PERFORMANCE CHARACTERISTIC OF A CYCLONE GASIFIER FOR POWER GENERATION

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UNIVERSITI SAINS MALAYSIA
KAMPUS KEJURUTERAAN

2008

UNIVERSITI SAINS MALAYSIA

Laporan Akhir Projek Penyelidikan Jangka Pendek

Performance Characteristic of a Cyclone Gasifier for Power Generation

by

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PEJABAT PENGURUSAN & KREATIVITI PENYELIDIKAN
RESEARCH CREATIVITY AND MANAGEMENT OFFICE [RCMO]

LAPORAN AKHIR PROJEK PENYELIDIKAN JANGKA PENDEK
FINAL REPORT OF SHORT TERM RESEARCH PROJECTS

1) **Nama Ketua Penyelidik** :
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Muhamad Azman bin Miskam	School of Mechanical Engineering

Nama Penyelidik Bersama
(Jika berkaitan) :
Name/s of Co-Researcher/s
(if applicable)

Penyelidik Bersama *Co-Researcher*	PTJ *School/Centre*
Prof. Madya Zainal Alimuddin Zainal Alauddin	School of Mechanical Engineering
En Khairil Faizi Mustafa	School of Mechanical Engineering

2) **Tajuk Projek** :
Title of Project:

Performance Characteristic of a Cyclone Gasifier for Power Generation.

3) **Abstrak untuk penyelidikan anda**

(Perlu disediakan di antara 100 – 200 perkataan di dalam **Bahasa Malaysia dan Bahasa Inggeris**. Ini kemudiannya akan dimuatkan ke dalam Laporan Tahunan Bahagian Penyelidikan & Inovasi sebagai satu cara untuk menyampaikan dapatan projek tuan/puan kepada pihak Universiti & luar).

Abstract of Research

(Must be prepared in 100 – 200 words in Bahasa Malaysia as well as in English. This abstract will later be included in the Annual Report of the Research and Innovation Section as a means of presenting the project findings of the researcher/s to the university and the outside community)

Abstract

A new technique of gasifying pulverized biomass fuel based on cyclonic motion concept is being developed for power generation. Sawdust has been used as a fuel for cyclone gasifier reactor to produced producer gases of typically 3 – 5 MJ/m^3. The work of this project involved both theoretical and experimental work to understand the operation as well as the performance and characteristics of a cyclone gasifier. The primary goals of this project were to characterize the sawdust as a pulverized biomass fuel for cyclone gasifier, determine the temperature profiles of the producer gas and wall temperature profiles inside the cyclone chamber, analyze the producer gas, perform thermodynamics analysis, and obtain gasifier efficiency and thermal output of the cyclone gasifier.

Ground sawdust from furniture industries is used as a fuel with size distribution from 0.25 to 1 mm is about 80%. The low heating value was found to be about 16.54 MJ/kg with moisture content of 8.25%. Sawdust was injected into the cyclone gasifier with air as a gasifying agent. The gasification tests were made with varying air flow rate and fuel feed rate. Experiments were conducted with varying equivalence ratios. The typical wall temperature for initiating gasification process was about 400^{o}C. The average temperature of producer gas was about 600 – 800^{o}C. The highest average heating value of producer gas was 3.9 MJ/kg with flow rate 0.01471m^3/s. The highest thermal output from the cyclone gasifier was 57.35 kW$_T$. The highest value of mass conversion efficiency and enthalpy balance were 60% and 98.7% respectively. Generally, the efficiency of cyclone gasifier increases with the increase in equivalence ratios and the highest efficiency of the cyclone gasifier obtained was 73.4% and this compares well with other researchers. The thesis has identified the optimum operational condition for gasifying sawdust in cyclone gasifier system and made conclusions as to how the steady state gasification process can be achieved.

Abstrak

Satu teknik baru untuk mengaskan bahanapi biojisim terhancur berasaskan kepada konsep pergerakan siklon telah dibangunkan untuk tujuam penjanaan kuasa. Habuk kayu telah digunakn sebagai bahanapi untuk reaktor pengas siklon bagi menghasilkan gas-gas terhasil secara tipikalnya 3-5 MJ/m^3. Kerja-kerja projek ini termasuklah secara teori dan eksperimen untuk memahami operasi dan juga prestasi serta pencirian bagi pengas siklon tersebut. Matlamat utama projek ini adalah untuk mencirikan habuk kayu sebagai bahanapi biojisim terhancur untuk pengas siklon, mengenalpasti profil suhu gas-gas terhasil dan juga profil suhu dinding didalam kebuk siklon, menganalisa gas-gas terhasil secara termodinamik dan juga mendapatkan kecekapan dan keluaran terma pengas siklon.

Habuk kayu daripada industri perabut dikisar dan digunakan sebagai bahan api dengan agihan saiz dari 0.25 ke 1 mm adalah sebanyak 80%. Nilai pemanasan rendah didapati 16.54 MJ/kg dengan kandungan lembapan 8.25%. Habuk kayu disuntik ke dalam penggas siklon dengan udara sebagai agen penggasan. Ujian penggasan dibuat dengan mengubah kadar aliran udara dan kadar suapan bahan api. Eksperimen-eksperimen dijalankan dengan nisbah kesetaraan diubah. Suhu dinding tipikal bagi memulakan proses penggasan ialah 400^{o}C. Suhu keluaran semasa ujian dijalankan secara puratanya didapati diantara 600 – 800^{o}C. Nilai pemanasan purata tertinggi adalah 3.9 MJ/kg dengan kadar aliran 0.01471 m^3/s. Kuasa keluaran terma tertinggi dari penggas siklon adalah 57.35 kW$_T$. Nilai maksimum kecekapan penukaran jisim dan imbangan entalpi adalah masing-masing 60% dan 98.7%. Umumnya, kecekapan meningkat dengan peningkatan nisbah kesetaraan dan kecekapan maksimum penggas didapati 73.4% dan ini dalam lingkungan

penyelidik-penyelidik lain. Tesis ini telah mengenalpasti keadaaan operasi optimum untuk menggaskan habuk kayu di dalam sistem penggas siklon dan kesimpulan dibuat bagaimana proses penggasan berkeadaan mantap boleh dicapai.

4) Sila sediakan Laporan teknikal lengkap yang menerangkan keseluruhan projek ini. [Sila gunakan kertas berasingan]
Kindly prepare a comprehensive technical report explaining the project
(Prepare report separately as attachment)

Senaraikan Kata Kunci yang boleh menggambarkan penyelidikan anda :
List a glosssary that explains or reflects your research:

Bahasa Malaysia	Bahasa Inggeris
Pengasan biojisim	Biomass gasification
Pengas siklon	Cyclone gasifier
Habuk kayu	Sawdust
Penjanaan kuasa	Power generation

5) **Output Dan Faedah Projek**
Output and Benefits of Project

(a) * Penerbitan *(termasuk laporan/kertas seminar)*
Publications (including reports/seminar papers)
(Sila nyatakan jenis, tajuk, pengarang, tahun terbitan dan di mana telah diterbit/dibentangkan).
(Kindly state each type, title, author/editor, publication year and journal/s containing publication)

1. **M.A. Miskam**, Z.A.Z Alauddin, Characterization of Sawdust as a Fuel for Cyclone Gasifier, Proceeding of The 5th 21st Century COE International Symposium on Global Renaissance by Green Energy Revolution, 7-10 August 2005, Pulau Pinang Malaysia.

2. **M.A. Miskam**, Z.A.Z Alauddin, Experimental Investigation of a Cyclone Gasifier, Proceeding of a National Conference on Advances in Mechanical Engineering NAME05, 18-20 May 2005, Kuala Lumpur Malaysia.

3. **M.A. Miskam**, Z.A.Z Alauddin, Imbangan Alam Melalui Penggasan Biojisim, Prosidin bagi Persidangan Kebangsaan Ke-2, Keharmonian Hidup, Imbangan Alam dan Pembangunan PK2-PPSPP, 5-6 September 2005, Bangi Malaysia

4. **M.A. Miskam**, Z.A.Z. Alauddin, M.Y.Idroas, Evaluation of Cyclone Gasifier Performance for Gasification of Sawdust, Proceeding of an International Conference on Energy and Environment 2006 (ICEE06), 28 August – 30 August 2006, UNITEN Kajang, Selangor Malaysia

5. Laporan Kemajuan Penyelidikan, Performance Characteristic of a Cyclone Gasifier for Power Generation, RCMO USM, 15 Mac 2006

(b) **Faedah-Faedah Lain Seperti Perkembangan Produk, Prospek Komersialisasi Dan Pendaftaran Paten atau impak kepada dasar dan masyakarat.**
Other benefits such as product development, product commercialisation/patent registration or impact on source and society

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3

(c) **Latihan Gunatenaga Manusia**
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i) Pelajar Siswazah : Tiada
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(perincikan nama, ijazah dan status)
(Provide names, degrees and status)

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ii) Pelajar Prasiswazah *:* 2 Orang
Undergraduate students:
(Nyatakan bilangan)
(Provide number)

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iii) Lain-Lain : Tiada
Others:

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6. **Peralatan Yang Telah Dibeli :**
Equipment that has been purchased:

Alat-alat guna habis seperti:

1. Penapis udara
2. Penyuntik udara
3. Gas regulator
4. Gas flow meter

5. Pressure gauge
6. Gas sampling train
7. LPG burner
8. Air compressor 1HP
9. Thermocouple Rig

4

KOMEN JAWATANKUASA PENYELIDIKAN PUSAT PENGAJIAN
Comments of the Research Committees of Schools/Centres

Projek telah berjalan dengan baik dengan penghasilan penemuan yang diterbitkan dalam jurnal & perbentangan dalam persidangan. Projek mempunyai potensi tinggi untuk pengkomersialan dalam beberapa tahun. Projek perlu diteruskan dengan permohonan geran ST lagi.

Alimuddin

TANDATANGAN PENGERUSI
JAWATANKUASA PENYELIDIKAN PUSAT PENGAJIAN
Signature of Chairman
[Research Committee of School/Centre]

27/8/04
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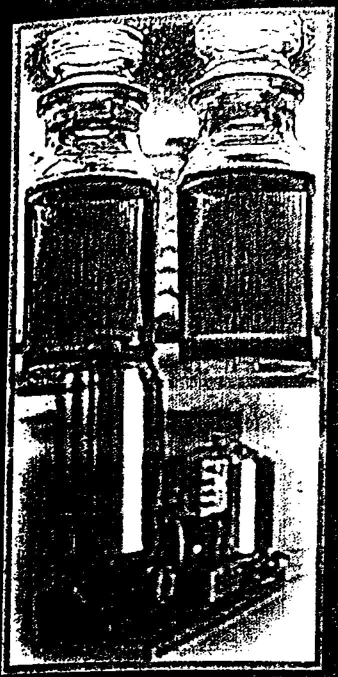
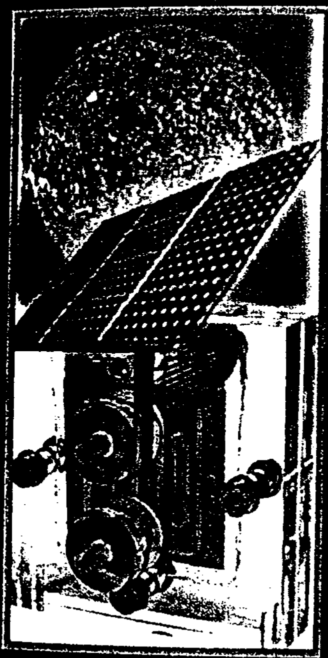
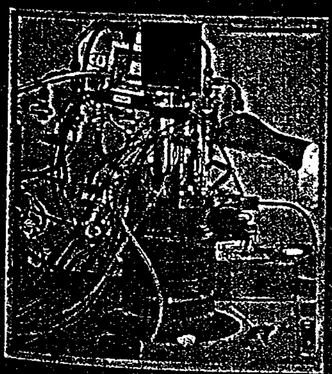
Date

Updated : 16MAC2006







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CHARACTERIZATION OF SAWDUST AS A FUEL FOR CYCLONE GASIFIER

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KEY WORDS: cyclone gasifier, sawdust, gasification

ABSTRACT
This paper focuses on advanced gasification techniques for electricity generation using sawdust as a fuel. In order to access the performance of the gasification process using sawdust as a fuel, cyclone gasifier system was developed. This gasifier, whose capacity was around 60 kg/h. Therefore, the characterization of the sawdust is essential to determine the best technical, economic and environmental alternative. The gas produced from cyclone gasifier able to be burned in an internal combustion engine, as long as it is appropriately cleaned.

INTRODUCTION
A cyclone gasifier system has been developed at University Science of Malaysia using sawdust as a fuel with capability to produce thermal output of 200 kW. The objective of this project was to develop and to demonstrate a cyclone gasifier system using swirling flow reactor to suspend and react pulverized biomass (sawdust) into a low tar and particle content wood gas suitable for fuelling an internal combustion engines with minimal post processing equipment for gas cleaning. In this paper the characterization of sawdust as a fuel for cyclone gasifier has been presented.

EXPERIMENTAL PROCEDURE
Experimental studies were carried out with sawdust from furniture industries as the test samples. Several key analyses had been done such as sieve test, proximate analysis, and ultimate analysis in order to study the fuel characteristics of sawdust.

