims to eliminate AFRL and tars, and substantial reduction in suspended particulate matters and volatile organic compounds in the exhaust gas. The B2E conversion system consists of 3 main components: 1) Pyrolysis Chamber, (2) Tar Removal or Conversion Chamber, and (3) Combustible Fuel Gas-to-Heat Energy

Conversion Chamber. Designs and engineering functions of the detailed individual components of B2E conversion system are described in the following sections.

1. **Stage 1: Pyrolysis Chamber**

- A ladder for input of feedstock into the hopper;
- A conveyor attaches onto the upper hopper which helps convey feedstock into the pyrolysis chamber automatically (Figure 5.10);
- A blower that introduces ambient air to the pyrolysis chamber;
- A 3-inch (7.62 cm) diameter ball valve for adjustment of air flow rate (Figure 5.10);
- A 11.5-inch (29.21 cm) opener on the side of pyrolysis chamber for initial ignition purpose (Figure 5.8);
- Two thermometers with 500 mm long detector to measure the temperatures of upper and lower parts of the pyrolysis chamber (Figure 5.12); and
- Interior wall of pyrolysis chamber is insulated with a 3-inch (7.62 cm) thick refractory cement and encapsulated in between two layers of 3-mm thick steel for sustaining elevated temperatures.

2. **Stage 2: Tar Removal Chamber**

- The tar removal chamber consists of 15.5-inch (39.37 cm) (W) x 17.5-inch (44.45 cm) (H) steel plates;
- Equipped with 2 numbers of 1-inch (2.54cm) diameter openings at the upper side to allow sufficient supply of ambient air for extended or complete conversion of tars and other residues;

- A 2.5-inch (6.35cm) diameter ball valve for control of air supply;
- The mechanism used for removal of tar by thermal conversion.
- Tar removal chamber is insulated with a 3-inch (7.62cm) refractory cement embedded between 2 layers of 3mm steel for resisting high temperature; and
- A thermometer with 300 mm long detector for measurement of temperatures inside the Tar Removal/Conversion Chamber (Figure 5.13).

3. Stage 3: Combustible Fuel Gas-to-Heat Energy Conversion Chamber

- This stage of the system serves as a combustion chamber for raw combustible fuel gases;
- This compartment consists of mild steel opener with 6-inch x 6-inch x 0.234-inch (15.24cm x 15.24cm x 0.6cm) (Figure 5.9); and
- A thermometer with 300 mm long detector for measurement of temperatures inside the fuel gas-to-heat energy conversion chamber (Figure 5.13).

Figure 5.5: A view of B2E conversion system

The following photos illustrate engineering design to detail of B2E conversion system:-

Figure 5.6: A view of B2E (Onsite)

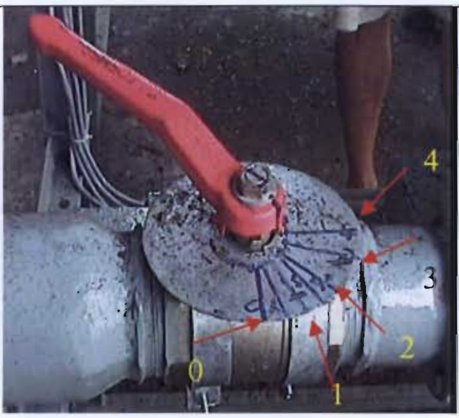


Figure 5.7: Air supply adjustments

Figure 5.8: A view of pyrolysis chamber

Figure 5.9: Exhaust gas exit point of B2E

Figure 5.10: Feedstock input rate

Figure 5.11: Temperature indicators

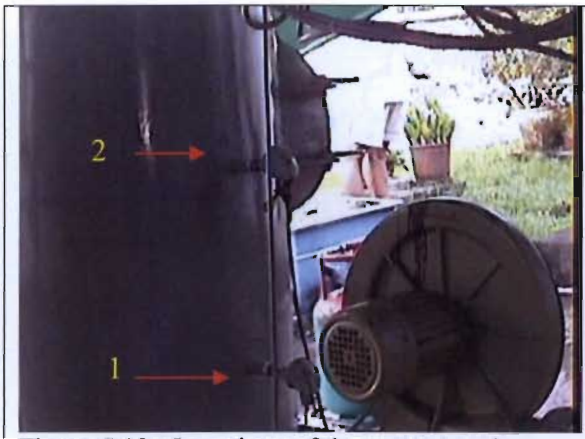


Figure 5.12: Locations of thermometers 1 and 2

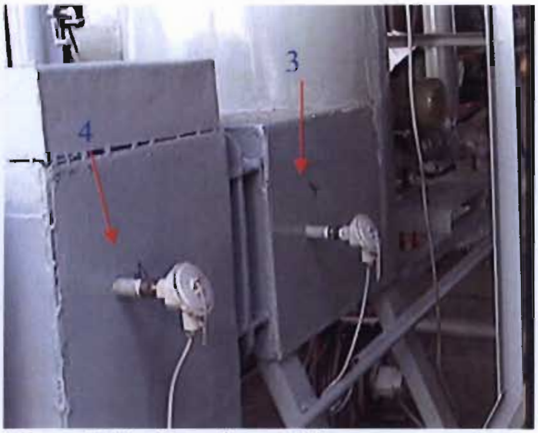


Figure 5.13: Locations of thermometers 3 and 4

Figure 5.14: Initial ignition of feedstock in pyrolysis chamber

5.3.2 Summaries of B2F and B2E Conversion Systems

The design and operational details of B2F and B2E are summarized in Figure 5.15 and Figure 5.16, respectively while Table 5.11 summarizes the operational characteristics.

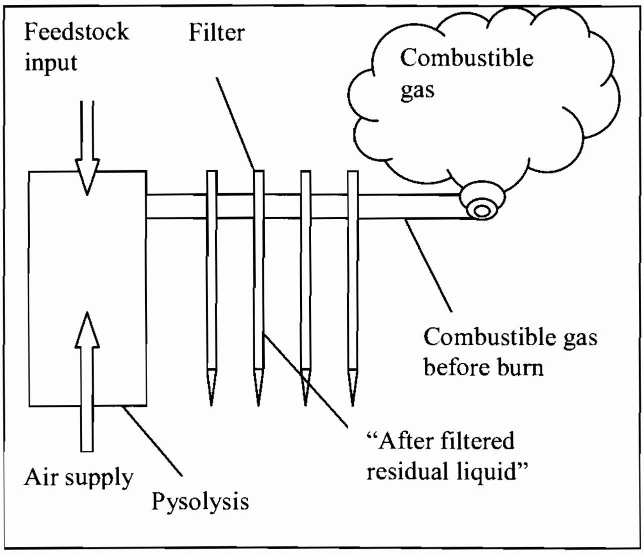


Figure 5.15 Summary design of B2F conversion systems

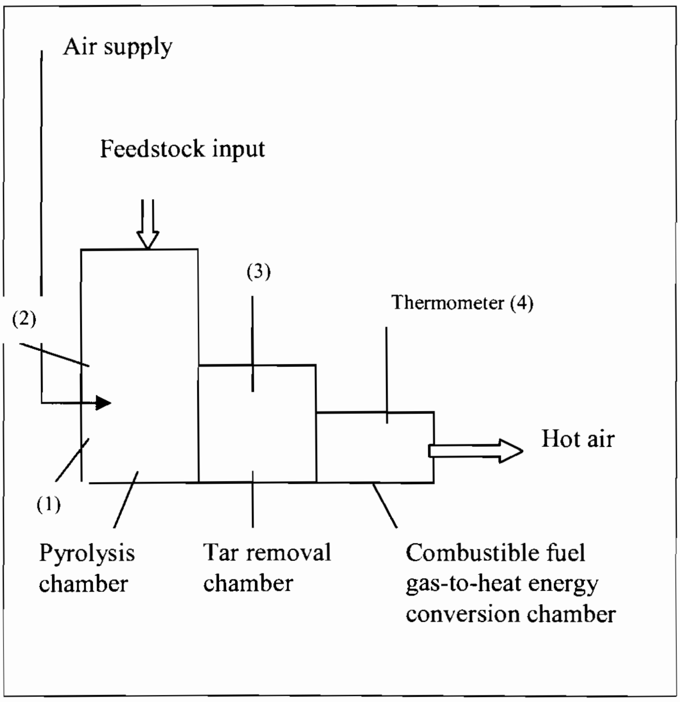


Figure 5.16 Summary design of B2E conversion system

Table 5.11: Summary of operational characteristics of B2F and B2E conversion systems

	Parameter	**B2F conversion system**	**B2E conversion system**
1	Overall design	Updraft	Downdraft
2	Feedstock input	Batch process	Continues
3	Air supply	Upward	Downward
4	"After filtered residual liquid"	Yes	No
5	Condensation filter	Yes	No
6	Tar removal camber	No	Yes
7	Fuel gas-to-heat energy conversion	No	Yes
8	CO, ppm	> 10, 000	< 3
9	H_2S, ppm	6-10	< 5
10	AFRL, mg/L	5,310	0
11	Total suspended particulate, $\mu g/m^3$	80 - 110	< 50

5.3.3 Nearby Incremental Levels of CO, Combustible Gases and Suspended Particulate Matters During Operation of B2E

Assessment of exhaust gas, i.e. combustion byproducts of combustible fuel gases produced by low grade Balingian-Mukah coal and wood chips (feedstock) are summarized in Table 5.12 for comparison purposes with B2F conversion system. Nearby incremental air pollutants emitted from exhaust tailpipe recorded <3 ppm CO, <5 ppm H_2S, <50 $\mu g/m^3$ suspended particulate matters, <10 $\mu g/m^3$ PM_{10}, negligible ash and charcoal, zero or negligible AFRL and tars. This was mainly due to the presence of high temperature within the gasifier and sufficient amount of contact time (detention time) available for conversion. The highest temperature recorded within the gasifier was 1,113°C.

Table 5.12: Nearby incremental air pollutant levels during operation

Emission Source	**Nearby Air Pollutants During Operation**
Exhaust Gas Emissions (combustion byproducts of combustible fuel gas)	• <3 ppm CO • <5 ppm H_2S • <50 $\mu g/m^3$ suspended particulate • <10 $\mu g/m^3$ PM_{10} • Negligible ash and charcoal • Zero/negligible H_2O condensate • Zero/negligible tar

5.3.4 Preliminary Performance Evaluation of B2E Conversion System

Phase III focused on the determination of performance of B2E conversion system and exhaust gas temperature distribution at combustible fuel gas-to-heat energy conversion chamber. The primary parameters understudied are as follows.

a) Exergy destroyed, $X_{destroyed}$,

b) Overall efficiency of B2E,

c) Second Law efficiency of B2E,

d) Air flow rates,

e) Effects of air flow rate on temperature distribution at combustible fuel gas-to-heat energy conversion chamber.

a) Exergy Destroyed, $X_{destroyed}$

In terms of the analysis of exergy destroyed, the results showed that exergy destroyed was 24.13 kJ/s (refer to Appendix C2) indicating that approximately 24.13 kJ/s could have been converted to work. Exergy balance equation for control volume can be written in the following expression.

Control volume: $$\sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k-\dot{W}+\sum\dot{m}_i\psi_i-\sum\dot{m}_e\psi_e-\dot{X}_{destroyed}=\Delta\dot{X}_{system} \tag{2.29}$$

$$\sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k+\left[\dot{m}_{air}\left(h_1-T_oS_1\right)\right]_{Air}+\left[\dot{m}_{Biomass}\left(h_1-T_oS_1\right)\right]_{Biomass}-\left[\dot{m}_{Air+Biomass}\left(h_2-T_oS_2\right)\right]_{Air+Biomass}=\dot{X}_{destroye} \tag{5.1}$$

$_i$ denoted as inlet (through pyrolysis chamber), $_e$ denoted as outlet (through combustible fuel gas-to-heat energy conversion chamber).

T_o = ambient temperature = 298 K

T_k = temperature at the exit of the gasifier = 671 K

h_1 = 298.182 kJ/kg

h_2 = 682.21 kJ/kg

s_1 = 1.695278 kJ/(kg.K)

s_2 = 2.52748 kJ/(kg.K)

m_{air} = 0.227 kg/s

$m_{Biomass}$ = 0.0447 kg/s

$\dot{X}_{destroyed(Air+Biomass)}$ = 24.13 kJ/s

b) Overall Efficiency of B2E Conversion System

The overall efficiency of B2E conversion system was approximately 90.48% (refer to Appendix C3), which means that if 90.48% of energy had been converted to useful work, approximately 9.52% of energy could have been wasted due to dry the biomass moisture content, heat transfer through surrounding, resistance to airflow design, and chemical reaction during combustion. The overall efficiency of B2E was higher than the conventional gasifier (about 10%) by only taking into consideration of pure air (did not include other gas such as methane).

$$\textit{Overall efficiency} = \left(\frac{\mathrm{HV}_{\text{gaseous products}}}{HV_{Biomass}\ x\ \dot{m}_{fuel}} \right) 100\% \qquad (2.8)$$

Where

$\mathrm{HV}_{\text{gaseous products}}$ = Heat value of gaseous products = 86.55 kJ/s

$\mathrm{HV}_{\text{Biomass}}$ = Heat value of biomass = 21.40 MJ/kg

$\dot{m}_{fuel} = mass\ flow\ rate\ of\ biomass$ = 0.227kg/s

$\mathrm{HV}_{\text{Biomass}}$ x $\dot{m}_{fuel}$ = 95.66 kJ/s

Overall efficiency = 90.48%

c) Second-Law Efficiency of B2E conversion system, η_{II}

The Second-Law efficiency of B2E conversion system was approximately 74.78% (refer to Appendix C4).

$$\eta_{II} = 1 - \frac{Exergy\ \ destroyed}{Exergy\ \ \sup plied} \qquad (2.31)$$

$$\eta_{II} = \left(1 - \frac{24.13}{95.66} \right) 100\%$$

$$\eta_{II} = \underline{74.78\%}$$

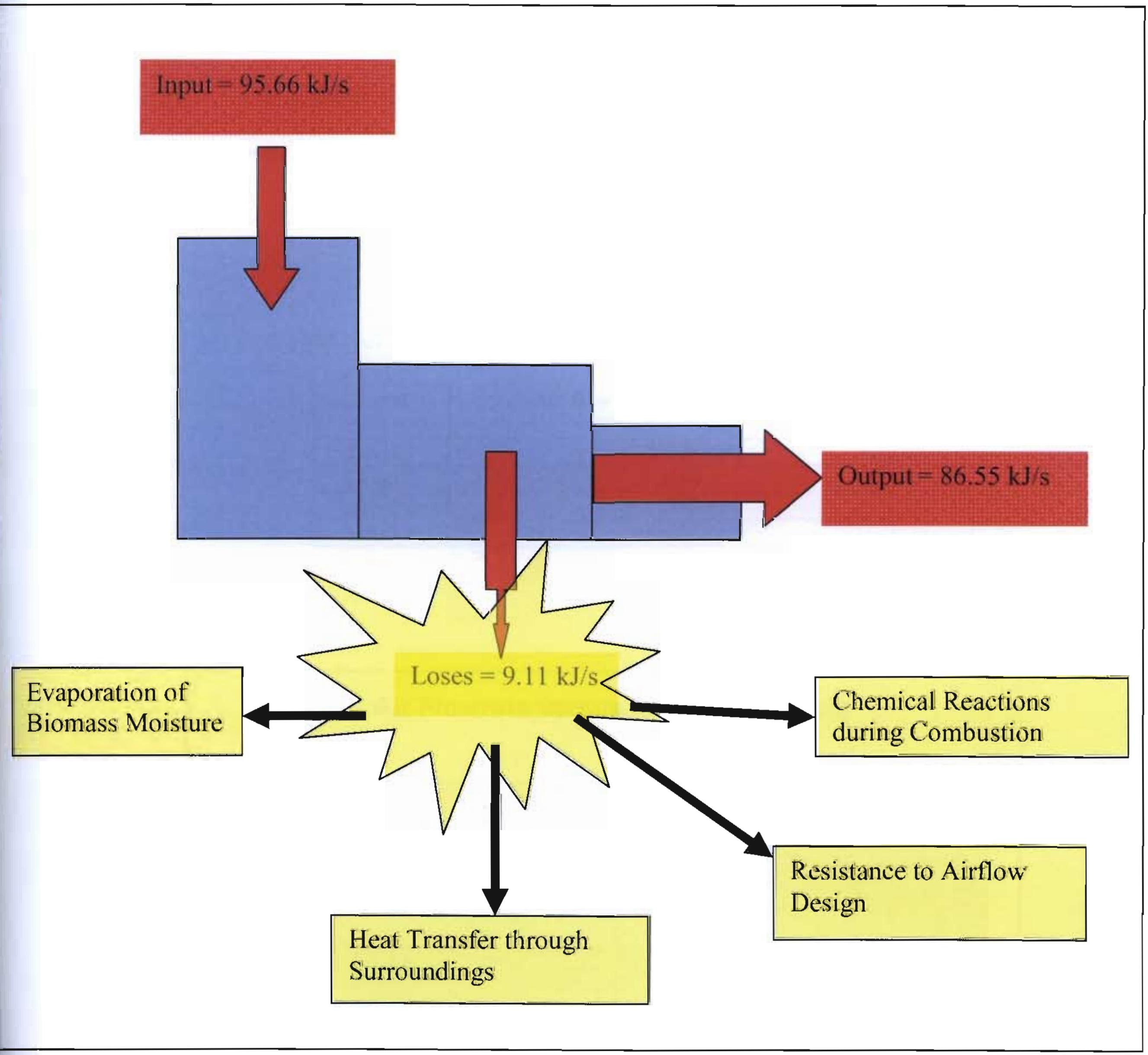


Figure 5.17 Overall performance of B2E conversion system

d) Air Flow rate

i) Air flow rate of B2E for Levels 1, 2, 3 and 4 were 0.00 m^3/s, 0.0160 m^3/s, 0.0398 m^3/s and 0.0558 m^3/s, respectively (Table 5.13 and Figure 5.18).

ii) The highest air flow rate was Level 4 delivering 0.0558 m^3/s and the lowest was <0.00 m^3/s (Level 1).

iii) Level 1 was not suitable for the operation of B2E because of zero air supply.

Table 5.13: Air flow rates versus blower adjustment levels

Level	**Air flow rate, Q = AV (m^3/s)**
Level 1	0.00
Level 2	0.0160
Level 3	0.0398
Level 4	0.0558

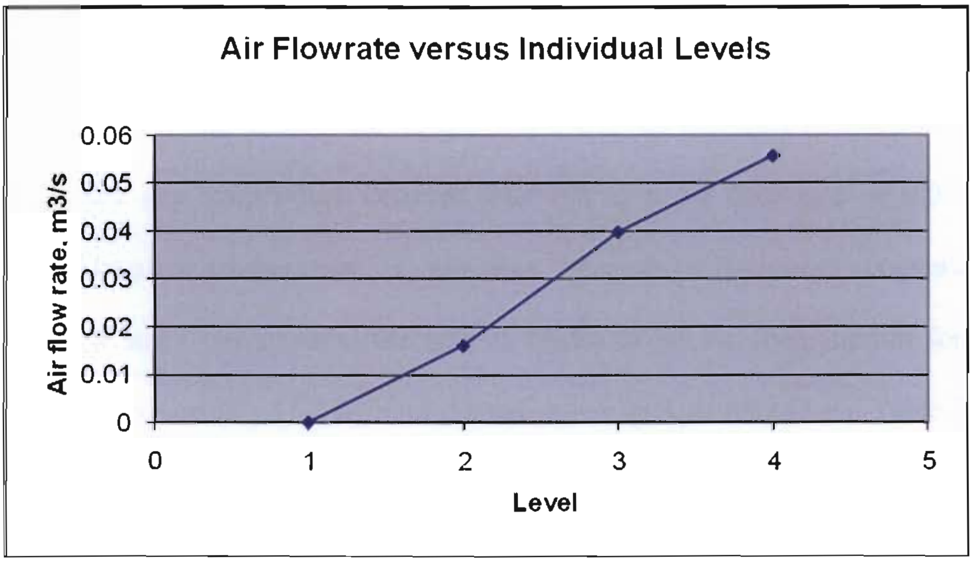


Figure 5.18: Plot of air flow rate versus adjustment level

e) Temperature Distribution at Combustible Fuel Gas-to-Heat Energy Conversion Chamber with Respect to Time, and Air Flow Rate

In this research, preliminary assessment of heat distribution focused on combustible fuel gas-to-heat energy conversion chamber, i.e. the exhaust or exit point of the system.

i) Air Flow Rate and Temperature versus Time

Figure 5.19 shows air flow rate and temperature detected in the exhaust gas versus operation time. In this experimental fieldwork, air flow rate served as independent variable, which means the air flow rate had been regulated from time-to-time to determine the effect of air flow rate on temperature distribution at combustible fuel gas-to-heat energy conversion system. Results showed that exhaust gas temperatures detected were directly proportional to air flow rates. The average temperature was 110°C with air flow rate of $0.016m^3/s$, followed by 242°C with air flow rate of $0.028m^3/s$, and 328°C with air flow rate of $0.0398m^3/s$, and 380°C with air flow rate of $0.0558m^3/s$. The highest exhaust gas temperature detected was 398°C at air flow rate of $0.0558m^3/s$. Generally, elevated temperature is desirable because it promotes conversion or elimination of tars. On average, the rate of feedstock (POS) consumption for whole process was approximately 16.0 kg/hour (Detail shown in Appendix D and Table D1).