RESULTS AND DISCUSSION
The characterization of sawdust had been performed in order to compare the characteristics of the existing sample of sawdust with the one in the literature review. From both ultimate and proximate analysis, it is found that there is a good agreement between the experimental result and the literature review. From the proximate analysis, it is found that the moisture content of sawdust is 8% on wet basis, Fixed Carbon content is 14%, volatile matter is 76% and ash content is about 1.5%. The calorific value yielded from the bomb calorimeter test is approximately 15 MJ/kg. And the ultimate analysis reveals the chemical composition of sawdust as 42.38% for Carbon, 5.27% for Hydrogen, 19.83% for Nitrogen and 0.62% for Sulphur. In reference to the above results, it indicates that the sample of sawdust taken for this particular project is comparable in terms of its fuel characteristic to the early tested sawdust as reported in the literature review as well as to the other major biomass fuels such as bagasse, coffee ground and rice husk. Thus, the findings affirm that sawdust is suitable to be utilized as a biomass fuel to the existing cyclone gasifier system.

CONCLUSIONS
The characterization of sawdust is important in determining the suitability of sawdust as a biomass fuel for the cyclone gasifier system. Several important characteristics such as moisture content (%), ash content (%), fixed carbon content (%), volatile matter (%) and calorific value in MJ/kg must be determined via proximate analysis, moisture test and bomb calorimeter test. And from the ultimate analysis, it is possible to determine the chemical constituents of the sawdust (C, H, N, S) which later can be used to set the biomass chemical reaction of sawdust for the system operation. These characteristics are very important in order to cater for the design requirement of the cyclone gasifier.

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[1] Mohamed Gabra, Anders Nordin, Marcus Öhman, Björn Kjellström (2001), Alkali retention/separation during bagasse gasification: a comparison between a fluidised bed & a cyclone gasifier, Biomass & Bioenergy, 21(6), pp. 461-476, 2001.

[2] C. Syred, W. Fick , A. J. Griffiths and N. Syred, Cyclone gasifier and cyclone combustor for the use of biomass derived gas in the operation of a small gas turbine in cogeneration plants, Fuel, retrieved 5 March 2004, http://www.sciencedirect.com

[3] Fredriksson, C., Exploratory experimental and theoretical studies of cyclone gasification of wood powder, PhD thesis, Department of Mechanical Engineering, Division of Energy Engineering, Luleå University of Technology, Luleå, Sweden, 1999.

Characterization of Sawdust as a Fuel for Cyclone Gasifier

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KEY WORDS: cyclone gasifier, sawdust, gasification

ABSTRACT
This paper focuses on advanced gasification techniques for electricity generation using sawdust as a fuel. In order to assess the performance of the gasification process using sawdust as a fuel, cyclone gasifier system was developed with a capacity around 60 kg/h. Characterization of the sawdust is essential in determining the best technical, operational, economical and environmental aspects of the gasifier. The gas produced from gasification of sawdust is able to be burned in an internal combustion engine, as long as it met the specified conditions.

INTRODUCTION
Biomass is a substance made of organic compounds originally produced by fixing carbon dioxide in the atmosphere during the process of plant photosynthesis. Since, the concentrarion of carbon dioxide in the atmosphere theoretically remain constant in cyclic flow, biomass is expected to become one of the key sources of renewable energy in the sustainable development in society of the future [1].

Biomass fuelled gasification has been found to be one of the promising technologies for electric power generation. In the gasification process, biomass is subjected to partial pyrolisis under stoichiometric condition, where the air quantity is limited to a suitable kg of air per kg of biomass. The resultant mixture of gases generated during the gasification process, called producer gas, contains CO and H_2 and is combustible.

A cyclone gasifier system has been developed at University Sains Malaysia using sawdust as fuel with capability to produce thermal output of 200 kW. The objective of this project was to develop and to demonstrate a cyclone gasifier system using swirling flow reactor to suspend and react pulverized biomass into a low tar and particle content. The gas produced should be made suitable for fuelling an internal combustion engines with minimal post processing equipment for gas cleaning. A schematic diagram of the atmospheric cyclone gasifier system is shown in Fig. 1. The gasifier system consisted of hopper, screw feeder, down-comers, blower, cyclone's chamber and char collector.

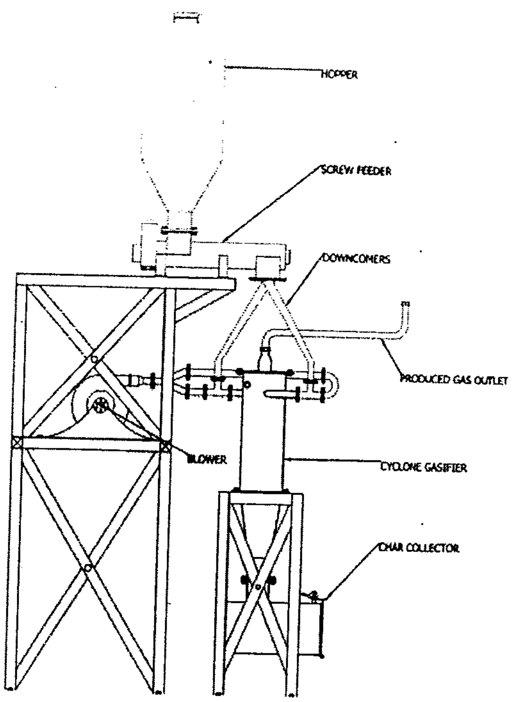

Fig 1. Schematic diagram of a cyclone gasifier system

The sawdust is transferred from the hopper to the gasifier by means of a single screw feeder, into the two downcomers. The powder falls by gravity through the downcomers to the two opposite tangential inlet. Air was injected from blower to the cyclone gasifier through two opposite ejectors. The cyclone gasifier, which is designed as a standard cyclone separator, works as a particle separator as well. The cyclone is mounted vertically standing on a char collector at the cyclone bottom where the char is separated.

Biomass fuels differ greatly in their chemical, physical and morphological properties so that it require different method of gasification and consequently require different reactor designs or even gasification technologies. Thus it follows that the universal gasifier, able to handle all or most fuels or fuel types, does not exist, and in all probability will not exist in the foreseeable future.

Any typical gasifier will operate satisfactorily with respect to stability, gas quality, efficiency and pressure losses only within certain ranges of the fuel properties of which the most important are the energy content, moisture content, volatile matter, ash content and ash chemical composition, reactivity, size and size distribution, bulk density and charring properties. In this paper the characterization of sawdust as a fuel for cyclone gasifier has been presented.

EXPERIMENTAL PROCEDURE

Several key analyses had been done such as sieve test, proximate analysis, and ultimate analysis in order to study the fuel characteristics of sawdust. Experimental studies were carried out with sawdust from furniture industries as the test samples. Particle size and distributions of sawdust is determined using sieve shaker. While proximate analysis was carried out using TGA7 together with TG controller. The TGA system interfaced to a microcomputer for data acquisition and control task. The operation was fully automatic. The TGA consist of sample pan that was suspended from the weighing mechanism with wire the balance accuracy is 0.1% and the sensitivity is 0.1μg. The furnace can withstand up to 1150°C and the reactor temperature was measured by a chromel-alumel thermocouple located exactly below sample pan. The temperature programming in TGA analysis was made in accordance to Standard Method described in ASTM D3173-87, ASTM D3173-97 and ASTM D3175-89a. From the Data Acquisition System, the results were processed for Volatiles, Fixed Carbon, Moisture and Ash Contents. Fuel higher heating value was obtained in an adiabatic bomb calorimeter. These values include the heat of condensation of the water that is produced during combustion. The Ultimate Analysis of sawdust is done using Perkin Elmer CHNS/O Analyzer.

RESULTS AND DISCUSSION

The characterization of sawdust had been performed in order to compare the characteristics of the existing sample of sawdust with the one in the literature review [2-4]. The size distribution of the fuels particles is important for particle flow in the downcomers, the injector and the cyclone gasifier. The size distribution also determines the time required for gasification and the carry-over particles with the product gas. The sawdust was produced by grinding the raw material in a disk mill and then sieved to 98% under 1.2 mm. The size distributions determined by sieving are shown in Table 1.

Size (mm)	Weight%
S>2	1.81
1.0 – 2.0	1.54
0.5 – 1.0	48.57
0.250 – 0.5	32.56
0.125 – 0.250	8.33
0.063 – 0.125	3.51
0.045 – 0.063	3.55
S<0.045	0.13
Sum	100.0

Table 1. Size distribution of sawdust

The ultimate analysis regarding C,H,N and S was made by Perkin Elemer CHNS/O Analyzer. The proximate analysis was made by Perkin Elemer TGA7. Table 2 show the ultimate analysis of the sawdust used.

Ultimate analysis	Dry weight%
C	42.38
H	5.27
N	0.14
S	0.62
O (diff.)	41.79
Ash	1.50
Moisture content	8.30

Table 2. Ultimate analysis of the sawdust

The results from proximate analysis are shown in Table 3, while figure 2 show show the graph of Weight Loss and Temperature versus Time in Thermal Gravimetric Analysis (TGA).

Proximate analysis	Dry weight%
Volatiles	76.2
Fixed Carbon	14.0
Ash	1.5

Table 3. Proximate analysis of the sawdust

From both ultimate and proximate analysis, it is found that there is a good agreement between the experimental result and the literature review. From the proximate analysis, it is found that the moisture content of sawdust is 8% on wet basis, Fixed Carbon content is 14%, volatile matter is 76% and ash content is about 1.5%.

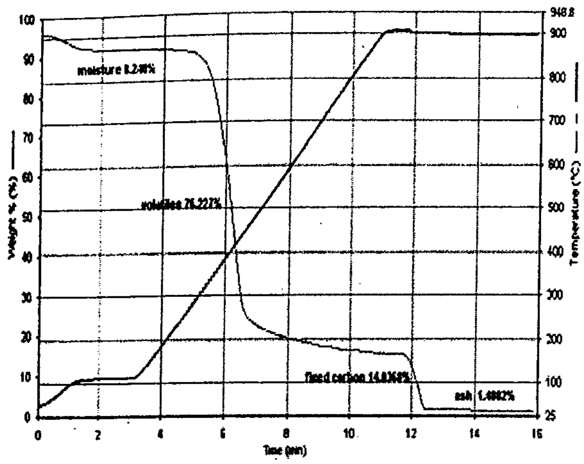

Fig. 2. Weight Loss and Temperature versus Time in Thermal Gravimetric Analysis (TGA)

The calorific value yielded from the bomb calorimeter test is approximately 15 MJ/kg. And the ultimate analysis reveals the chemical composition of sawdust as 42.38% for Carbon, 5.27% for Hydrogen, 19.83% for Nitrogen and 0.62% for Sulphur. In reference to the above results, it indicates that the sample of sawdust taken for this particular project is comparable in terms of its fuel characteristic to the early tested sawdust as reported in the literature review.

Thus, from the findings in this study sawdust has all the key ingredients as an alternative fuels as well as the suitability for existing cyclone gasifier system since it has a high calorific value, low moisture content, rich volatile content and low ash content with appropriate particle size and distributions.

CONCLUSIONS

The characterization of sawdust is important in determining the suitability of sawdust as a biomass fuel for the cyclone gasifier system. Several important characteristics such as moisture content (%), ash content (%), fixed carbon content (%), volatile matter (%) and calorific value in MJ/kg must be determined via proximate analysis, moisture test and bomb calorimeter test. And from the ultimate analysis, it is possible to determine the chemical constituents of the sawdust (C, H, N, S) which later can be used to set the biomass chemical reaction of sawdust for the system operation. These characteristics are very important in order to cater for the design requirement of the cyclone gasifier.

Acknowledgements

This study was supported by a University Sciences Malaysia Short Term Grant is gratefully acknowledged.

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EXPERIMENTAL INVESTIGATION OF A CYCLONE GASIFIER

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ABSTRACT

The paper presents gasification process of sawdust in cyclone gasifier. The approach utilized a cyclonic flow concept to gasify sawdust, which was driven by air injected at atmospheric pressure conditions. The objectives are to apply a new gasification technology in utilizing sawdust as a source of energy to generate power since sawdust abundantly available from sawmill and wood-based industries. The gasifier was sized to process 60kg/hr of sawdust corresponds to desired thermal output of 200 kW_T. The cyclone should be heat up at temperature of 700°C by a diesel burner and the temperature should be limit at a range of 600°C - 900°C for stable gasification process. As an experimental device, 6 type K thermocouples were use to detect and monitor the temperature distribution in 6 different points in the cyclone. These thermocouples will prove the assumption that the temperature in cyclone is uniformly distributed. The result was a low calorific value wood gas of low tar and particle content. The system included further gas cleaning to separate any fine ash particles, moisture and tars from the wood gas before firing a diesel Internal Combustion (IC) engine.

Keywords: Cyclone gasifier, Gasification, Sawdust.

INTRODUCTION

Concern over the depletion of fossil fuels in the near future has drawn worldwide attention [1]. One of the promising renewable sources of energy is the energy from biomass. According to the World Energy Assessment report, 9.5 % of the world's primary energy consumption is contributed by biomass. Biomass is a substance made of organic compounds originally produced by fixing carbon dioxide in the atmosphere during the process of plant photosynthesis [2]. The technologies for the primary conversion of biomass for electricity production are direct combustion, gasification and pyrolisis [3]. Gasification for power production involves the devolatilization and conversion of biomass in an atmosphere of steam or air to produce a medium or low calorific value gas.

Malaysia has abundant biomass waste resource coming mainly from its palm oil, wood and agro-industries. A total of about 665 MW capacities can be expected if the estimated overall potential of about 20.8 millions tone of biomass residues from this main source is used for power generation. This biomass residue could further supplement future biomass-based power generation in the country. In particular, biomass fuels currently account for about 16% of the energy consumption in the country, of which about 51% is palm oil biomass waste and about 22% is wood waste. In addition, about 2177 kton/year wood residues come from wood industries sector. From this great amount of waste, it's potentially produced 68 MW power generation capacities.