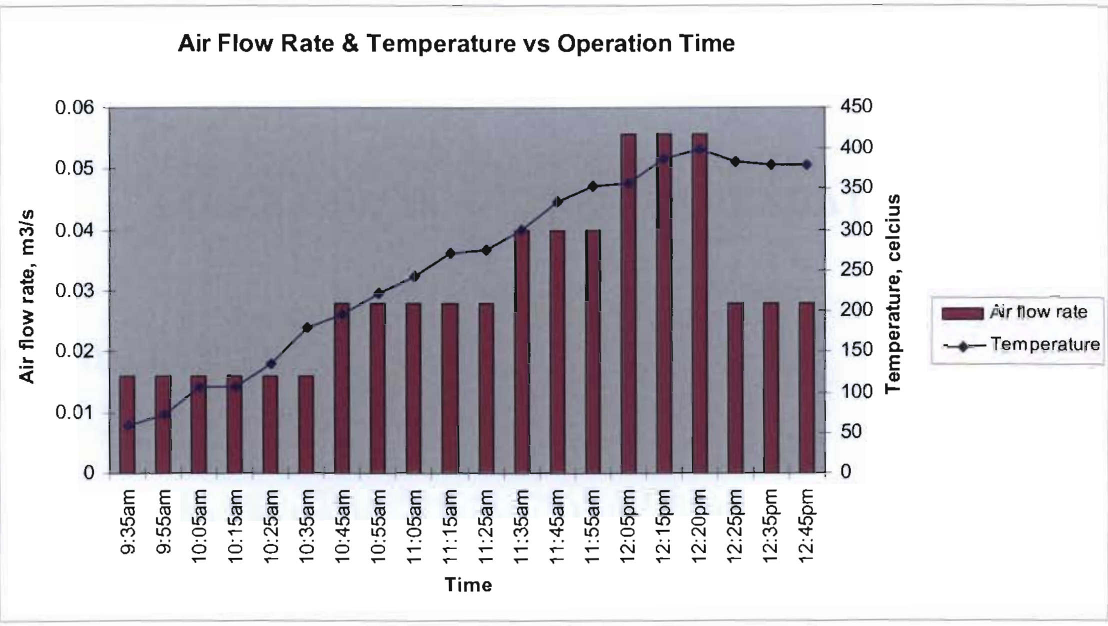


Figure 5.19: Air flow rate and temperature versus time

Table 5.14: Operational parameters of B2E conversion system

Operational Parameters	**Biomass-to-Energy (B2E) conversion system**
Feedstock	Palm oil shell
Throughput, kg/hour: Overall	16.00
Oxidation agent	Air
Range of exit temperature detected at the gasifier, °C	60 - 398
Overall performance, %	90.48
Second law of efficiency, %	74.78

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

From this study, some conclusions can be drawn from (1) investigation of moisture content versus calorific values of 5 selected biomass of different origins, (2) assessment of the operational parameters of B2F, and (3) preliminary performance evaluation (focused on field tests) of B2E, and are summarized in the following paragraphs.

1) Biomass Moisture Content versus Calorific Values

The calorific value or “energy content” of feedstock (biomass) greatly affects the heat distribution of B2E conversion system. From this research, it can be concluded that wood chips had the highest heating value of 22.41 MJ/kg in dry state, followed by palm oil shell 21.40 MJ/kg, sago bark 19.56 MJ/kg, palm oil empty fruit bunch 17.82 MJ/kg, and paddy straw 15.33 MJ/kg. From the experimental data, it can also be concluded that the calorific value increases as the moisture content decreases.

2) Major operational and environmental drawbacks of the existing B2F gasifier were as follows:-

    i) The phenol contained in AFRL recorded approximately 5,310 mg/L as compared to 0.001 mg/L of the Standard A and Standard B established under the Environmental Quality (Sewage and Industrial Effluents) Regulations, 1979; and

ii) Approximately 1.5% tars and 13% AFRL were produced as by-products. The chemical compositions of AFRL showed that the AFRL should not be discharged directly into the public watercourses without pretreatment;

iii) Emission or leakage of incomplete or unburnt combustible gas; and

iv) System tended to get overheated and tremendous heat wastage.

3) Onsite experimental fieldworks (field tests) showed that problems (i) to (iv) in (2) above encountered by B2F conversion system could be eliminated or minimized to a great extent as reflected by the B2E conversion system. Based on field observed experimental data of B2E, the following conclusions can be drawn.

   i) The B2E was capable of complete conversion of tars resulting in zero tar and combustion of combustible fuel gases inside the system itself (within the Combustible Fuel Gas Combustion Chamber) before being exhausted.

   ii) Considerable amount of relatively clean and hot exhaust gas can be harvested as heat energy;

   iii) The exergy destroyed was estimated to 24.13 kJ/s;

   iv) The overall efficiency of B2E conversion system was approximately 90.48%;

   v) The second-law efficiency of B2E conversion system was approximately 74.78%; and

vi) The temperature output of the B2E conversion system were directly proportional to air flow rate at an average feedstock input rate of 16 kg of wood chips per hour.

6.2 RECOMMENDATIONS

For future research work, the proposed recommendations are as follows:-

i) Construct an appropriate cooling system for B2E. This helps to continually operate without shut down, while the heated water can be used for heating and drying purposes; and

ii) Integrate B2E gasification system with run shaft power system to produce electricity.

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APPENDIX A: Heating Values versus Drying Hour

1) Paddy Straw

Table A1: Determination of calorific values of paddy straw

No.	Dried hours	Weight of sample before dried, g	Weight of sample after dried, g	Weight loss, g	Calorific value, KJ/g
1	0 (Natural state)	101.749	-	-	5.43
2	16	101.749	78.980	22.769	14.53
3	45	2.232	2.187	0.045	15.00
4	16.5 (Dry state)	2.378	2.288	0.090	15.33

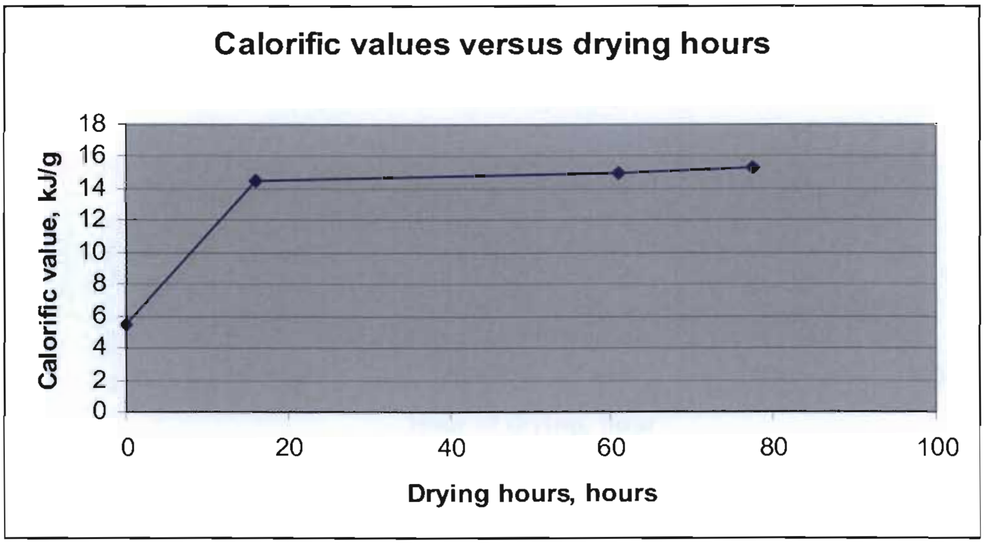


Figure A1: Calorific values versus drying time (paddy straw)

2) Sago Bark

Table A2: Determination of calorific values of sago bark

No.	Dried hours	Weight of sample before dried, g	Weight of sample after dried, g	Weight loss, g	Calorific value, KJ/g
1	0 (Natural state)	125.795	-	-	10.63
2	16	125.795	86.706	39.089	19.06
3	45	5.174	4.969	0.205	19.56
4	16.5 (Dry state)	5.318	4.970	0.348	18.39

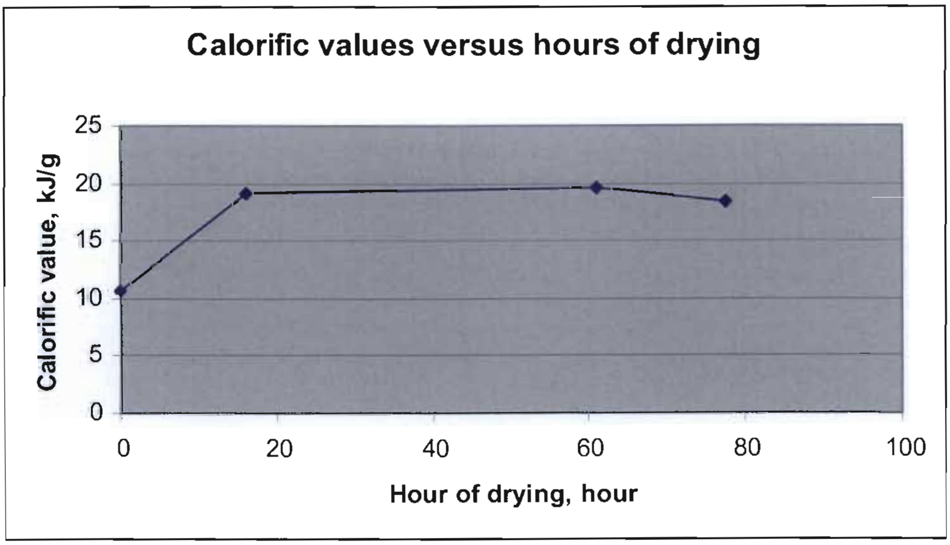


Figure A2: Calorific values versus drying hours (sago bark)

3) Wood Chips

Table A3: Determination of calorific values of wood chips

No.	Dried hours	Accumulation of dried hours	Weight of sample before dried, g	Weight of sample after dried, g	Weight loss, g	Calorific value, KJ/g
1	0 (Natural state)	0	132.812	-	-	18.05
2	16	16	132.812	123.356	9.456	19.53
3	45	61	121.111	120.206	0.905	19.60
4	16.5 (Dry state)	77.5	118.784	117.398	1.386	22.41

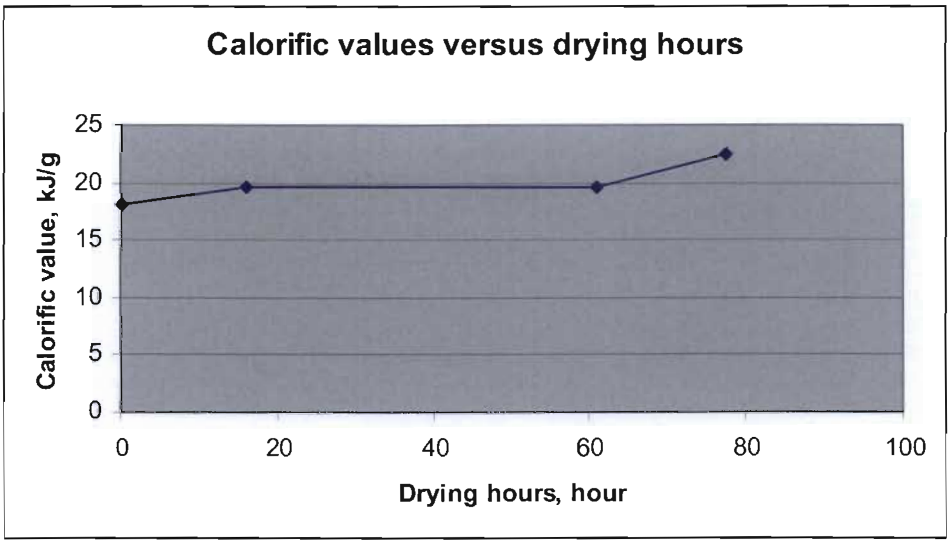


Figure A3: Calorific values versus drying hours (wood chips)

4) POS

Table A4: Determination of calorific values of POS

No.	Dried hours	Weight of sample before dried, g	Weight of sample after dried, g	Weight loss, g	Calorific value, KJ/g
1	0 (Natural state)	372.115	-	-	17.13
2	16	372.115	336.417	35.698	21.40
3	45	28.005	27.424	0.581	20.68
4	16.5 (Dry state)	18.687	17.550	1.137	20.45

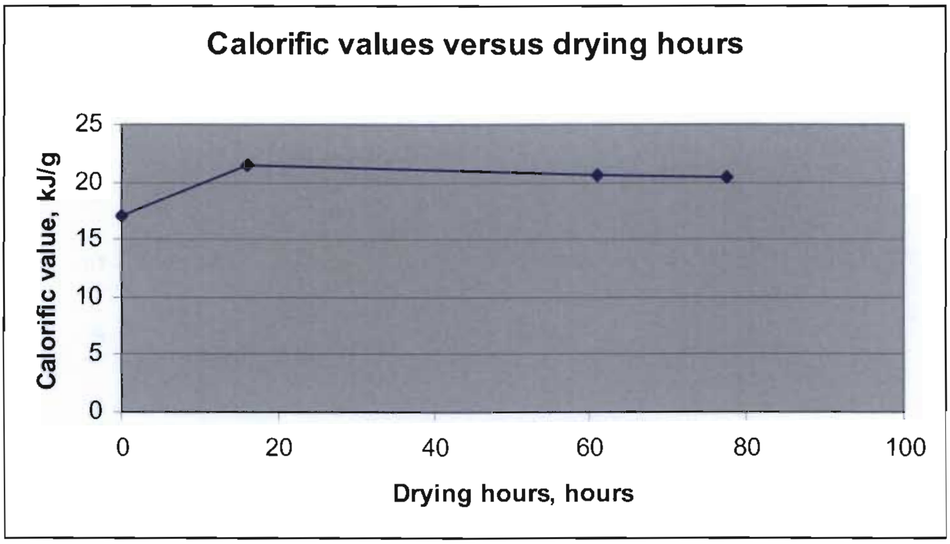


Figure A4: Calorific values versus drying hours (POS)

5) EFB

Table A5: Determination of calorific values of EFB

No.	Dried hours	Weight of sample before dried, g	Weight of sample after dried, g	Weight loss, g	Calorific value, KJ/g
1	0 (Natural state)	258.370	-	-	10.89
2	16	258.370	151.666	106.704	17.23
3	45	6.460	6.286	0.174	17.82
4	16.5 (Dry state)	12.623	12.041	0.582	16.67

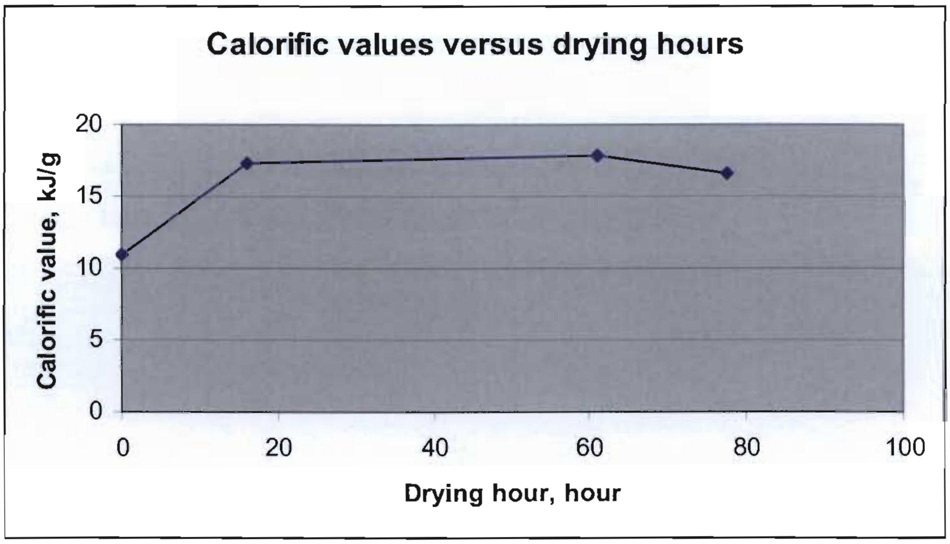


Figure A5: Calorific values versus drying hours (EFB)

Calorific values of paddy straw, EFB, POS, sago bark and chip woods

Table A6: Calorific values of paddy straw, EFB, POS, sago bark, wood chips waste

Sample	**Paddy straw**	**EFB**	**Sago bark**	**POS**	**Chip wood waste**
Natural state	5.43 MJ/kg	10.89 MJ/kg	10.63 MJ/kg	17.13 MJ/kg	18.05 MJ/kg
Dry state	15.33 MJ/kg	17.82 MJ/kg	19.56 MJ/kg	21.40 MJ/kg	22.41 MJ/kg

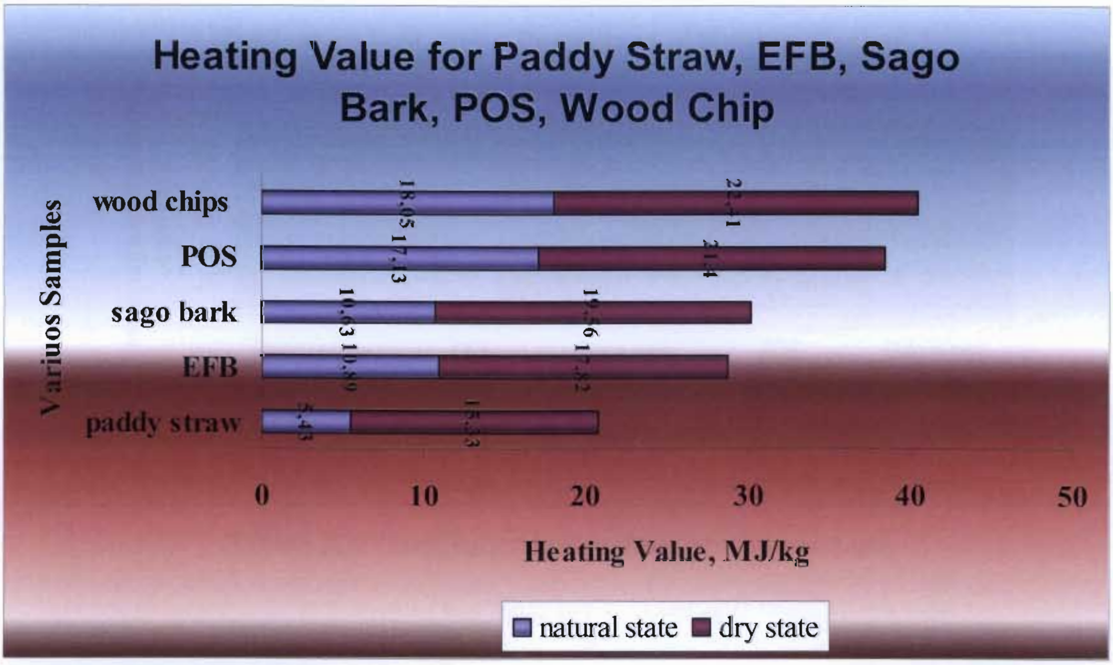


Figure A6: Calorific values of paddy straw, EFB, sago bark, POS, and wood chips waste

Moisture content of locally available biomass

Table A7: Moisture contents of various gasification fuels

Gasification fuel	**Moisture content on wet basic (%)**
Paddy straw	97.75
EFB	95.34
Sago bark	96.05
POS	95.28
Chip wood waste	11.605

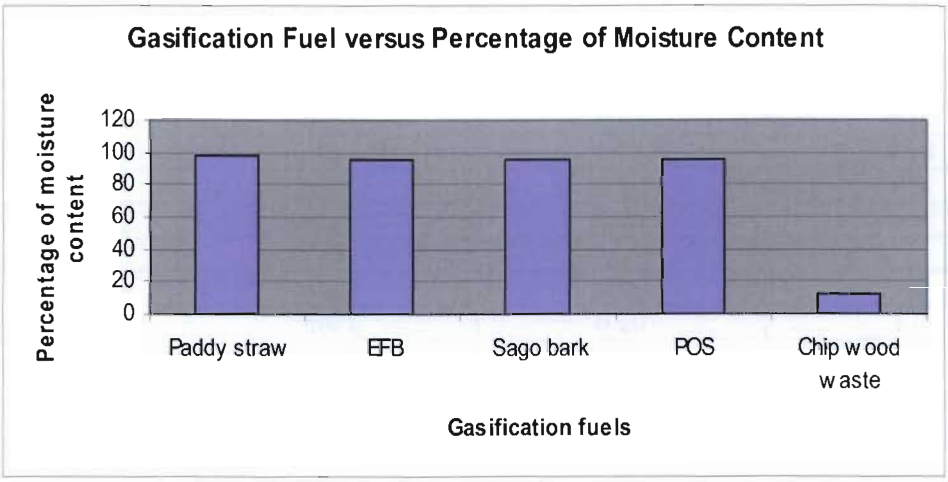


Figure A7: Gasification fuel versus moisture content

Appendix B: Environmental Quality (Sewage and Industrial Effluents) Regulation 1978 [Regulation 8 (1), 8(2), 8(3)]

Table B1: Parameter limits of effluent of Standards A and B

Parameter	**Unit**	**Standard**	
		A	**B**
(1)	**(2)**	**(3)**	**(4)**
Temperature	°C	40	40
pH value	mg/L	6.0-9.0	5.5-9.0
BOD_5 at 20°C	mg/L	20	50
COD	mg/L	50	100
Suspended Solids	mg/L	50	100
Mercury	mg/L	0.005	0.05
Cadmium	mg/L	0.01	0.02
Chromium	mg/L	0.05	0.05
Hexavalent			
Arsenic	mg/L	0.05	0.10
Cyanide	mg/L	0.05	0.10
Lead	mg/L	0.10	0.5
Chromium	mg/L	0.20	1.0
Trivalent			
Copper	mg/L	0.20	1.0
Manganese	mg/L	0.20	1.0
Nickel	mg/L	0.20	1.0
Tin	mg/L	0.20	1.0
Zinc	mg/L	2.0	2.0
Boron	mg/L	1.0	4.0
Iron (Fe)	mg/L	1.0	5.0
Phenol	mg/L	0.001	1.0
Free Chlorine	mg/L	1.0	2.0
Sulphide	mg/L	0.5	0.50
Oil and grease	mg/L	Not detectable	10.0