Biomass energy technology is the states of art of capturing the energy stored in biomass and make it in useful forms. There are a wide range of technologies available in the market. The classification is based on the conversion principal in which the energy in the biomass being convert to other useful energy. Gasification is a thermo chemical process that produces combustible gas called producer gas. A lot of advantages associate with this technology such as flexibility to fuel a wide range of power system, easier to distribute and control the gaseous fuel. Two types of gasifier that widely available in the market are Fixed bed gasifier and Fluidised bed gasifier. This type of gasifier basically uses solid biomass fuel such as wood chip and oil palm empty-fruit-branches chip. With smaller particle sizes, such as sawdust, rice husk and baggase, cyclone gasifier was developed to gasify smaller particle size biomass fuel utilizing cyclonic motion concept. The advantage of this technique are the particle of biomass fuel is held in suspension over a period of time in a cyclone motion to allow the reaction take place thus producing combustible gas.

METHODOLOGY

Experimental Equipment

The experimental work comprised design and construction of the experimental set-up, planning, performance and evaluation of the test. A schematic diagram of the experimental set-up can be seen in Fig. 2. The system consists of cyclone, air supply component, the feeding port, the ignition port and removing compartment. The sawdust is partially combusted in the cyclone with air to produce combustible gases. The sawdust is supplied to the cyclone inlets from the hopper via screw feeder and two downcomers. The wood powder is injected in to the cyclone by two tangentially directed air driven injectors into the cyclone. The hopper designed applied funnel flow where the fuel flows through the core. The degree of inclination of the tapered side is 45° from vertical wall to make sure the hopper provide mass flow effect properly. The hopper volume is 0.225 m^3 consist of 60 kg sawdust with the mass density of dry sawdust (10% moisture) is 267 kg/m^3 for 1-hour operation time. The sawdust feeding is manual and semi-continuous, introducing fixed quantities. The cyclone gasifier are at present in use is conical reverse flow cyclone with two tangential inlet. The cyclone gasifier consists of both conical and cylindrical parts which together form the body of the cyclone. The gasifier body is made of Mild Steel plate with 6mm thickness. The cylindrical body has a 472 mm internal diameter and 1262 mm height and the conical part connected with a char collector at the bottom. The inlet pipe of the cyclone is mounted tangentially on to the sidewall of the cylindrical part of the cyclone body 170 mm from the top of the cyclone. The exit tube usually called the vortex finder or the vortex tube is fixed on the top of the cyclone and it protrudes 680 mm in to the body of the cyclone. Part of the internal diameter is insulated with 75 mm refractory cement and 50 mm calcium silicate to minimize heat loss. The gasifier built has capacity to process approximately 60 kgh^{-1} of sawdust corresponds to desired thermal output of 200 kW_T.

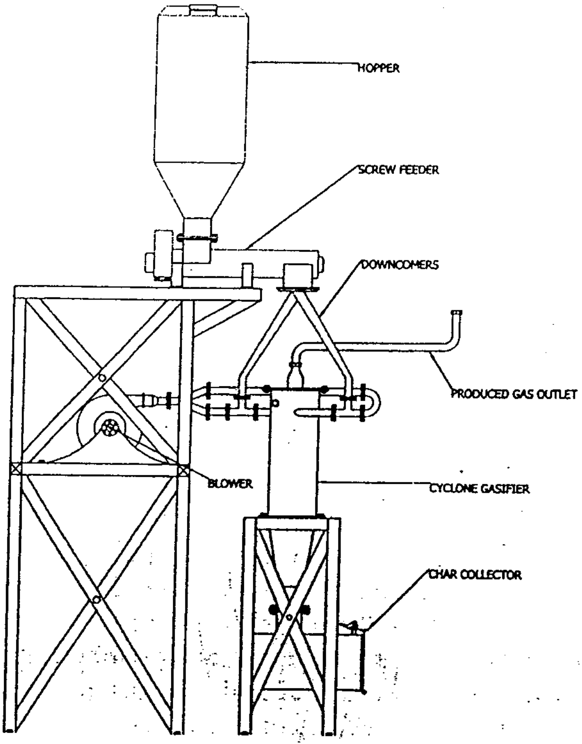

Figure 1: Schematic diagram of a cyclone gasifier system

Gasification air was supplied to the cyclone together with the sawdust directed the air/fuel mixture to enter the cyclone in a tangential direction, which generates a swirl flow in the cyclone. The swirl will force the incoming sawdust particles to follow the trajectories close to the cyclone wall, where the main part of the reactions takes place. The producer gas leaves through the top outlet of the cyclone, while the ungasified char particles fall downwards towards char collector.

Fuel Characteristics and Preparation

Sawdust from furniture industries were the raw materials. Table 1 shows the characteristics of the sawdust used in the previous experiments [5]. Approximately 10 sacks (100 kg) of sawdust were taken from several places.

Experimental Procedures

In the cyclone gasifier, the experiments were started by pre-heating the cyclone with a diesel burner before the fuel feeding. The blower should be turn on at minimum flow rate while the diesel burner is turned on at minimum valve open. The diesel burner is located tangentially within the reactor to make sure the heat uniformly distributed inside the cyclone. The fuel particles should be heated in sufficient high temperature after entering the cyclone to initiate volatiles and gasification reaction. So, the cyclone wall temperature is very important for this heating process. For stable process of gasification the experience shows that the wall temperature exceeds 600°C – 950°C [4]. As a result, a gas temperature inside the cyclone should be heat up at the range of 600°C to 800°C to make sure the gasification process is running smoothly. To heat up the cyclone to the desired operating temperature the diesel burner is used. The burner is positioned in an opening situated about 140 mm from the top of the cyclone. During the heat up of the cyclone, the hot gases produced by the burner are sucked by special designed ejector system. The heating time is about 15 minute if the burner is used in a moderate way and about 10 minute if the burner is operated at full air valve opened. The heat up producer was optimized to obtain minimum time and minimum diesel consumption. There are 6 type-K thermocouple is located at different places to investigate the thermal effect and gas temperature distribution inside the cyclone gasifier. Figure 2 show the positions of the thermocouple used for monitoring wall temperature and product gas in the cyclone gasifier. There are 4 thermocouple type K to measure the temperature of the wall at different point. The 2 thermocouple are situated at almost the same level as the cyclone inlet while the other two are place at the cylindrical and cone body. The air flow rate is measured by rotameter. The diesel burner is turned off when the temperature reached up to 700°C. The cyclone was operated between the lowest and highest possible equivalent ratio.

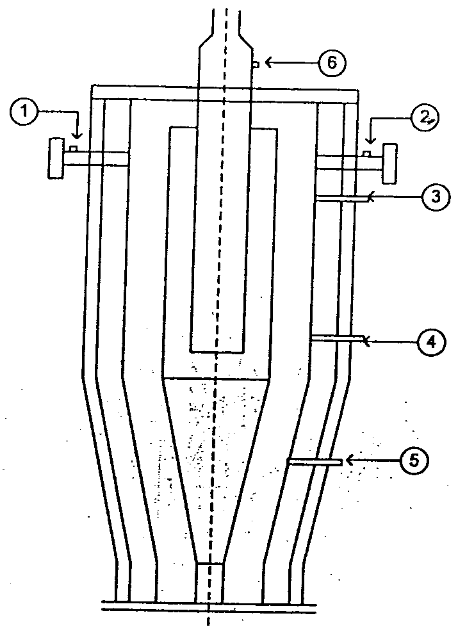

Figure 2: Thermocouple positions

Table 1: Size distribution

Size (mm)	Weight %
S>1	0.45
0.5-1.0	21.89
0.25-0.5	38.50
0.125-0.25	22.41
0.1-0.125	4.12
0.074-0.1	4.95
0.063-0.074	4.62
0.04-0.063	2.95
S<0.04	0.12
Sum	100

RESULTS

The specification of Diesel burner is shown in table 2, while the wall temperature results from heat-up process shown below.

Table 2: Specification of diesel burner

Capacity	6.17~ 12.1 liter/hr
Firing rate	60 ~ 118 kW
Motor power	0.13 kW
Pump pressure	1.2 MPa
Weight	12 kg

1. The valve in diesel burner is half open

Time (minute)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)
10	723.6	591.7	293.8	154.7	194.3	353.7
15	653.5	576.3	274.6	127.3	174.9	334.2

2. The valve in diesel burner is fully open

Time (minute)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)
5	764.1	627.3	319.4	193.5	219.4	376.4

DISCUSSION

The experimental work was done during January and Mac 2005. The wood powder used in these test was taken directly from furniture industries without further treatment or analyzed. After the first test series, some modification should be made for the feeding system. After 30 minute operation the sawdust inside the screw feeder was compressed and the flow stopped at the downcomers. As a result, the fuel characteristics should be investigated such as size distribution, moisture content and their tendency to bridge. One ejector system also has been developed to suck the hot air during heat-up process. It also helped the producer gas exit through the vortex finder. The schematic diagram is shown in Figure 3.

CONCLUSION

One of the conclusion from the first experimental series was the heat-up process is done manually and the Diesel burner work properly. The temperature increased tremendously inside the cyclone chamber after a few minute up to 700°C at the upper level of cyclone but at the lower part the wall temperature only increased slowly. From the results shows, the heat from the burner not properly distributed inside the cyclone, where it can be monitored through thermocouple installed. The cyclone system performance was not satisfactory. Work was therefore should be initiated to improve the feeding system by modifying the existing screw feeder and downcomers. The size distribution of the fuel particles is important for the particle flow in the downcomers, the injector feeder and the cyclone gasifier. The size distribution also determines the time required for gasification.

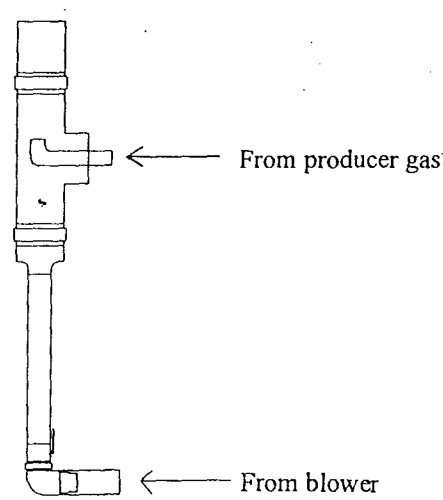

Figure 3: Systematic diagram of ejector

ACKNOWLEDGEMENT

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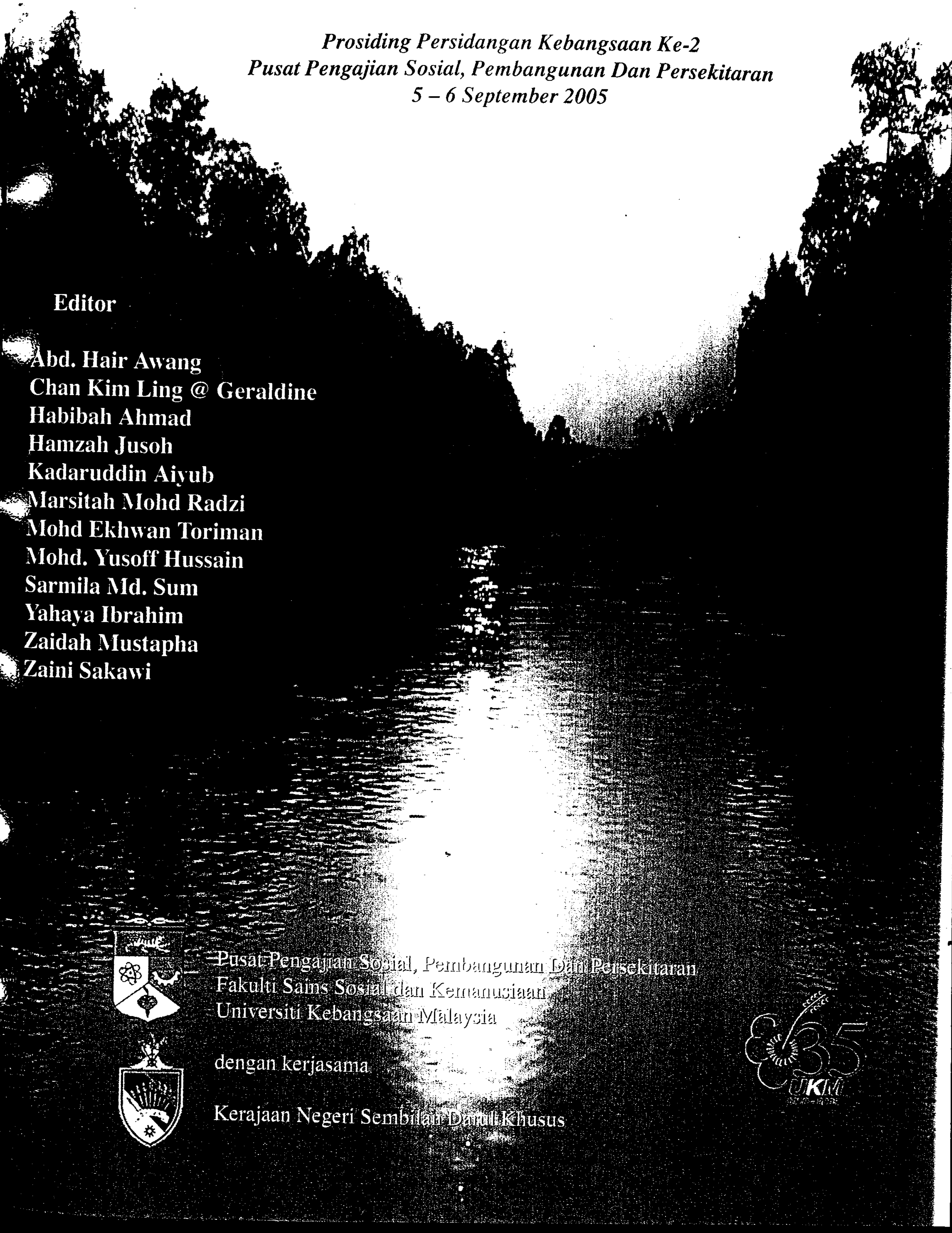

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Kerajaan Negeri Sembilan Darul Khusus

IMBANGAN ALAM MELALUI PENGGASAN BIOJISIM

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ABSTRAK

Berdasarkan isu global mengenai tenaga diperbaharui dan pengurangan gas-gas rumah hijau, biojisim mendapat perhatian yang tinggi sebagai sumber berpotensi tenaga diperbaharui. Mengikut penilaian tenaga dunia, 9.5% daripada penggunaan tenaga utama dunia disumbangkan oleh tenaga diperbaharui. Dalam sektor industri mahupun dalam sektor domestik, tenaga elektrik merupakan satu elemen yang amat penting. Namun begitu, faktor peningkatan kos bahan api dan perlindungan alam sekitar membawa pendekatan baru dalam penggunaan sumber tenaga diperbaharui. Tambahan lagi, jenis-jenis sumber tenaga diperbaharui merupakan sumber tenaga mesra alam. Biojisim merupakan bahan yang terbentuk daripada sebatian organik secara tulennya dihasilkan melalui penggunaan karbon dioksida dalam persekitaran semasa proses fotosintesis tumbuh-tumbuhan. Oleh kerana kepekatan karbon dioksida dipersekitaran secara teorinya kekal malar dalam kitaran, biojisim dijangkakan menjadi salah satu sumber utama tenaga diperbaharui pada masa akan datang. Penggunaan bahanapi biojisim dilihat menjadi semakin penting di kebanyakan negara terutamanya tempat yang sukar mendapatkan bekalan bahanapi fosil. Penggasan ialah proses penukaran biojisim kepada bahanapi gas bolehbakar melalui pemanasan menggunakan medium penggasan seperti udara, oksigen atau stim. Gas yang terhasil daripada proses penggasan adalah bersifat boleh bakar yang mana boleh digunakan untuk menjanakan kuasa. Oleh sebab itu terdapat pelbagai jenis sistem penggasan telah dibangunkan dan sesetengahnya telahpun dikomersilkan. Pusat pengajian kejuruteraan mekanik, Universiti Sains Malaysia di bawah Kumpulan Penyelidikan Tenaga telah membangunkan pelbagai jenis penggas seperti 200 kW penggas lapisan terbendalir, 80 kW penggas siklon, 20 kW penggas alir bebas bawah, 5 kW penggas alir bebas bawah dan penggas-pembakar untuk bahan buangan sisa pepejal. Di dalam kertas kerja ini, imbangan alam melalui penggasan biojisim akan dipersembahkan untuk membina kefahaman dalam menghargai alam sekitar.

PENGENALAN

Apabila harga bahanapi fosil semakin menigkat dan bertambahnya perhatian dan kerisauan terhadap keselamatan sumber tenaga mendominasi perdebatan umum, tenaga diperbaharui dilihat menjadi tenaga alternatif utama untuk jangka masa panjang. Keperluan yang mendesak terhadap keseimbangan elemen-elemen sosial, ekonomi dan alam sekitar memberi kesan yang besar kepada penggunaan sumber tenaga yang kekal [1]. Selain itu, bagi menyahut isu-isu global dalam mengekalkan tenaga dan pengurangan dalam penghasilan gas-gas rumah hijau, tenaga diperbaharui semakin mendapat perhatian sebagai salah satu tenaga yang sangat berpotensi pada masa kini [2]. Menurut Laporan Penilaian Tenaga Dunia (World Energy council, 2001) 14% daripada penggunaan tenaga yang utama di dunia telah disumbangkan oleh tenaga diperbaharui. Peratusan ini dijangka akan terus meningkat disebabkan permintaan tenaga yang semakin tinggi dan diikuti pula meningkatnya kesedaran tentang pemeliharaan alam daripada pencemaran. Sumber tenaga diperbaharui yang dikenalpasti dapat menyumbang kepada penjanaan tenaga dunia ialah tenaga suria, tenaga angin, tenaga biojisim, tenaga biogas, tenaga geotermal, tenaga lautan dan tenaga hidro bersaiz kecil. Secara asasnya kesemua tenaga ini berasal daripada tenaga suria, namun ianya dibahagikan kepada tenaga lazim dan tenaga diperbaharui. Banyak kelebihan dan kepentingan menggunakan tenaga diperbaharui ini. Pertamanya ialah sumber tenaga diperbaharui lebih bersih, selamat, sumber berkekalan dan memberikan kesan pencemaran yang minimum kepada alam sekitar. Selain itu sumber tenaga diperbaharui boleh didapati di tempatan iaitu tidak perlu diimport dan ianya juga tidak terkesan dengan senario politik dunia seperti terjadi dengan bahanapi fosil.

Malaysia kaya dengan sumber bahan buangan biojisim yang sejumlah besarnya datang daripada kilang memproses kelapa sawit, perindustrian berasaskan kayu dan pertanian [3]. Oleh itu, Kerajaan Malaysia akhir-akhir ini mengubah polisinya untuk mempelbagaikan lima sumber bahanapi utama iaitu minyak, gas asli, arang batu dan tenaga boleh diperbaharui. Kerajaan telah mengarahkan 5% daripada sumber tenaganya adalah daripada tenaga boleh diperbaharui menjelang tahun 2005. Penekanan telah diberikan kepada teknologi berasaskan minihidro, biojisim, solar dan angin. Sementara itu, rizab bahanapi berasaskan fosil semakin berkurangan dan permintaan terhadap tenaga semakin meningkat telah memajukan teknologi tenaga alternatif di dunia. Biojisim merupakan salah satu bidang yang diterokai dengan meluas bagi menampung kekurangan bahanapi pada masa akan datang.

Penggassan biojisim memainkan peranan yang penting pada masa dahulu sebagai pengganti kepada bahan api berasaskan minyak di dalam injin pembakaran dalam. Namum begitu selepas tamatnya perang dunia kedua, kepentinganya merosot disebabkan bahan api berasaskan minyak yang diimport secara relatifnya lebih murah. Pada pertengahan tahun 1970, harga minyak didapati meningkat dengan banyak menyebabkan penggunaan penggasan biojisim sebagai bahan api kembali diminati terutamanya kepada negara yang bergantung sepenuhnya kepada pengimportan bahan api berasaskan minyak serta mempunyai sumber bahan api biojisim yang banyak [4].

Sehubungan dengan itu, banyak penyelidikan telah dijalankan untuk membangunkan teknologi bagi sistem penggas dimana sesetengahnya telah berjaya dikomersilkan. Sistem tenaga yang digunakan dikebanyakkan negara membangun terutamanya dikawasan pedalaman ialah injin pembakaran dalam yang membolehkan tenaga elektrik dijana. Di dalam kertas kerja ini, imbangan alam sekitar melalui penggasan biojisim akan dipersembahkan untuk membina kefahaman dalam menghargai alam sekitar.

TENAGA BIOJISIM

Merujuk kepada Persekutuan Industri Tenaga Diperbaharui (TREIA), tenaga diperbaharui ditafsirkan sebagai apa-apa sumber tenaga yang dijanakan secara semulajadi dalam skala yang singkat daripada matahari (seperti terma, fotokimia dan fotoelektrik), juga yang tidak secara terus daripada matahari (seperti angin, kuasahidro dan tenaga fotosintesis yang tersimpan dalam biojisim), atau daripada pergerakan semulajadi lain dan mekanisma alam sekitar (seperti geohaba dan tenaga tidal). Tenaga diperbaharui tidak termasuk sumber tenaga yang dihasilkan daripada bahanapi fosil, produk buangan sumber fosil atau produk buangan daripada sumber bukan organik.

Biojisim adalah tenaga diperbaharui disebabkan tenaga yang dikandungnya datang dari matahari. Menurut laporan Penilaian Tenaga Sedunia, 9.5% daripada keperluan tenaga utama dunia dibekalkan oleh biojisim. Biojisim ialah bahan yang dihasilkan daripada sebatian organik yang terhasil semasa proses fotosintesis tumbuh-tumbuhan [2]. Bahan api pepejal ini biasanya mengandungi elemen-elemen karbon, hidrogen dan oksigen. Selain itu mungkin terdapat nitrogen dan sulfur, namun begitu oleh kerana kehadirannya terlalu sedikit ia boleh diabaikan. Biasanya biojisim dalam bentuk kayu dan merupakan sumber tenaga yang paling lama digunakan oleh manusia samaada dalam sektor domestik dan juga industri. Sumber tenaga ini digolongkan dalam sumber tenaga diperbaharui kerana tumbuh-tumbuhan boleh ditanam secara berulang-ulang. Melalui proses fotosintesis, klorofil dalam tumbuhan mendapatkan tenaga dari matahari menerusi penukaran gas karbon dioksida dalam udara dan air daripada tanah kepada karbohidrat dan sebatian komplek terdiri daripada karbon, hidrogen dan oksigen. Apabila karbohidrat ini dibakar, ia akan kembali berbentuk gas karbon dioksida dan air serta membebaskan tenaga suria yang dikandungnya. Dalam keadaan ini, fungsi biojisim adalah seperti bateri semulajadi untuk menyimpan tenaga suria. Selama mana biojisim sentiasa dihasilkan, bateri ini pastinya tidak akan habis.

Proses fotosintesis boleh digambarkan dalam bentuk persamaan:

Karbon dioksida + Air + Tenaga (radiasi suria) = Biojisim + Oksigen

$$CO_2 + H_2O + \text{Cahaya} \rightarrow (CH_2O) + O_2 \qquad 1$$

Jika biojisim tersebut adalah bahan bolehbakar, proses tersebut akan menjadi terbalik dan tenaga dibebaskan.

Biojisim + Oksigen = Karbon dioksida + Air + Tenaga haba

Semasa penuaian, biasanya biojisim mengandungi kandungan air yang tinggi dan ini akan memberi kesan kepada tenaga sedia ada. Nilai pemanasan tipikal bagi kayu kering-udara (20% kandungan air, asas basah) ialah 15 MJ/kg. Biojisim memberikan pelbagai kelebihan jika digunakan sebagai bahan api untuk menukarkan tenaga terkandung kepada bentuk tenaga yang boleh digunakan, samaada elektrik atau gas bolehbakar. Oleh kerana terdapat pelbagai jenis sumber biojisim, kelebihan sesuatu biojisim bergantung kepada cara bahan tersebut digunakan. Diantara kelebihan tenaga biojisim ialah:

- Ianya tenaga diperbaharui, banyak didapati dan sumber tenaga semulajadi.
- Boleh didapati dengan mudah dimana-mana tempat. Boleh juga ditanam secara perladangan seperti rumput kisar dan kayu getah.
- Walaupun pembakaran biojisim menghasilkan CO_2, ianya boleh digunakan oleh tumbuh-tumbuhan. Jadi ia akan membawa keputusan pengeluaran bersih kosong gas-gas rumah hijau, membolehkan kedua pihak industri dan kerajaan bekerjasama untuk menjaga kualiti alam sekitar.
- Ianya sesuai untuk menjana tenaga elektrik, menghasilkan tenaga haba, dan bahan api.
- Ianya boleh berbentuk pepejal, bendalir dan gas.
- Ianya merupakan bentuk tersimpan tenaga diperbaharui, boleh di pindahkan dan boleh digunakan 24 jam sehari.
- Ia berupaya menyediakan tenaga dalam skala kecil atau besar secara penghasilan setempat.
- Menyediakan peluang pekerjaan setempat di kawasan luar bandar.
- Mengurangkan jumlah bahan buagan, jadi membantu komitmen pihak berkuasa tempatan mencapai bahan buangan sifar.

Tambahan lagi, diantara faktor yang lebih terperinci yang menyebabkan pembangunan tenaga biojisim ini lebih memberangsangkan ialah tumbuhnya kesedaran mengenai perubahan iklim global yang memandu kepada polisi pencemaran alam sekitar.

PENGGASAN

Pada masa kini, terdapat pelbagai teknologi penukaran tenaga biojisim di dalam pasaran. Pengklasifikasianya berdasarkan prinsip penukaran yang digunakan. Teknologi utama penukaran biojisim kepada tenaga untuk penjanaan tenaga elektrik ialah pembakaran, penggasan dan pirolisis. Penggasan ialah salah satu teknologinya yang melibatkan proses kimia haba dimana gas bolehbakar dihasilkan dipanggil gas terhasil.

Penggasan biojisim secara relatifnya merupakan inovasi atau teknologi terkini. Kerja yang sebenarnya dimulakan selewat tahun 1930. Minat terhadap penggasan biojisim ini bermula daripada alternatif kepada kos penggasan arang batu yang murah semasa perang dunia kedua disebabkan terputusnya bekalan bahanapi fosil untuk kenderaan. Definasi lengkap penggasan ialah penukaran bahanapi pepejal kepada gas bolehbakar dalam keadaan suhu terkawal dan kuantiti terhad agen penggasan seperti oksigen, hidrogen atau stim. Teknologi penggasan berbeza dalam pelbagai aspek tetapi terletak pada empat faktor kejuruteraan iaitu:

- Atmosfera reaktor penggas (aras oksigen atau kandungan udara)
- Rekabentuk reaktor
- Pemanas luar dan dalam
- Suhu pengoperasian

Bahan mentah yang tipikal yang digunakan dalam penggasan ialah arang, bahan asas petroleum dan bahan organik. Bahan ini akan disediakan samaada dalam keadaan kering atau lembap akan disuap kedalam ruang reaktor tertutup dipanggail penggas. Bahanapi biojisim ini seterusnya akan dikenakan suhu yang tinggi, tekanan dan keadaan banyak oksigen atau kurang oksigen. Terdapat tiga produk utama penggasan iaitu:

- Gas hidrokarbon
- Cecair hidrokarbon
- Arang (karbon hitam dan debu)

Gas hidrokarbon sebenarnya mengandungi karbon monoksida dan hidrogen (lebih 85% berbanding isipadu) dan kuantiti kecil karbon dioksida dan metana. Gas hidrokarbon ini boleh digunakan bahanapi untuk menjana tenaga elektrik atau stim. Campuran gas hidrokarbon dengan udara boleh digunakan dalam injin diesel dengan hanya sedikit pengubahsuaian.