Appendix C1: B2E Conversion System

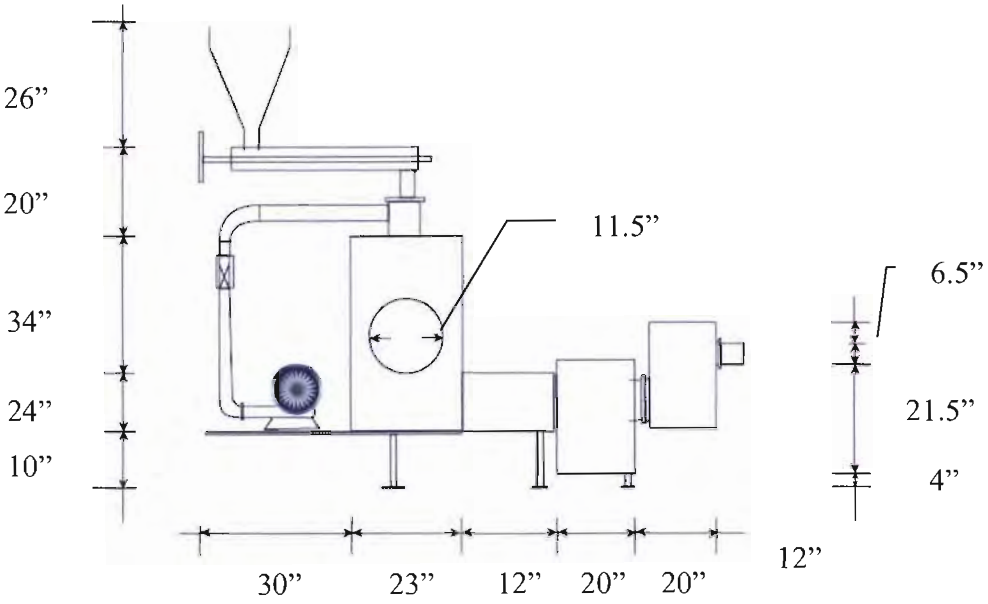


Figure C1: Sectional dimensions of B2E conversion system

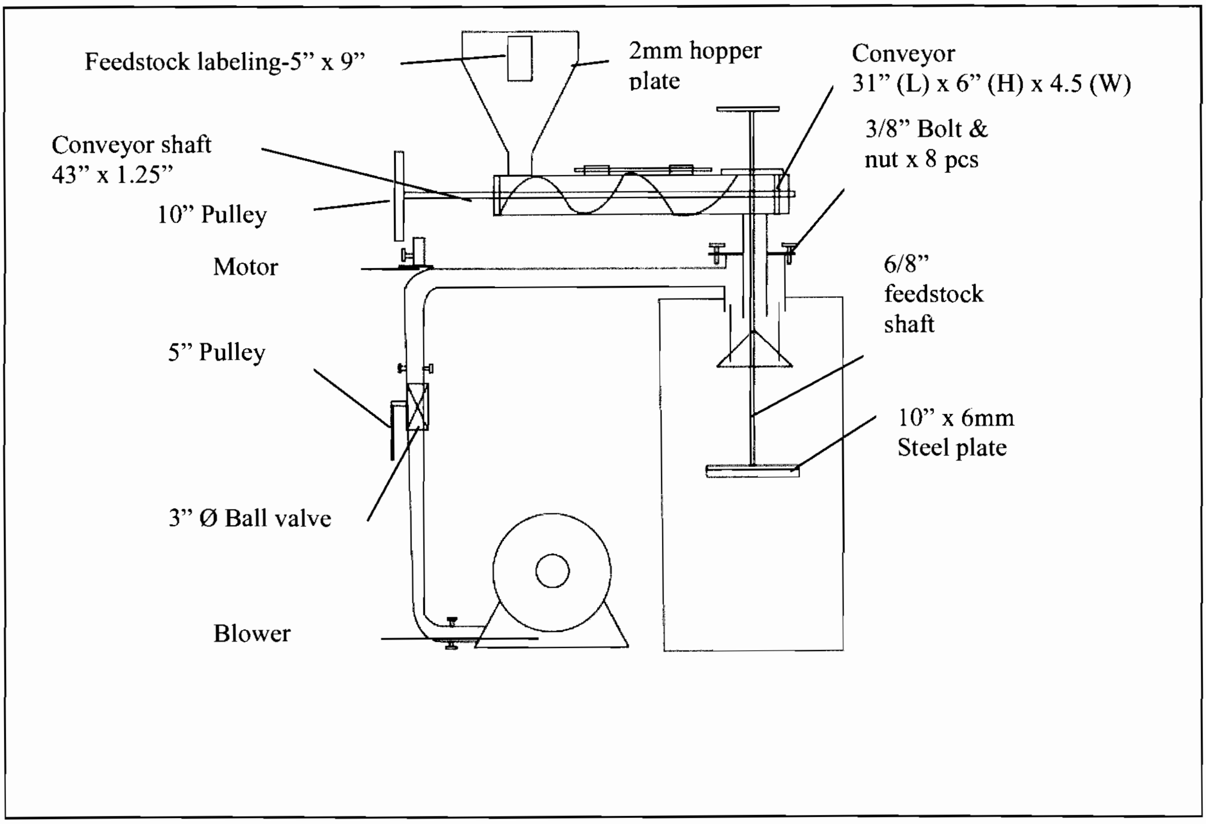


Figure C2: Cross-sectional view and dimensions of pyrolysis chamber and accessories of B2E conversion system

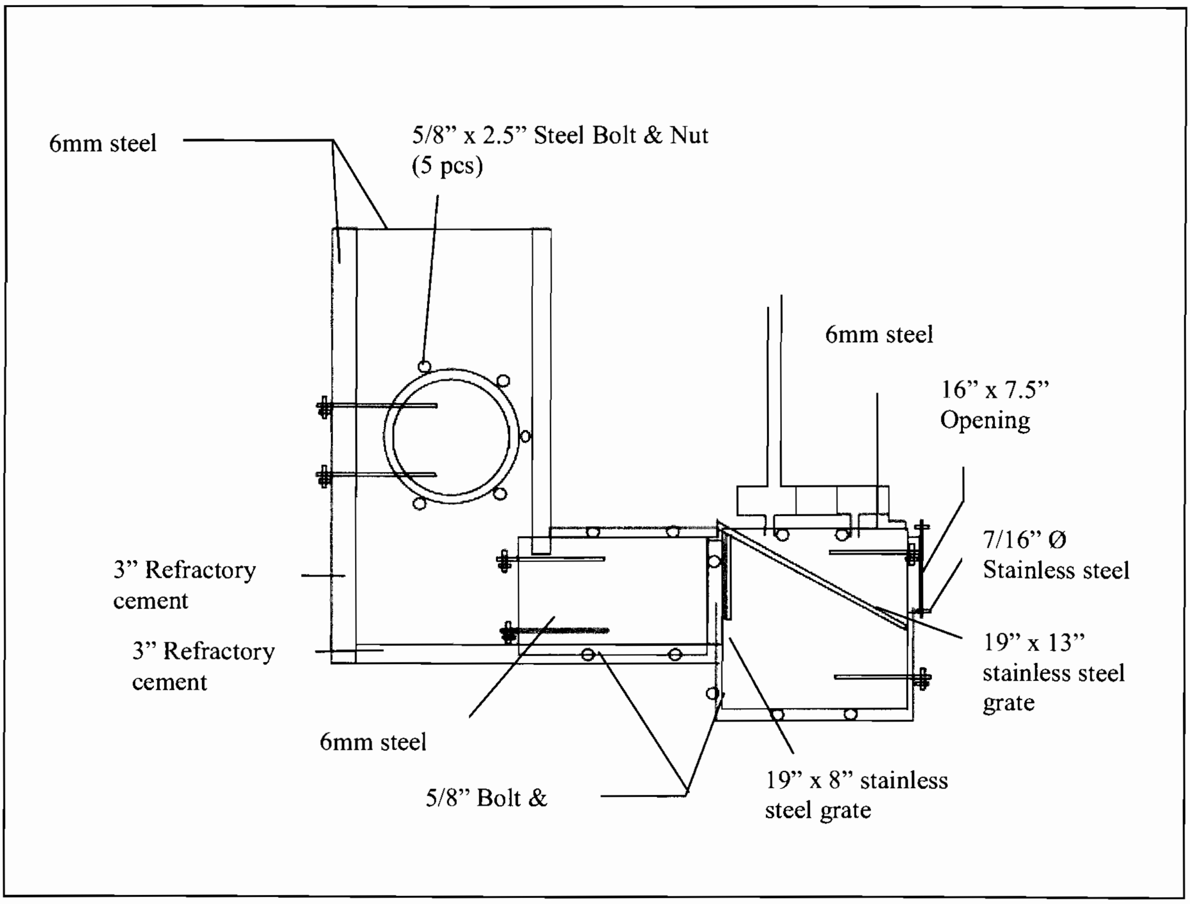


Figure C3: Details of construction materials of B2E conversion system

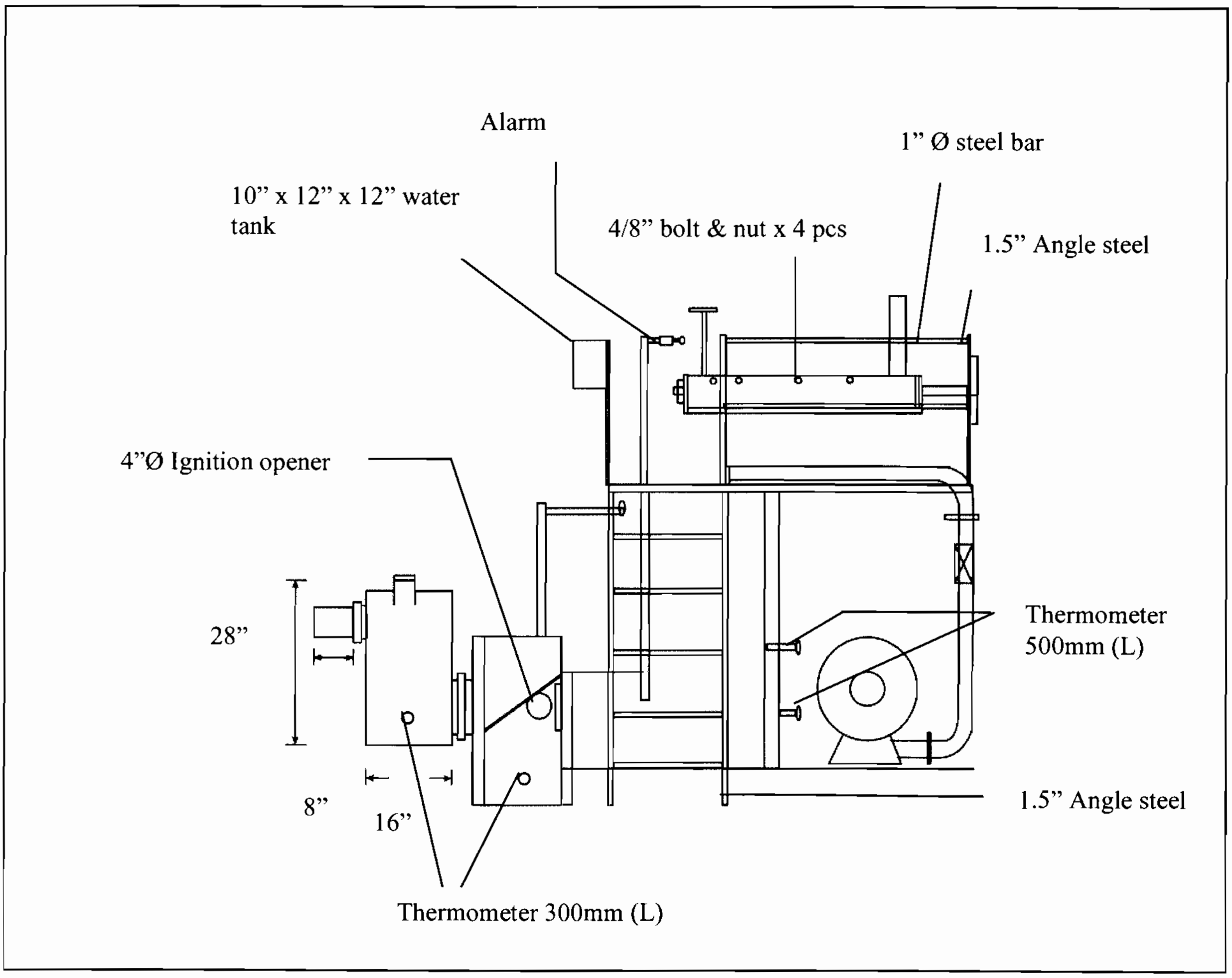


Figure C4: Thermometer locations of B2E conversion system

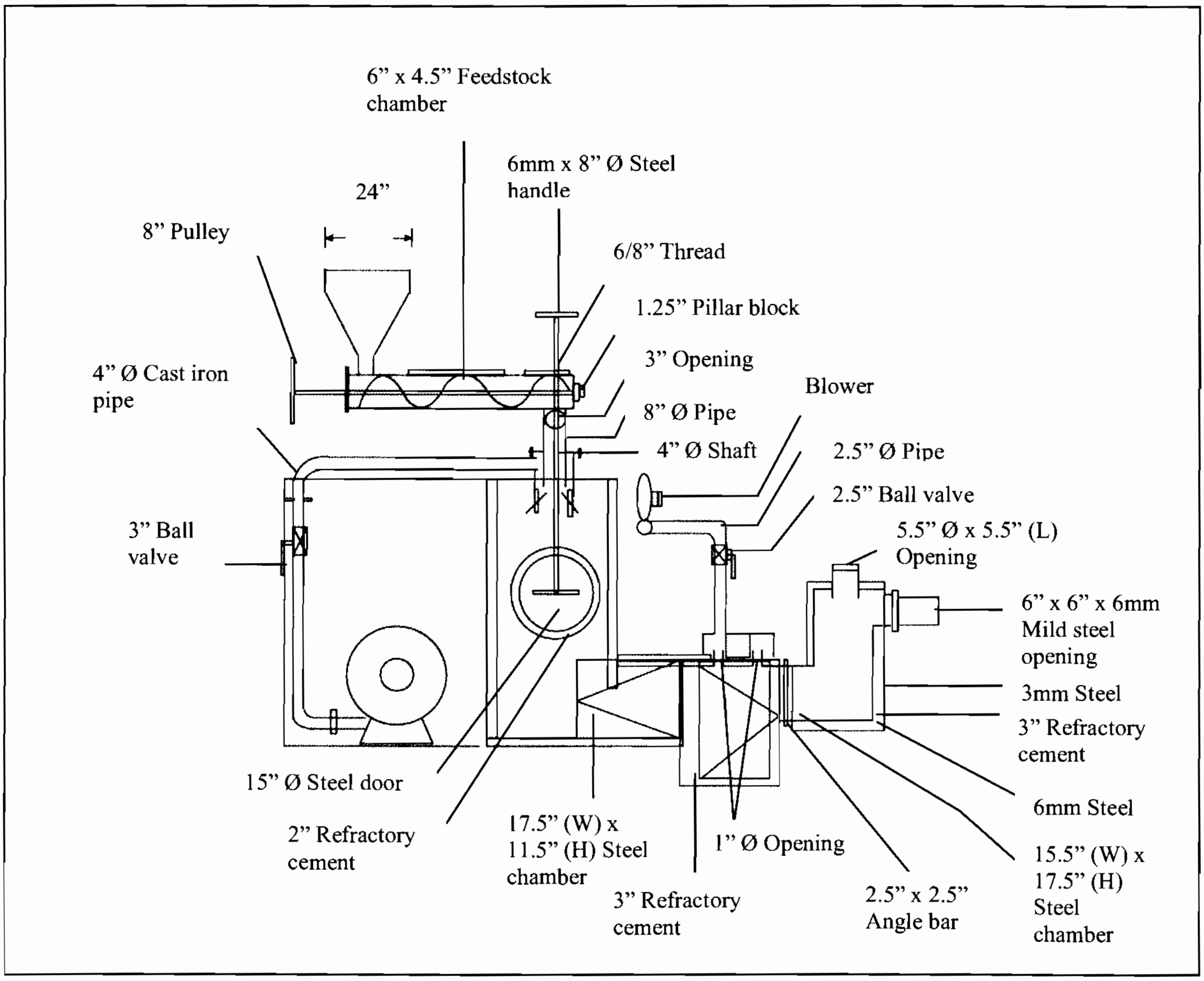


Figure C5: Design specifications of B2E conversion system

Appendix C2: Calculation for Exergy Destroyed of B2E Conversion System

$$\sum\left(1-\frac{T_o}{T_k}\right)\dot{Q}_k+\left[\dot{m}_{Air}\left(h_1-T_oS_1\right)\right]_{Air}+\left[\dot{m}_{Biomass}\left(h_1-T_oS_1\right)\right]_{Biomass}-\left[\dot{m}_{Air+Biomass}\left(h_2-T_oS_2\right)\right]_{Air+Biomass}=\dot{X}_{destroye}$$

At Combustible fuel gas-to-heat energy conversion chamber, where temperature = 671K

$\dot{Q}_k = 95.66 kJ/s$

$T_o = 298K$

$T_k = 671K$

$h_1 = 298.182$ kJ/kg

$h_2 = 682.21$ kJ/kg

$s_1 = 1.695278$ kJ/(kg.K)

$s_2 = 2.52748$ kJ/(kg.K)

$\dot{m}_{air} = 0.227 kg/s$

$\dot{m}_{Biomass} = 0.00447 kg/s$

$\dot{m}_2 = \dot{m}_{Air} + \dot{m}_{Biomass}$

Energy input:

$\dot{Q}_k = CV_{POS}\, x\, \dot{m}_{Biomass}$

$\dot{Q}_k = 21.40 MJ/kg\, x\, 0.00447 kg$

$\dot{Q}_k = 95.66 kJ/s$

Mass flow rate for air

$$\dot{V} = 11.5 m^3 / \min$$
$$\dot{V} = 0.192 m^3 / s$$

$$\dot{m}_{air} = \rho \dot{V}$$
$$\dot{m}_{air} = (1.184\, kg / m^3)(0.192\, m^3 / s)$$
$$\dot{m}_{air} = 0.227\, kg / s$$

Overall fuel consumption rate for biomass:

$$\dot{m}_{Biomass} = \frac{51\, kg}{3.176\, hour}$$
$$= 0.209\, kg / \min$$
$$\dot{m}_{Biomass} = 0.00447\, kg / s$$

$$\dot{X}_{destroyed} = 24.13\, kJ / s$$

Appendix C3: Calculation for Overall Efficiency of B2E Conversion System

$$Overall\ efficiency = \left(\frac{\mathrm{HV}_{\text{gaseous products}}}{HV_{Biomass}\ x\ \dot{m}_{fuel}} \right) 100\% \qquad (4.26)$$

Where

$\mathrm{HV}_{\text{gaseous products}}$ = Heat value of gaseous products

$\mathrm{HV}_{\text{Biomass}}$ = Heat value of biomass

$\dot{m}_{fuel} = Mass\ \ flow\ rate\ of\ \ fuel$

Energy balance for B2E conversion system:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system} = 0 \quad ; \Delta\dot{E}_{system} = 0\ (steady)$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \Sigma\dot{m}_{i}\left(h_{i} + \frac{v^{2}{}_{i}}{2} + gz_{i} \right) = \dot{Q}_{out} + \dot{W}_{out} + \Sigma\dot{m}_{e}\left(h_{e} + \frac{v^{2}{}_{e}}{2} + gz_{e} \right)$$

$$\dot{Q} - \dot{W} = \dot{m}_{i}\left[h_{2} - h_{1} + \frac{v^{2}{}_{2} - v^{2}{}_{1}}{2} + g(z_{2} - z_{1}) \right]$$

At Combustible fuel gas-to-heat energy conversion chamber, where temperature = 671K

$\dot{m}_{air} = 0.227 kg/s$

$\dot{m}_{air} = 0.227 kg/s$

h_2 = 682.21 kJ/kg

h_1 = 298.18 kJ/kg

v_2 = 2.61 m/s (From Table C2)

v_1 = 23.68 m/s

$z_2 = 0.5715$m (From Figure 5.8a)

$z_1 = 0.508$m (From Figure 5.8a)

$$\dot{v} = 11.5m^3/\min$$
$$= 0.192m^3/s$$
$$v_1 = \frac{\dot{v}}{A}$$
$$v_1 = \frac{0.192m_3/s}{0.0081m^2}$$
$$v_1 = 23.68m/s$$

A = Cross section of 4" pipe from blower (Figure 5.8e)

$$A = \Pi\frac{D^2}{4}$$
$$A = \Pi\frac{0.1016^2}{4}$$
$$A = 0.0081m^2$$

$$Overall\ efficiency\ of\ B2E\ conversion\ System = \left(\frac{\mathrm{HV}_{\text{gaseous products}}}{HV_{Biomass}\ x\ \dot{m}_{fuel}}\right)100\%$$

$\dot{Q} = \mathrm{HV}_{\text{gaseous products}} = 95.66$ kJ/kg

$$\therefore Overall\ Efficiency\ of\ B2E\ Conversion\ System = \left(\frac{86.55kJ/s}{95.66kJ/s}\right)100\%$$
$$= 90.48\%$$

Appendix C4: Second Law Efficiency of B2E Conversion System

Second law efficiency, $\eta_{II} = \left(1 - \frac{Exergy \quad destroyed}{Exergy \quad \sup plied}\right)100\%$

$$\eta_{II} = \left(1 - \frac{24.13}{95.66}\right)100\%$$

$$\eta_{II} = \underline{74.78\%}$$

Appendix C5: Air Flow Rate (m^3/s)

Air flow rate = ambient air supply rate

Exit diameter: 0.1651 m (6.5inch)

$$\text{Area of the exit diameter} = \Pi\left(\frac{D^2}{4}\right)$$

$$= 0.0214\ m^2$$

Air flow rate, Q = AV

Table C1: Air flow rate at Level 4

No.	**Exit velocity, m/s**	**Air flow rate, Q = AV (m^3/s)**
1	2.67	0.0571
2	2.56	0.0548
3	2.50	0.0535
4	2.65	0.0567
5	2.65	0.0567
Average	2.61	0.0558

Table C2: Air flow rate at Level 3

No.	**Exit velocity, m/s**	**Air flow rate, Q = AV (m^3/s)**
1	1.79	0.0383
2	1.86	0.0398
3	1.90	0.0407
4	1.84	0.0394
5	1.91	0.0409
Average	1.81	0.0398