JENIS-JENIS PROSES PENGGASAN

Jenis-jenis proses penggasan dapat dikenalpasti melalui jenis ejen penggasan yang digunakan. Ejen penggasan ini menyediakan suhu dan keadaan yang sesuai untuk membantu proses penggasan. Terdapat lima jenis utama proses penggasan iaitu penggasan pirolisis, penggasan udara, penggasan oksigen, penggasan hidro dan penggasan stim.

Penggasan pirolisis

Ejen penggasan yang digunakan hanyalah haba. Proses pirolisis ialah proses utama untuk menghasilkan arang dan minyak, dimana sebahagian gas yang dihasilkan akan dibakar semula untuk menyediakan haba bagi proses yang dijalankan. Walaubagaimanapun, sesetengah proses membakar semula minyak dan arang untuk mengekalkan haba supaya tenaga gas medium yang lebih tinggi terbentuk.

Penggassan udara

Penggasan udara adalah yang paling biasa digunakan, mudah dan murah. Udara mengandungi 79% berbanding isipadu bagi nitrogen yang mana tidak bertindakbalas dengan biojisim. Jadi apabila menggunakan udara sebagai ejen penggasan, nitrogen akan mencairkan gas terhasil dan menyebabkan nilai pemanasan diantara 4–5 MJ/m^3. Namun begitu gas yang terhasil sesuai untuk operasi dandang atau injin tetapi terlalu cair jika dipindahkan melalui paip yang panjang.

Penggasan oksigen

Tenaga gas sederhana sebanyak 8 MJ/m^3 akan dihasilkan jika menggunakan oksigen sebagai ajen penggasan dan ianya sesuai untuk pengagihan dalam paip yang terhad. Gas ini sesuai untuk digunakan dalam proses industri haba atau gas sintesis untuk menghasilkan metanol, gasolin, amonia, metana atau hidrogen.

Penggasan hidro

Proses ini juga dikenali sebagai pemetanaan. Hidrogen digunakan sebagai agen penggasan yang menghasilkan metana sebagai produk. Hidrogen boleh ditambah di dalam sistem atau dijana dalam tindakbalas melalui tindakbalas perpindahan diantara karbon dioksida dan stim.

Penggasan stim

Stim kadangkala ditambah dengan udara sebagai agen penggasan untuk menambah kualiti gas terhasil dan mengurangkan haba tindakbalas yang melampau. Kehadiran sedikit kuatiti stim menolong penghasilan metana. Stim juga dijanakan daripada proses pengeringan biojisim itu sendiri.

JENIS PENGGAS

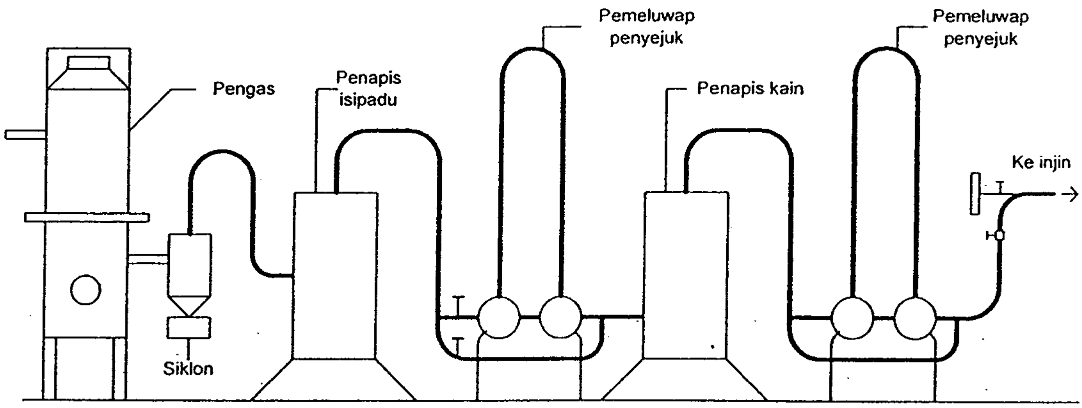
Jenis penggas utama ialah penggas lapisan tetap dan penggas lapisan terbendalir. Bagi penggas lapisan tetap terdapat beberapa kategori iaitu sedut bawah, sedut atas, sedut silang dan pemeruapan. Jadual 1 menunjukan pencirian pelbagai jenis penggas.

Sistem pembersih gas terhasil

Jika gas terhasil mahu digunakan di dalam injin pembakaran dalam, adalah penting untuk membersihkan gas tersebut dahulu untuk membuang kandungan tar dan partikel pepejal. Sistem yang diperlukan agar kompleks, namun begitu penyelengaraan yang kerap diperlukan untuk jangka masa panjang. Faktor persekitaran seperti bising dan asap perlu dipertimbangkan. Rajah 1 menunjukan contoh susunan sistem penggas termasuk sistem pembersih.

Jadual 1. Pencirian penggas

Jenis penggas		Pencirian
Penggas lapisan tetap (10 – 100 mm saiz bahanbakar)	Sedut atas	• Mudah dan jenis tertua • Secara relatifnya insentif untuk saiz dan kandungan lembapan (<60% asasbasah) • Menghasilkan minyak dan tar yang akan mencemarkan gas terhasil • Masalah pelupusan
	Sedut bawah	• Sensitif kepada jenis, saiz dan kandungan lembapan (<25% asasbasah) bahanbakar. • Kandungan abu dan bebanan yang berubah-ubah • Sedikit tar, abu dan habuk
	Sedut silang	• Saiz kecil (< 10 kW_e) • Bahan bakar arangbatu • Suhu operasi yang tinggi (~1500°C) • Kandungan tar dalam gas kurang
	Pemeruapan	• Bersaiz besar • Membakar tar, minyak dan lain-lain di ruang terasing
Lapisan terbendalir (1-10 mm saiz bahanbakar)	Sedut gelembung	• Secara asasnya daripada pengas sedut atas dengan zon tindakbalas dan udara secukupnya dibekalkan untuk mengelembungkan partikel dalam sedutan • Kes khas lapisan terbendalir dengan udara stoikiometri • Lapisan sedut terdiri dari bijian halus atau bahanbakar terhancur • Kandungan tar yang tinggi • Tindakbalas yang lemah terhadap sebarang perubahan • Peralatan kawalan diperlukan



Rajah 1. Contoh susunan pembersih dalam sistem gas terhasil

Nilai tenaga pemanasan

Bahanbakar yang digunakan dalam penggas di USM terdiri dari bahan buangan industri kayu seperti serpih dan habuk. Bahagian ini akan menerangkan pencirian bahan biojisim ini untuk memberikan pemahaman yang lebih. Kandungan utama dalam kayu kering ialah:

- Selulos, $CH_{1.66}O_{0.83}$
- Hemiselulos
- Lignin, $CH_{1.23}O_{0.38}$
- Sedikit mineral dan damar

Daripada analisis muktamad, komposisi kimia bagi kayu, asas jisim (kering dan bebas abu) ialah:

- Karbon, C = 47.3%
- Hidrogen, H = 5.8 %
- Oksigen, O = 45%
- Nitrogen, N = 0.8%
- Sulfur, S ≐ 0%
- Abu = 1.1%

Komposisi kimia ini berubah sedikit sebanyak mengikut spesis yang berlainan. Daripada analisis muktamad di atas, nilai kalori untuk kayu dapat dikira:

$$HHV = 0.341C + 1.323H - 0.12O - 0.00153A + 0.0685 \text{ MJ/kg} \quad 2$$

Kandungan tenaga bagi kayu kering adalah diketahui tetap disekitar 20 MJ/kg. Apabila kayu kering ini dibakar, 20 MJ/kg haba akan dibebaskan sebagai gas panas. Jika stim ini memeluwap, haba tentu akan di ganti (nilai kalori kasar). Jika hilang, haba yang berguna ini akan berkurang (nilai kalori bersih) kepada 1.38 MJ/kg untuk memberi nilai bersih 18.6 MJ/kg. Kandungan kelembapan bagi kayu (MW) pada kebiasaannya diberi berdasarkan asas basah dimana:

$$MW = (W - D) / W \times 100 \quad 3$$

dan W = jisim basah, D = jisim kering

Semasa penuaian, kandungan kelembapan kayu ialah 50%. Jadi, setengah daripada 1 kg jisim kayu tuaian adalah air, tenaga bersih 9.3 MJ daripada setengah kilogram kayu akan kemudiannya mengurang disebabkan tenaga diperlukan untuk meruapkan setengah kilogram air untuk mendapatkan nilai tenaga bersih hanya 8.03 MJ/kg. Biasanya, kayu yang baru dituai dikeringkan terlebih dahulu sekitar 20% sebelum fasa penukaran tenaga. Tenaga bersih per kilogram kayu pada kelembapan 20% adalah sekitar 14.4 MJ/kg. Apabila bahanbakar biojisim digaskan, komposisi umum gas terhasil ialah CO 20%, H_2 15%, CO_2 15%, CH_4 2%, N_2 45%, and O_2 3%. Jadi, nilai kalori bagi gas terhasil dapat dikenalpasti iaitu,

$$(LHV)_{CO}.x_{CO} + (LHV)_{H2}.x_{H2} + (LHV)_{CH4}.x_{CH4} \qquad 4$$

Didapati bahawa nilai pemanasan untuk gas terhasil dari biojisim adalah sekitar 4 MJ/m^3 ke 5 MJ/m^3. Ianya kelihatan nilai kalori ini adalah rendah berbanding dengan bahan mentahnya disebabkan kehadiran N_2. Jadual 2 dibawah menunjukkan perbandingan nilai pemadanan untuk pelbagai bahan biojisim dan juga bahanbakar fosil.

Jadual 2 Nilai pemanasan untuk pelbagai bahan

Bahan	LHV (MJ/kg)
Kelompang	17.3
Serat	10.9
Sisa tandan buah kelapa sawit	7.2
Sekam padi	13.2
Kayu	11.4
Sisa tebu	7.8
Buangan sisa pepejal	10
Najis haiwan	14
Disel	40.9
Arang	29.5
Minyak mentah	42.1
Gas asli	14

Tindakbalas kimia dalam penggasan biojisim

Penggasan biojisim boleh dilihat sebagai tindakbalas global diantara biojisim dan agen penggasan. Tindakbalas penggas ideal dengan oksigen boleh ditulis sebagai,

$$CH_{1.4}O_{0.6} + 0.2\ O_2 \rightarrow CO + 0.7\ H_2 \qquad 5$$

dimana $CH_{1.4}O_{0.6}$ ialah formula kimia untuk kayu dimana ia kelihatan hampir dengan formula selulosa dan lignin. Haba diperlukan untuk menukarkan pepejal kayu kepada karbon monoksida dan hidrogen. Tindakbalas ini adalah tindakbalas seraphaba. Tambahan lagi sejumlah oksigen hendaklah dibekalkan untuk menyediakan haba pembakaran untuk tindakbalas pengasan. Tindakbalas oksigen terbabit adalah sekitar tiga dari karbon monoksida dan hidrogen secara idealnya terhasil. Tindakbalas diatas menjadi teori tindakbalas pengasan global.

$$CH_{1.4}O_{0.6} + 0.45O_2 \rightarrow 0.7CO + 0.3CO_2 + 0.55H_2 + 0.2H_2O \qquad 6$$

Tindakbalas penggasan diatas sebahagiannya dapat digambarkan melalui tindakbalas penggasan homogen dengan pengantian tindakbalas dianggap seimbang. Keseimbangan malar pengantian tindakbalas boleh ditulis sebagai:

$$K = \frac{PH2P\ CO2}{PCOP\ H20} = \frac{0.55 \times 0.3}{0.7 \times 0.2} = 1.1786 \qquad 7$$

dimana P_{H2}, P_{CO2}, P_{CO} and P_{H2O} adalah pecahan mol bagi hidrogen, karbon monoksida dan wap air. Daripada jadual keseimbangan malar, suhu keseimbangan ialah 768.28°C. Ini menunjukkan suhu teori penggasan ialah 768.28 °C. Suhu diperolehi berasaskan kepada bahan biojisim kering. Biasanya bahan biojisim dicirikan oleh kandungan kelembapan. Semakin tinggi kandungan kelembapan semakin banyak tindakbalas air dan gas berlaku. Hadnya ialah 36% dimana kesetaraan ketepuan mencapai 100% dan seterusnya menurunkan suhu kepada 500°C. Ini seterusnya mengurangkan kepekatan gas bolehbakar dan nilai kalori. Ini adalah benar untuk penggas tertentu seperti penggas sedut bawah. Bagaimanapun penggas terbendalir atau sedut atas boleh menggas bahan biojisim yang mengandungi kelembapan sehingga 60%.