Table C3: Air flow rate at Level 2

No.	**Exit velocity, m/s**	**Air flow rate, Q = AV (m^3/s)**
1	0.76	0.0163
2	0.75	0.0161
3	0.73	0.0156
4	0.74	0.0158
Average	0.75	0.0160

Table C4: Air flow rate at Level 1

No.	Exit velocity, m/s
1	*
2	*
3	*
4	*
5	*
Average	-

Table C5: Average air flow rates at individual levels

Level	Air flow rate, Q = AV (m^3/s)
Level 1	0
Level 2	0.0160
Level 3	0.0398
Level 4	0.0558

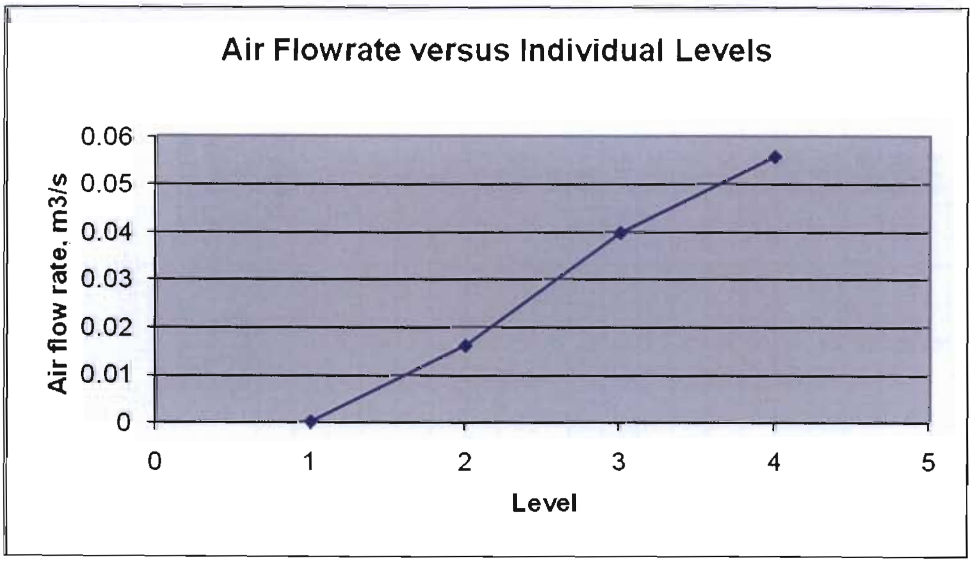


Figure C6: Plot of air flow rate versus different levels

APPENDIX D: Temperature Distribution at Combustible Fuel Gas-to-Heat Energy Conversion Chamber with Respect to Time, and Air Flow Rate
Fieldwork conducted on: 13.1.08

Table D1: Observed Blower adjustment levels versus Temperature during fieldwork conducted on 13.1.08
(overall average feedstock throughput = 16.0 kg/hour)

Levels	Air Flow Rate	Time	Feedstock Input to the Hopper	Temperature at Location 1	Temperature at Location 2	Temperature at Location 3	Temperature at Location 4
	m^3/s			Celsius	Celsius	Celsius	Celsius
2	0.0160	9:35am	20	119	41	209	60
2	0.0160	9:55am	5	281	35	248	72
2	0.0160	10:05am	3	665	36	345	107
2	0.0160	10:15am	0	711	37	227	106
2	0.0160	10:25am	3	773	38	315	136
2	0.0080	10:35am	0	835	38	333	180
2.5	0.0280	10:45am	3	841	39	307	197
2.5	0.0280	10:55am	0	841	41	315	222
2.5	0.0280	11:05am	0	849	42	316	243
2.5	0.0280	11:15am	3	884	41	383	270
2.5	0.0280	11:25am	0	872	43	319	274
3	0.0398	11:35am	3	889	45	285	300
3	0.0398	11:45am	3	914	46	366	333
3	0.0398	11:55am	0	918	50	395	353
4	0.0558	12:05pm	3	910	52	370	356
4	0.0558	12:15pm	5	926	320	410	387
4	0.0558	12:20pm	0	915	620	439	398
2.5	0.0280	12:25pm	0	874	557	298	384
2.5	0.0280	12:35pm	0	842	654	257	380
2.5	0.0280	12:45pm	0	792	862	251	379