Nisbah bahanbakar–udara untuk teori proses penggasan

Di dalam pengenalpastian jumlah udara diperlukan untuk menggaskan sejumlah bahan biojisim, nisbah udara bahanbakar penting untuk diketahui. Dengan menggunakan Tindakbalas Kimia Global seperti yang dijelaskan sebelum ini, nisbah bahanbakar-udara boleh dikira. Tindakbalas global boleh ditulis dalam bentuk jisim dengan mengandakan pecahan molar bagi biojisim dan gas melalui jisim molekulnya. Oleh itu persamaannya menjadi,

$$\begin{aligned}&(23\text{kg})\ CH_{1.4}O_{0.6} + 0.45(32\text{kg})\ O_2 \rightarrow 0.7(28\text{kg})CO \\ &+ 0.3(44\text{kg})CO_2 + 0.6(2\text{kg})H_2 + (18\text{kg})H_2O\end{aligned} \qquad 8$$

Ini menjadi,

$$23CH_{1.4}O_{0.6} + 14.4O_2 \rightarrow 19.6CO + 13.2CO_2 + 1.2H_2 + 1.8H_2O \qquad 9$$

Untuk 1 kg $CH_{1.4}O_{0.6}$, jumlah O_2 diperlukan ialah 0.626 kg. Jadi, jumlah udara yang digunakan sebagai agen penggasan per kg biojisim diberikan oleh 0.626 kg/0.233 = 2.687 kg. Jadi nisbah bahanbakar–udara gravitian untuk penteorian proses pengassan diberi oleh, $(A/F)_{teori}$ = 2.69. Isipadu udara diperlukan bagi pengasan teori ialah 2.69/1.2 = 2.24 m^3/kg bojisim. Ini menunjukan bahawa 2.24 m^3 udara diperlukan untuk 1 kg bahan biojisim. Walaubagaimanapun, kadar biojisim dan kadar aliran udara tidak dipertimbangkan dalam memperolehi nilai ini. Semakin tinggi kadar aliran udara dibekalkan, semakin tinggi kadar biojisim diperlukan dan semakin tinggi kadar pengasan seterusnya meningkatkan keluaran tenaga bagi gas terhasil

Nisbah kesetaraan

Jumlah udara yang diperlukan untuk pembakaran sempurna bagi bahan biojisim untuk membentuk karbon dioksida dan wap air boleh dipersembahkan melalui, 2006 ICEE

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Evaluation of Cyclone Gasifier Performance for Gasification of Sawdust

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Keywords: Sawdust, Cyclone gasification, Producer gas, Heating value.

Abstract

This paper covers the results obtained for gasification of sawdust in cyclone gasifier at atmospheric pressure. A method for gasifying sawdust from furniture industries has been studied and evaluated. The main objective is to characterize the cyclone gasifier using smaller biomass particles as a fuel. The sawdust is gasified in cyclone gasifier with the particle size distribution from 1 mm to 0.04 mm and the moisture content (wt %) is 12.6. Sawdust was injected into the cyclone with air as transport medium. The gasification tests were made with different feeding rates from 8 to 40 kg/h. The experiments were conducted with the equivalence ratios being varied from 0.23 to 0.40 and the gasification temperature is ranging from 800°C to 950°C. It was found that the heating value of the producer gas is determined in the range of 3.3 to 4.1 MJ/kg (dry basis), which is sufficient for stable engine combustion. Optimization of the particle size and residence time has a significant influence on improving the performance of the cyclone gasifier.

1 Introduction

The green house effect has become a serious world issue. In particular, the green house gas emission from the use of fossil fuels has critically affected the environment. In view of this, renewable energies such as biomass fuels can play a significant role in reducing the green house emissions as well as other pollution in relation to fossil fuels. The biomass fuels can be used as an alternative to the fossil fuels mainly in the area of power generation and the sources are not depleted with time (Z.A. Zainal et al., 2001). Biomass fuels can be derived from various agricultural resources and the focus of this work is on the sawdust from saw mill and wood based industries. The sawdust is feasible to be used as the biomass fuel due to its easy availability as an abundant in many countries.

A biomass-fuelled gasification has become a capable process of generating electricity with a high efficiency and low emissions at a competitive cost if the biomass fuel is available at low cost. Thus, such gasification technologies could also be used to maximise the electricity output in the wood based industry in the developing countries. There are many gasification technologies available in the market. The classification is based on the conversion principal in which the energy in the biomass being converted to other useful energy. Basically, gasification refers to a thermo chemical process that produces combustible gas called producer gas. A lot of advantages associate with this technology such as flexibility to fuel, a wide range of power system, easier to distribute and control the gaseous fuel. Two types of gasifier which are widely available in the market are Fixed bed gasifier and Fluidised bed gasifier. Basically, these gasifiers use solid biomass such as wood chip and oil palm empty-fruit-branches chip as a fuel. With the availability of smaller particle sizes of biomass such as sawdust, rice husk and baggase, cyclone gasifier was developed to gasify those types of biomass as a fuel utilizing cyclonic motion concept. The advantage of this technique are the particle of biomass fuel is held in suspension over a period of time in a cyclonic motion to allow the reaction take place and finally, producing combustible gas.

The mechanism of gasifying biomass particles in the cyclone gasifier is explained. Specifically, the combustible fraction of a solid fuel can be divided into volatile and non-volatile fractions. The overall rate of gasification of the biomass particle depends upon individual rates of the processes involved, i.e. drying, release of the combustible volatiles, mixing of the volatiles vapor and the oxidant, combustion of the volatiles and the gasification of non-volatile combustibles. The rates of these individual processes depend upon the size of a fuel particle, the heat transfer with surroundings and the gas composition in the vicinity of the particle. The amounts of fuel gasified will also depend on the residence time, which will be quite different in different types of gasifiers.

When the biomass fuel particle enters the hot cyclone, it will get dried and is pyrolysed, which implies that a self-sustaining exothermic reaction takes place in which the natural structure of the biomass particle breaks down and devolatilisation starts. The volatile combustibles are released and mixed with surrounding air. A diffusion flame is stabilised around the particle where the combustibles and the oxygen form a flammable mixture. Little oxygen can penetrate through the flame into the fuel particle. During this process, the size of the particles is only slightly reduced but the particle density is decreasing. The result is a residual solid (char) and a gas mixture composed primarily of carbon dioxide, carbon monoxide, hydrogen, water vapour, nitrogen and pyrolysis products including tar and hydrocarbons.

Biomass contains 75–85% volatile matter compared to 50% or less for coal, so pyrolysis plays a larger role in biomass gasification. After the oxygen around the particle is consumed and the volatile flame is extinguished, the char, tar and hydrocarbons are then gasified by reactions with the carbon dioxide and water vapour to give a fuel gas composed mainly of CO, H_2 and CH_4. Most of the hydrogen that is produced remains free. However, a portion of the hydrogen is found in methane and hydrocarbons, which are mainly results of the break-up of volatiles. Some methane may also be formed by reactions between hydrogen and carbon or hydrogen and carbon monoxide.

If high amount of steam injected with the fuel or high moisture content in the fuel, the so-called water shift reaction can be important. In the water shift reaction, the carbon monoxide reacts with water to produce carbon dioxide and hydrogen. This reaction is not favorable since it reduces the calorific value of the final gas. In the case of excess steam present during the gasification process, a considerable proportion of steam normally passes through the cyclone gasifier without reacting and simply becomes a component in the final gas stream.

There are three main factors to ensure a complete reaction of all tars, hydrocarbons and char with the gasification air. Those factors are the equivalence ratio, the geometry of the cyclone gasifier and the residence time. A fraction of the ash forming elements may be volatilised and released to the gas phase during the gasification process. A part of these volatiles may react or condense on the surfaces of the char separated at cyclone bottom and carryover particles contents in the producer gas and change the surface composition and size of them. The volatilisation fraction depends on the ash composition of the fuel, the particle size, the particle temperature and the gasification pressure.

School of Mechanical Engineering, Universiti Sains Malaysia (USM) are investigating a new approach for gasifying smaller size biomass fuels. Biomass fuel is gasified in a cyclone gasifier as well as cyclone separator operated at a relatively low temperature. Although several indications are available on theoretical regarding the technique surprisingly little work has been performed to quantify several effects through experimental. Therefore, more studies of biomass gasification in cyclone gasifier are required to better understand the technique.

In the present work, C Syred et al., 2004 have studied the inverted cyclone gasifier coupled to a cyclone combustor in series for indirect firing of a small-scale gas turbine. The experimental studies were carried out on Commercial Austrian sawdust and Commercial Swedish wood powder with the size distributions were between 0.063 and 2 mm. Mohamed Gabra et al., 2001 discussed the comparison of alkali retention using bagasse in a fluidized bed and cyclone gasifier. The alkali retention in the fluidised bed gasifier was 12-4% whereas in the cyclone gasifier was about 70%. Mohamed Gabra et al., 2001 also have studied the performance of cyclone gasifier using two different biomass fuels. The first experiment is gasification of crushed bagasse in a two-stage combustor at atmospheric pressure, where the first stage is a cyclone gasifier. M. Gabra et al., 1998 demonstrated the sugar cane residue feeding system for a cyclone gasifier that designed to operate without interruption or large fluctuations. It was found that to eliminate the blockage in the downcomer channels, the powder should be more homogeneous. Salman Hassan et al., 2000 discussed the possibility of using the steam-jet ejector to inject wood powder and sawdust into the pressurized cyclone gasifier.

The main purpose of this work is to evaluate the performance of the cyclone gasifier using sawdust as the biomass fuel, in which the cyclone gasification process will produce an output gas or producer gas that is highly potential for the operation of an internal combustion (IC) engine. Several key tests were conducted during the cyclone gasification process with the aim to:-

1. Determine the equivalence ratios for stable operation.

2. Determine the heating value of the producer gas.

3. Temperature distribution inside cyclone chamber

2 Fuel characteristics and preparation

The raw material of sawdust was collected from few furniture industries in Nibong Tebal, Penang. The size distribution of the fuel particles is important to be considered for determining the particle flow condition in the downcomer, the injector and the cyclone gasifier. The size distribution also influences the time required for gasification and the carry-over particles with the product gas. The sawdust was produced by grinding the raw material in a disk mill. The size distribution was determined by sieving analysis and the result are as shown in Table 1.

Size (mm)	Weight%
S>2	1.81
1.0 – 2.0	1.54
0.5 – 1.0	48.57
0.250 – 0.5	32.56
0.125 – 0.250	8.33
0.063 – 0.125	3.51
0.045 – 0.063	3.55
S<0.045	0.13
Sum	100.0

Table 1: Size distribution of sawdust

The ultimate analysis was conducted to determine the chemical composition of the sawdust and the proximate analysis was done to determine the contents of volatiles, fixed carbon and ash. The results of both analyses for sawdust are as shown in Table 2 and Table 3.

Ultimate analysis	Dry weight%
C	42.38
H	5.27
N	0.14
S	0.62
O (diff.)	41.79
Ash	1.50

Table 2: Ultimate analysis

Proximate analysis	Dry weight%
Moisture content	8.30
Volatiles	76.2
Fixed Carbon	14.0
Ash	1.5

Table 3: Proximate analysis

3 Experimental equipment

The experimental work comprises of design and construction of the experimental set-up, planning, performance and evaluation of the test. A schematic diagram of the atmospheric cyclone gasifier is shown in Figure 1. The fuel system consisted of a storage bin, a screw feeder in the bottom and a downcomer. The downcomer is connected to the cyclone gasifier and to the feeding bin. The fuel powder is transferred from the storage bin to the downcomer by means of a single screw feeder. Frequency adjusting devices are used to control the speed of the motor that drive the feeding screws. The fuel mass flow is controlled by the speed of the screw in the feeding bin and the feeding rate as a function of screw speed was determined by calibration tests.

The powder falls by gravity through the downcomer to the suction chambers of the fuel injector, where the fuel is sucked into the cyclone through the injector entering the cyclone in a tangential direction. Pressurised air was used to drive the injector. The injector is used also as suction pump to suck the air required for gasification. The inlets have a circular cross-section and the storage bin designed applied funnel flow where the fuel flows through the core. The storage bin volume is 0.225 m^3 consist of 60 kg sawdust with the mass density of dry sawdust (10% moisture) is 267 kg/m^3 for 1-hour operation time. The sawdust feeding is manual and semi-continuous, introducing fixed quantities.

The present cyclone gasifier is in conical reverse flow with one tangential inlet. This cyclone gasifier consists of both conical and cylindrical parts which together form the body of the cyclone. The gasifier body is made of Mild Steel plate and the conical part connected with a char collector at the bottom. The inlet pipe of the cyclone is mounted tangentially on to the sidewall of the cylindrical part of the cyclone body. The exit tube usually called the vortex finder or the vortex tube is fixed on the top of the cyclone and it protrudes in to the body of the cyclone. Part of the internal diameter is insulated with refractory cement and calcium silicate to minimize heat loss. The gasifier built has capacity to process approximately 60 kgh^{-1} of sawdust corresponds to desired thermal output of 200 kW_T. Furthermore, the cyclone gasifier, which is designed as a standard cyclone separator, works as a particle separator as well. The cyclone is mounted vertically standing on a dust bunker at the cyclone bottom where the char is separated. The dimensions of the tested cyclone gasifier are as shown in Figure 1.

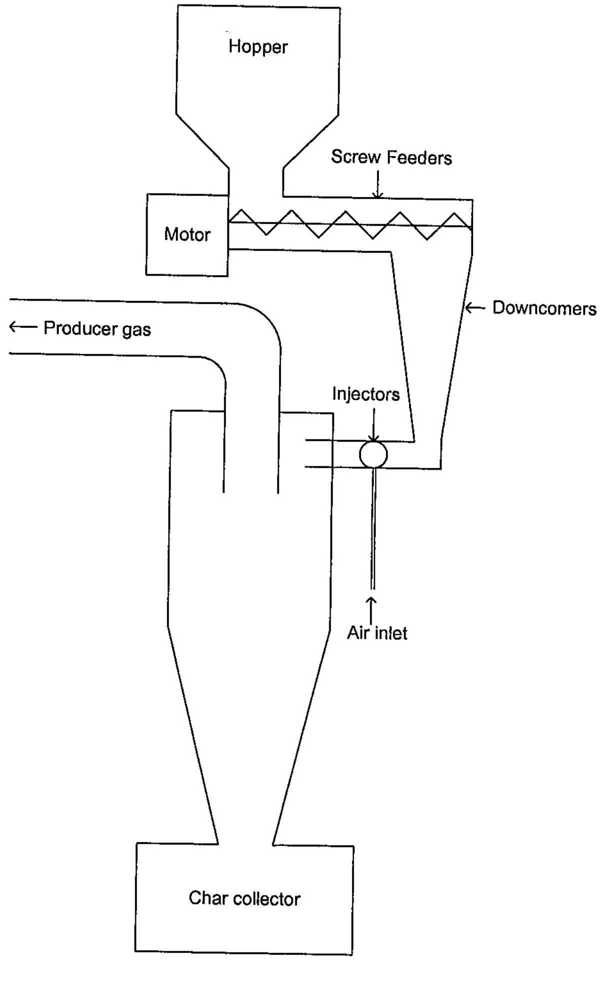

Figure 1: A schematic diagram of cyclone gasifier system

During the gasification test, cyclone gas and wall temperature and the flow of air is measured with sheathed thermocouple type K attached tangentially.

4 Experimental procedures

In the cyclone gasifier, the experiments were started by pre-heating the cyclone with a diesel burner before injecting the sawdust. The fuel injection was started when the outlet gas temperature was about 600°C to initiate volatiles and gasification reaction. The diesel burner is located tangentially within the reactor to make sure the heat uniformly distributed inside the cyclone. The burner is positioned in an opening situated about 140 mm from the top of the cyclone. The heating time is about 15 minute if the burner is used in a moderate way and about 10 minute if the burner is operated at full air valve opened. The heat up procedure was optimized to obtain minimum time and minimum diesel consumption.

There are 4 type-K thermocouple is located at different places to investigate the thermal effect and gas temperature distribution inside the cyclone gasifier. The data reader was turned on during the system start up to monitor the temperature distribution at specific location of the gasifier. Figure 2 shows the position of the thermocouple used for monitoring wall temperature and product gas in the cyclone gasifier. The position of the thermocouples were denoted using the non-dimensional position z/D_e, where z represents the axial distance from the gasifier outlet/exit (z=0 is at the gasifier exit rim) and D_e is the gasifier exit diameter. The locations are state as follow:

$T_1 = Z/De = 0.24$
$T_2 = Z/De = -0.87$
$T_3 = Z/De = -1.48$
$T_4 = Z/De = -2.91$

Once the outlet gas temperature has reached 600°C, the screwfeeder is switch on to cater for the required feed rate of the sawdust. When the sawdust was transfer to the downcomer, the air is injected from the air compressor at certain pressure. When the combustion was occur steadily, the burner was switched off and the required air is blown to the gasifier chamber to supply certain amount of air for gasification process. The system temperature is monitored and the air flow level is adjusted to achieve the ideal exit gas temperature of 800°C.

The feeding rate was controlled by adjusting the speed of the feeder screw. The desired equivalence ratios were produced by adjustment of the air flow. The producer gas was generated after a few minutes from the injection of sawdust and it leaves through the top outlet of the cyclone. After about 15 min the system reached stable condition and was running smoothly. When the cyclone was running at steady state conditions with stable temperature and at a specific equivalence ratio, a char sample was collected from the char collector at the bottom of the cyclone.

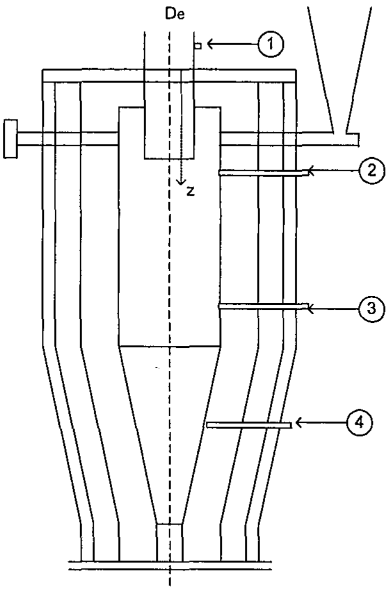

Figure 2: Thermocouple positions

5 Experimental results and discussion

Initiation of the devolatilisation and gasification reactions in the cyclone requires that the fuel particles are heated to a sufficiently high temperature after entering the cyclone. The temperature inside the cyclone chamber is important for this heating of the fuel particles. From the experiment, the gasification process is found stable as long as the temperature inside the cyclone chamber exceeds 400°C. The gasification tests with the equivalence ratio lower than 0.18 were found to be impractical since the temperature inside the cyclone chamber decreases below 400°C thus the gasification stability deteriorates. However, a very high wall temperature will also damage the cyclone gasifier. Thus, the operation temperature limits for the suggested cyclone have to be kept in the range of 400–600°C. This determines the equivalence ratios for stable gasification. With this fuel, the equivalence ratios could be varied between 0.23 and 0.40. This interval of the equivalence ratios gives a gas temperature ranging from 500°C to 950°C. The gasification process is stable and the system is running smoothly within this temperature range.

5.1 Temperature distribution inside the cyclone

In Figure 3 the measured temperature is plotted as a function of equivalence ratio for gasification with air as injection medium. In all cases, the experimental data show similar behaviour. The temperature increases with increasing equivalence ratio. When the equivalence ratio increased from 0.15 to 0.40 the product gas temperature increased from 780°C to 990°C.

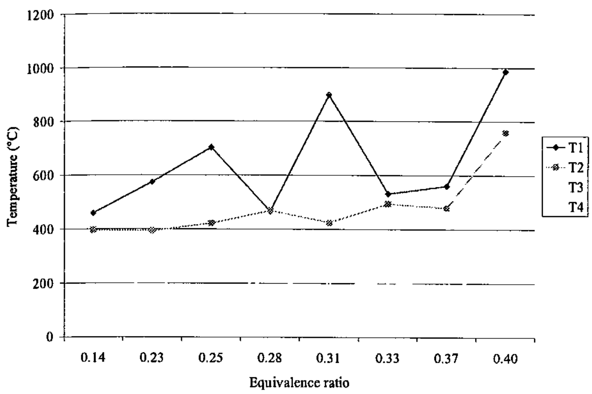

Figure 3: Gas temperatures as a function of equivalence ratio

5.2 Gas composition and heating value

The measured concentration of CO, CO_2 and CH_4 are as shown in figure 4, Figure 5 and Figure 6, respectively. There was a decrease of CO from about 13% to about 2% and the concentrations of CH_4 decrease from 4% to 2% when the equivalence ratio was increased from 0.15 to 0.40. At the same time the amount of CO_2 increased from approximately 11% to 17% as the equivalence ratio was increased.

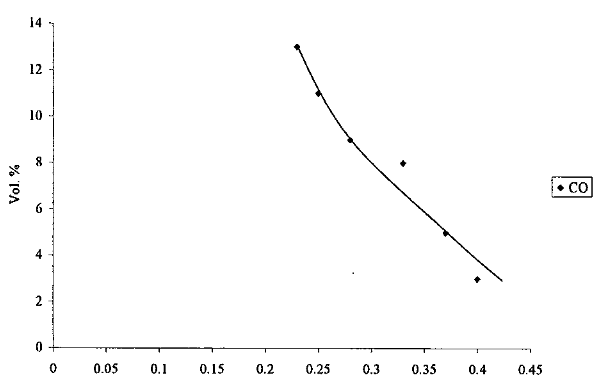

Figure 4: Measured content of CO in the gas from the cyclone

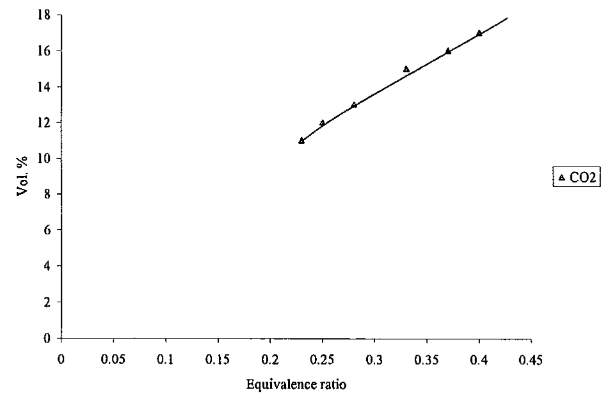

Figure 5: Measured content of CO_2 in the gas from the cyclone

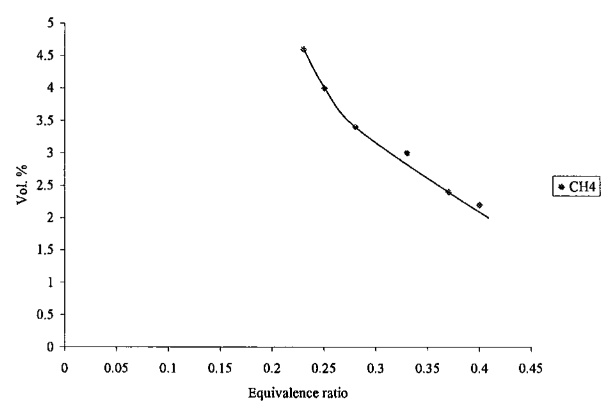

Figure 6: Measured content of CH_4 in the gas from the cyclone

The heating value of the producer gas is determined by the gas composition of the producer gas. The heating values of the producer gas from the gasification of sawdust are low, typically 3.3–4.1 MJ/Nm^3 (dry gas).

6 Conclusions

The objective of this work is to characterize the cyclone gasifier in order to develop the understanding on the temperature distribution inside the cyclone chamber, the stable gasification process at certain equivalence ratio, the gas composition and to determine the heating value of the producer gas. The main conclusions from the present study are:

- The cyclone gasifier should be heat up at temperature average 600°C at cyclone outlet and 400°C at cyclone chamber using diesel or gas burner to sufficiently heated the fuel particles when enter the cyclone chamber to initiate volatiles and gasification reaction. So, the heat up temperature is very important to enable the gasification process.

- When the equivalence ratio has been varied from 0.15 to 0.40, the gasification occurred in the cyclone chamber with average gas temperature ranging from 460°C to 987°C, while the average temperature at the cyclone inlet ranging from 397°C to 758°C and at the cylindrical part of the cyclone chamber ranging from 127°C to 241°C. Furthermore, the average temperature at the bottom part is ranging from 128°C to 269°C. The gasification is stable and the system is running smoothly.

- The heating value of producer gas at equivalence ratio 0.15 to 0.40 ranging from 3.3 to 4.1 MJ/Nm^3 (dry-gas).

Acknowledgements

The financial assistance from University Science Malaysia Short Term Grant gratefully acknowledged.

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[6] M. Gabra, H. Salman and B. Kjellström, Development of a sugar cane residue feeding system for a cyclone gasifier, *Biomass and Bioenergy*, 15(2), pp. 143-15, 1998.

[7] Salman Hassan and Kjellström Björn, Pneumatic conveying of wood powder by using a steam-jet ejector, *Biomass and Bioenergy*, 19(2), pp. 103-11, 2000.

YEARLY FINANCIAL REPORT

A **Program/Project Number: 6035136**
Project title: Performance characteristic of a cyclone gasifier for power generation
Project leader: Muhamad Azman bin Miskam
Tel: 04-5996333
Fax: 04-5941025

B **Actual Project Expenditure** (*Please report the expenditure for the past year*)
Period: 15 Mac 2005 – 14 Mac 2006

Project cost components	**Allocation***	**Actual expenditure (RM)***
Salary and wages (Vot 11000)	2000	0
Travelling and subsistence (Vot 21000)	5000	7119.20
Communication and utility (Vot 23000)	0	11.20
Research materials and supply (Vot 27000)	9000	6847.15
Repair and maintenance (Vot 28000)	0	0
Profesional services and hospitality (Vot 29000)	2000	3000
Asset	2000	0
Total	20000	16977.55

* Please refer the attachment.