Location 1

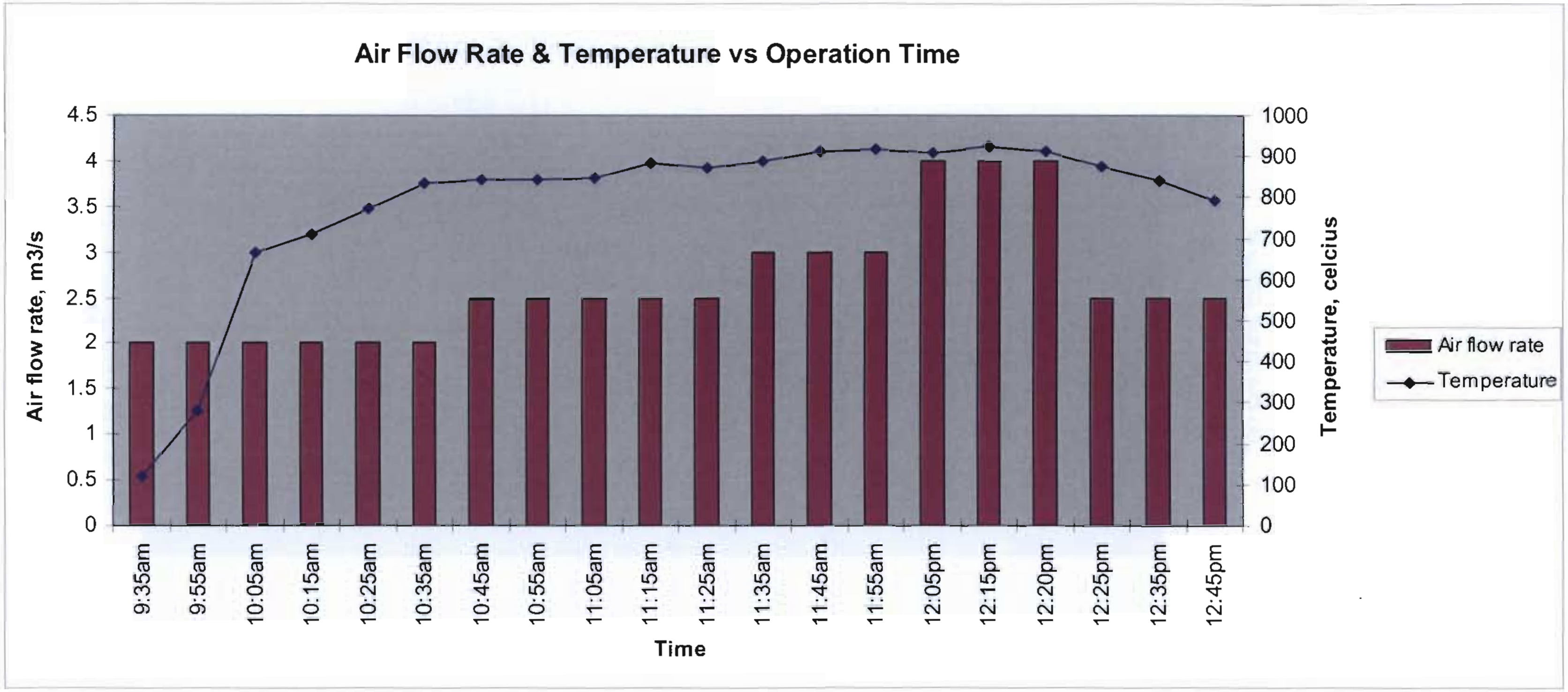


Figure D1: Air flow rate & temperature versus operation time at Location 1

Location 2

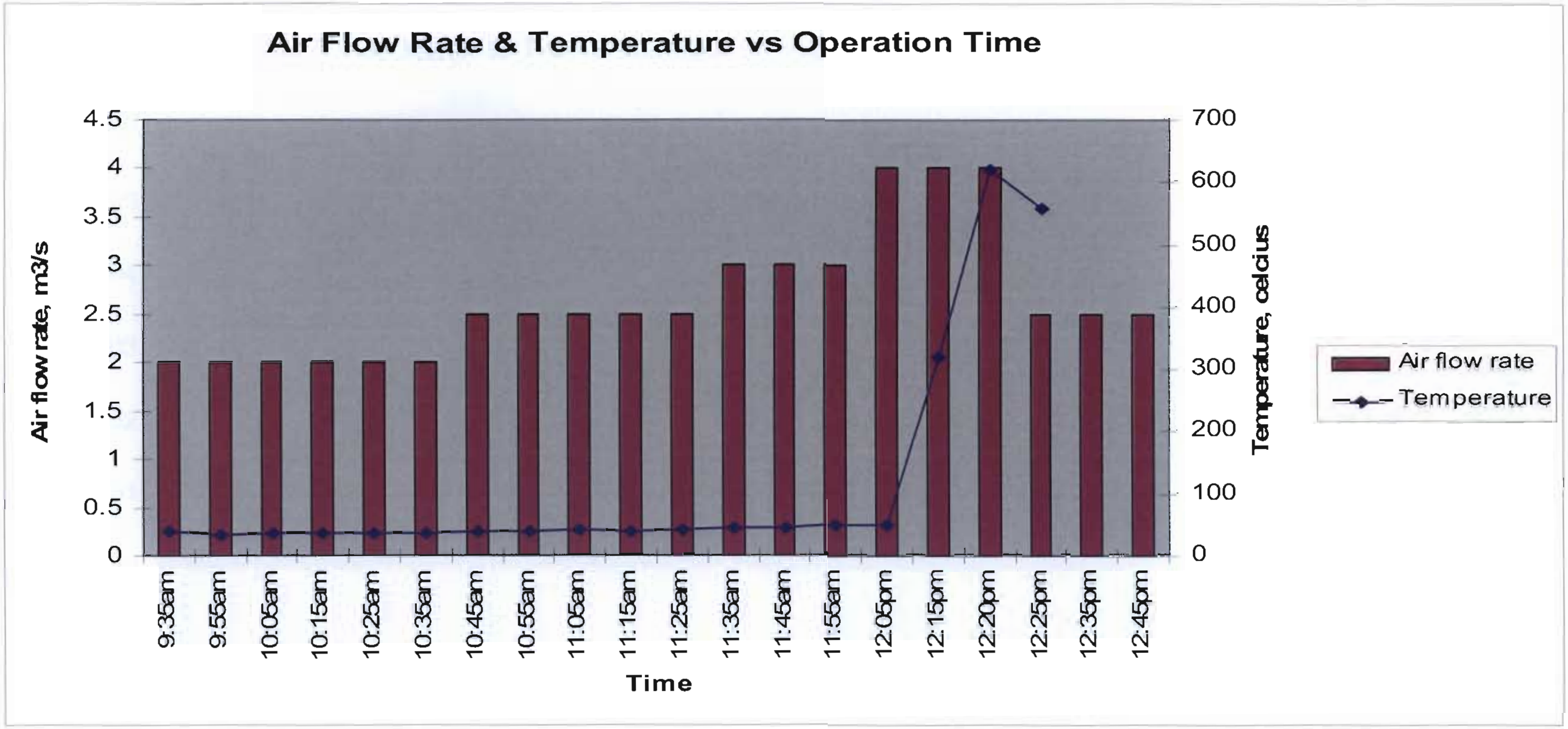


Figure D2: Air flow rate & temperature versus operation time at Location 2

Location 3

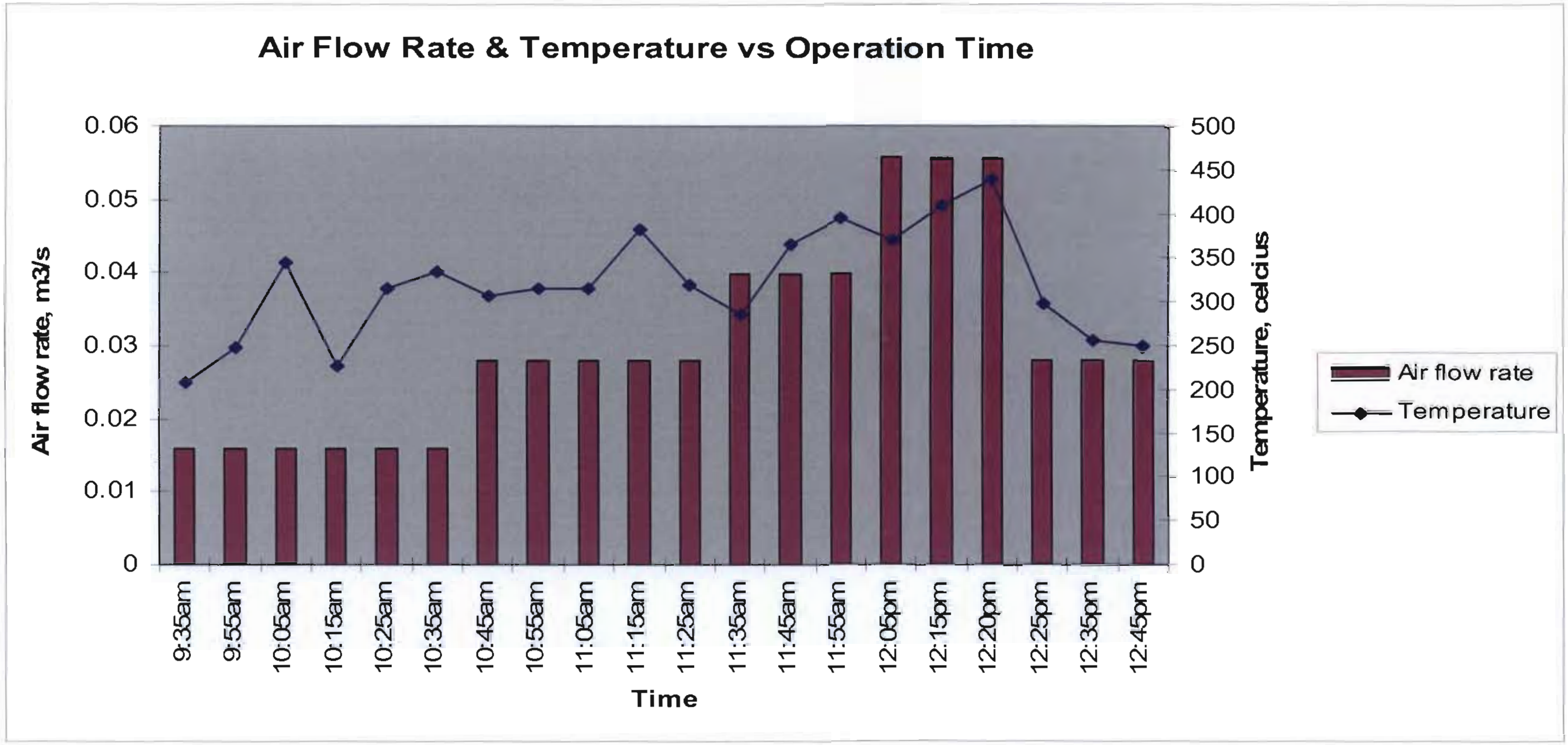


Figure D3: Air flow rate & temperature versus operation time at Location 3

Location 4

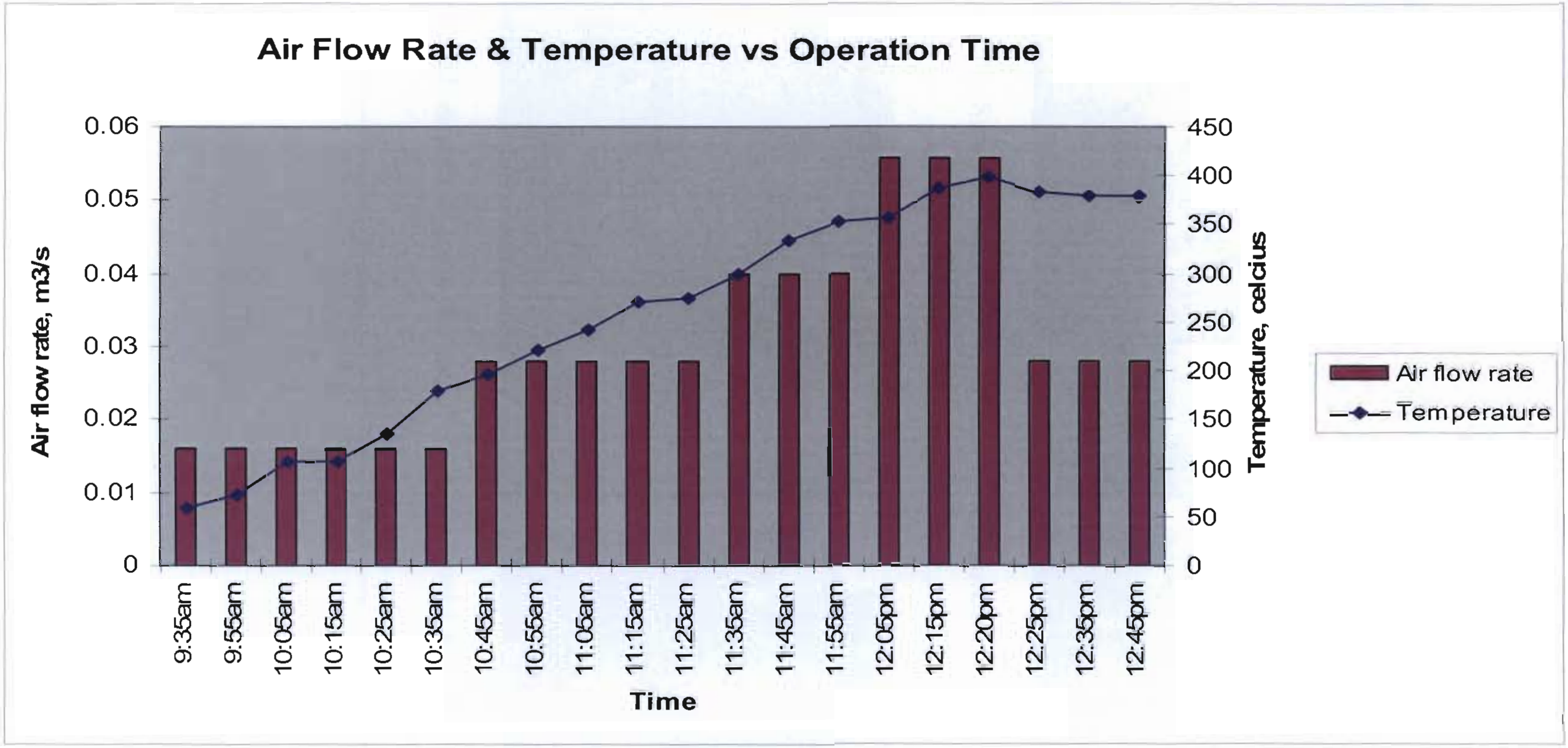


Figure D4: Air flow rate & temperature versus operation time at Location 4

Appendix E: Photos and Thermal Photos of B2E Conversion System

Figure E1: Side view of B2E

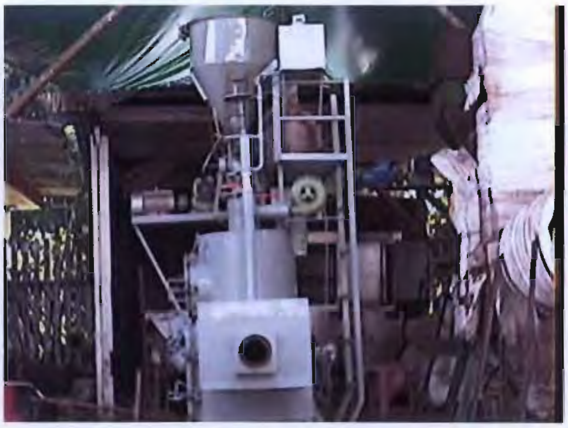


Figure E2: Front view of B2E

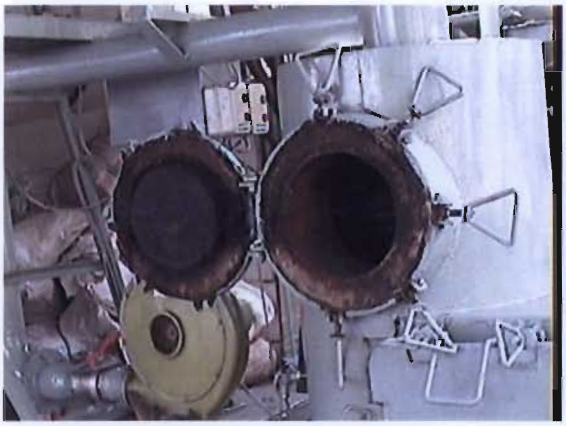


Figure E3: A view of pyrolysis chamber

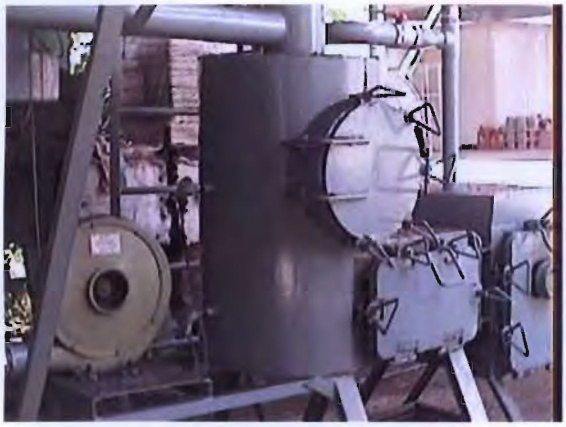
Figure E4: Natural gas being used as ignition starter

Figure E5: Initial ignition

Figure E6: Feedstock ignited inside pyrolysis chamber

Figure E7: Feedstock hopper

Figure E8: Thermometer indicators for Locations 1, 2, 3 and 4

 Figure E9: Projection view of B2E conversion System	