Is this performance in line with plan: Yes

C **Reason for the variation from the budget** (*Please provide the reasons*)
Traveling and subsistence: Attending the 2 National conferences and 2 International conferences, attending the IPTA Expo & Exhibition as a co-researcher (Bronze medal), Industrial visit at several location of wood-based industries, MODENAS for raw material and collaboration, attending meeting for research collaboration & advancement (COE, JSPS etc.), Research Visit at UM,UNITEN and TNBR. There are also a number of claim that are still not updated at amount about RM700
Communication & utility: Calling the supplier for supply raw material and research material.
Research material and supply: There are a number of buying a research material that are still not updated at amount about RM2285
Asset: No expenditure for asset because the previous tool/machine still can be used after repair and maintenance and it more beneficial

D **Proposed corrective action** (Please give details of the proposed action)

Date: 27 Mac 2007 Signature:

Perio	Kod Dok	No Dok	Tarikh Dok	El 1	El 2	El 3	El 4	El 5	Keterangan	Amaun
5/5	BL	46581	19/05/05	304	221	21102	PMEKANIK	6035136	NO BTP 40907 - DYNASTY HOTEL	149.50
5/5	BL	46712	25/05/05	304	221	21101	PMEKANIK	6035136	T/P 4/05 - G/J/PEN	67.50
5/5	BL	46712	25/05/05	304	221	21104	PMEKANIK	6035136	T/P 4/05 - G/J/PEN	50.00
5/5	BL	46712	25/05/05	304	221	21106	PMEKANIK	6035136	T/P 4/05 - G/J/PEN	316.00
5/5	BL	46712	25/05/05	304	221	21199	PMEKANIK	6035136	T/P 4/05 - G/J/PEN	16.10
5/6	BL	47595	22/06/05	304	221	21101	PMEKANIK	6035136	T/P 5/05 - G/J/PEN	180.00
5/6	BL	47595	22/06/05	304	221	21102	PMEKANIK	6035136	T/P 5/05 - G/J/PEN	55.00
5/6	BL	47595	22/06/05	304	221	21106	PMEKANIK	6035136	T/P 5/05 - G/J/PEN	316.00
5/7	BL	48769	26/07/05	304	221	21102	PMEKANIK	6035136	NO BTP 40909 - EN AZMAN MISKAM	435.00
5/8	BL	49041	03/08/05	304	221	21104	PMEKANIK	6035136	T/P 6/05 - G/J/PEN	50.00
5/8	BL	49041	03/08/05	304	221	21199	PMEKANIK	6035136	T/P 6/05 - G/J/PEN	15.60
5/10	BL	50969	05/10/05	304	221	21101	PMEKANIK	6035136	T/P 8/05 - G/J/PEN	36.40
5/10	BL	50969	05/10/05	304	221	21104	PMEKANIK	6035136	T/P 8/05 - G/J/PEN	70.00
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5/11	JP	2587	28/11/05	304	221	21104	PMEKANIK	6035136	PELARASAN PERBELANJAAN PROJEK	14.00
5/11	BL	52689	29/11/05	304	221	21101	PMEKANIK	6035136	T/P 9/05 - G/J/PEN	297.00
5/11	BL	52689	29/11/05	304	221	21102	PMEKANIK	6035136	T/P 9/05 - G/J/PEN	330.00
5/11	BL	52689	29/11/05	304	221	21106	PMEKANIK	6035136	T/P 9/05 - G/J/PEN	316.00
5/11	BL	52689	29/11/05	304	221	21104	PMEKANIK	6035136	T/P 9/05 - G/J/PEN	520.00
5/11	BL	52689	29/11/05	304	221	21199	PMEKANIK	6035136	T/P 9/05 - G/J/PEN	91.00
5/12	BL	52878	05/12/05	304	221	21102	PMEKANIK	6035136	NO BTP 40934 - COPTHORNE ORCHID	260.00
5/12	JR	5445	17/12/05	304	221	21104	PMEKANIK	6035136	BRG Q 056167 - KEND UNIVERSITI	6.50
5/12	JP	2670	31/12/05	304	221	21101	PMEKANIK	6035136	JERNAL PELARASAN PINDAHAN BAKI	179.80
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/2	BL	55566	17/02/06	304	221	21104	PMEKANIK	6035136	T/P 11/05 - G/J/PEN	70.00
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/2	BL	55567	17/02/06	304	221	21104	PMEKANIK	6035136	T/P 1/06 - G/J/PEN	60.00
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	BL	67359	28/01/07	304	227	27799	PMEKANIK	6035136	NO PO 141074 - AITEK ENT	175.60
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05/10	BL	51199	08/10/05	304	228	28908	PMEKANIK	6035136	NO PO 114137 - HOCK BEE HARDWAR	1,600.00
05/4	BL	45545	18/04/05	304	229	29107	PMEKANIK	6035136	YURAN-CONFERENCE NAME'05	300.00
05/8	BL	49967	26/08/05	304	229	29107	PMEKANIK	6035136	YURAN PERSIDANGAN KE 2	350.00
05/9	JP	2492	22/09/05	304	229	29107	PMEKANIK	6035136	BATAL CEK -126130 YURAN PERSIDA	(350.00)
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5/12	JR	5485	18/12/05	304	229	29107	PMEKANIK	6035136	BRG Q 056162 - YURAN JSPS-VCC	450.00
7/3	BL	69487	20/03/07	304	229	29107	PMEKANIK	6035136	T/P 2/07 - G/J/PEN	350.00
										3,000.00
									JUMLAH	16,977.55

COMPLETION OF FINAL REPORT

PERFORMANCE CHARACTERISTICS OF A CYCLONE GASIFIER FOR POWER PRODUCTION

Project begin date: 15 Mac 2005
Project ending date: 14 Mac 2007

MUHAMAD AZMAN MISKAM
PRINCIPLE RESEARCHER

UNIVERSITI SAINS MALAYSIA
RESEARCH CREATIVITY AND MANAGEMENT OFFICE

2007

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M.A. Miskam, Z.A.Z Alauddin (2005). Characterization of Sawdust as a Fuel for Cyclone Gasifier. Proceeding of The 5th 21st Century COE International Symposium on Global Renaissance by Green Energy Revolution. Pulau Pinang, Malaysia. August 7-10

M.A. Miskam, Z.A.Z Alauddin (2005). Experimental Investigation of a Cyclone Gasifier. Proceeding of a National Conference on Advances in Mechanical Engineering NAME05. Kuala Lumpur, Malaysia. May 18-20

M.A. Miskam, Z.A.Z Alauddin (2005). Imbangan Alam Melalui Penggasan Biojisim. Prosiding bagi Persidangan Kebangsaan Ke-2, Keharmonian Hidup, Imbangan Alam dan Pembangunan PK2-PPSPP. Kuala Lumpur, Malaysia. September 5-6

M.A. Miskam, Z.A.Z. Alauddin, M.Y.Idroas (2006). Evaluation of Cyclone Gasifier Performance for Gasification of Sawdust. Proceeding of an International Conference on Energy and Environment 2006 (ICEE06). UNITEN Kajang, Selangor, Malaysia. August 28-30

ABSTRACT

A new technique of gasifying pulverized biomass fuel based on cyclonic motion concept is being developed for power generation. Sawdust has been used as a fuel for cyclone gasifier reactor to produced producer gases of typically 3 – 5 MJ/m^3. The work of this project involved both theoretical and experimental work to understand the operation as well as the performance and characteristics of a cyclone gasifier. The primary goals of this project were to characterize the sawdust as a pulverized biomass fuel for cyclone gasifier, determine the temperature profiles of the producer gas and wall temperature profiles inside the cyclone chamber, analyze the producer gas, perform thermodynamics analysis, and obtain gasifier efficiency and thermal output of the cyclone gasifier.

Ground sawdust from furniture industries is used as a fuel with size distribution from 0.25 to 1 mm is about 80%. The low heating value was found to be about 16.54 MJ/kg with moisture content of 8.25%. Sawdust was injected into the cyclone gasifier with air as a gasifying agent. The gasification tests were made with varying air flow rate and fuel feed rate. Experiments were conducted with varying equivalence ratios. The typical wall temperature for initiating gasification process was about 400°C. The average temperature of producer gas was about 600 – 800°C. The highest average heating value of producer gas was 3.9 MJ/kg with flow rate 0.01471m^3/s. The highest thermal output from the cyclone gasifier was 57.35 kW_T. The highest value of mass conversion efficiency and enthalpy balance were 60% and 98.7% respectively. Generally, the efficiency of cyclone gasifier increases with the increase in equivalence ratios and the highest efficiency of the cyclone gasifier obtained was 73.4% and this compares well with other researchers. The thesis has identified the optimum operational condition for gasifying sawdust in cyclone gasifier system and made conclusions as to how the steady state gasification process can be achieved.

ABSTRAK

Satu teknik baru untuk mengaskan bahanapi biojisim terhancur berasaskan kepada konsep pergerakan siklon telah dibangunkan untuk tujuam penjanaan kuasa. Habuk kayu telah digunakn sebagai bahanapi untuk reaktor pengas siklon bagi menghasilkan gas-gas terhasil secara tipikalnya 3-5 MJ/m^3. Kerja-kerja projek ini termasuklah secara teori dan eksperimen untuk memahami operasi dan juga prestasi serta pencirian bagi pengas siklon tersebut. Matlamat utama projek ini adalah untuk mencirikan habuk kayu sebagai bahanapi biojisim terhancur untuk pengas siklon, mengenalpasti profil suhu gas-gas terhasil dan juga profil suhu dinding didalam kebuk siklon, menganalisa gas-gas terhasil secara termodinamik dan juga mendapatkan kecekapan dan keluaran terma pengas siklon.

Habuk kayu daripada industri perabut dikisar dan digunakan sebagai bahan api dengan agihan saiz dari 0.25 ke 1 mm adalah sebanyak 80%. Nilai pemanasan rendah didapati 16.54 MJ/kg dengan kandungan lembapan 8.25%. Habuk kayu disuntik ke dalam penggas siklon dengan udara sebagai agen penggasan. Ujian penggasan dibuat dengan mengubah kadar aliran udara dan kadar suapan bahan api. Eksperimen-eksperimen dijalankan dengan nisbah kesetaraan diubah. Suhu dinding tipikal bagi memulakan proses penggasan ialah 400°C. Suhu keluaran semasa ujian dijalankan secara puratanya didapati diantara 600 – 800°C. Nilai pemanasan purata tertinggi adalah 3.9 MJ/kg dengan kadar aliran 0.01471 m^3/s. Kuasa keluaran terma tertinggi dari penggas siklon adalah 57.35 kW_T. Nilai maksimum kecekapan penukaran jisim dan imbangan entalpi adalah masing-masing 60% dan 98.7%. Umumnya, kecekapan meningkat dengan peningkatan nisbah kesetaraan dan kecekapan maksimum penggas didapati 73.4% dan ini dalam lingkungan penyelidik-penyelidik lain. Tesis ini telah mengenalpasti keadaaan operasi optimum untuk menggaskan habuk kayu di dalam sistem penggas siklon dan kesimpulan dibuat bagaimana proses penggasan berkeadaan mantap boleh dicapai.

INTRODUCTION

The demand of energy around the world has been increasing at a very fast pace especially in the developing countries. In light of global issues of sustainable energy and reduction in greenhouse gases, renewable energy is getting increased attention as a potential alternative source of energy. There are nine general sources of energy on earth. There are geothermal, nuclear, fossil, solar, biomass, wind, wave, hydro and tidal energies. Except for the first three the remaining six are generally called renewable sources of energy, as they are not depleted with time.

Compared to other sources of renewable energy, biomass is seen as an interesting source of renewable energy. The significance of biomass as fuel has been amplified during the last decades driven by several reasons. Biomass technology offers a technology where the fuels needed are sustainable, resources are often locally available and conversion into secondary energy carriers is feasible without high capital investments.

Biomass technology is based on a wide range of feedstock as fuels. The main biomass sources in use for energy production varies from forest residues, agricultural residues, wood based industry waste, animal waste, landfill gas to energy crops. There are several major biomass conversion processes including thermal, chemical, biological, and oxidative methods. Similarly, there are many potential valuable products that may be produced from its conversion including heat energy, synthetic fuels, fertilizer, hydrogen, chemicals, bio-polymers, and even bio-pharmaceuticals.

Malaysia has recently adopted a five-fuel diversification policy, identifying oil, natural gas, coal and renewable energy as key fuels. The Malaysian Government has established a mandate that 5% of its energy basket should come from renewable energy by the year 2005 (Ministry of Energy, Water and Communications Malaysia). However, this target has not been achieved yet. The priority technology areas identified to be mini-hydro, biomass, landfill gas, solar and wind.

Biomass is a substance made of organic compounds originally produced by fixing carbon dioxide in the atmosphere during the process of plant photosynthesis (Yukihiko & Tomoaki, 2003). Photosynthesis is the process by which chlorophyll-containing organism – green plant, algae and some bacteria capture energy in the form of light and convert it to chemical energy.

Organic chemicals are formed and oxygen is released to the atmosphere when the inorganic materials such as carbon dioxide, CO_2 and water are converted to organic chemicals. CO_2 that was absorbed as the plants grew to the atmosphere is returned to the atmosphere when complete combustion of biomass occurs, thus creating a CO_2 cycle where the concentration of carbon dioxide in the atmosphere remains constant.

In Malaysia, tropical forests cover 58 % of landmass with most forests located in the East Malaysian States of Sabah and Sarawak. Including oil palm and rubber trees, the area covered by trees is estimated at 72 % of the Malaysian landmass. The Malaysian Government has reserved some 14 million hectares for permanent forests, of which 11 million hectares as sustained production forest and 3 million hectares as a logging-free natural reserve. Outside these permanent forest plans, another 1.8 million hectares is presently covered by forest. In 1994, the net log production in Malaysia was an estimated 19 million tons. At an assumed residue of 50 % this translated into 9.5 million tons of wood waste per year (PRESSEA, 2000).

The number of major saw mills, plywood mills and molding mills in Malaysia for 2003 is around 950 (Malaysia Forestry Department). The saw mills and wood based industries sector in Malaysia currently disposes abundantly of its residues (sawdust, bark and planer shaving) through environmentally incorrect means, with only a small amount going to be used as litter in the poultry industry. Malaysia's total round-wood production is 20.7 million cubic meters in 2003 (Malaysia Forestry Department). From this amount of logs, about 2000 tons of sawdust is produced daily. In view of the fact that, sawdust abundantly available in Malaysia, the utilization of sawdust as a source of biomass fuels is essential. Table 1 shows the biomass resources potential in term of power generation in Malaysia for the year 1999.

Table 1: Biomass Resource Potential in 1999

Sector	**Quantity (kton / yr)**	**Potential Annual Generation (GW)**	**Potential Capacity (MW)**
Rice Mills	424	263	30
Wood Industries	2177	598	68
Palm Oil Mills	17980	3197	365
Bagasse	300	218	25
POME	31500	1587	177
Total	72962	5863	665

Resources: MPOB, SIRIM, FRIM, Forestry Department and Ministry of Agricultural.

There are three major conversion processes available to extract biomass energy. These are direct combustion, biochemical and thermochemical conversion. The simplest use of biomass is direct burning the material in a furnace. Direct burning is an exothermic process that produces combustion products such as carbon dioxide, nitrogen oxides, and particulate matter. Biochemical conversion is a process that involves alcoholic fermentation and anaerobic digestion. Fermentation is a biochemical process where living organisms, such as yeasts and bacteria, change the composition of organic compounds. Anaerobic digestion is the decomposition of biomass through bacterial action in the absence of oxygen to produce a mixed gas of methane and carbon dioxide Thermochemical conversion processes can be subdivided into gasification and pyrolysis (Ayhan, 2000). Pyrolysis is a thermal destruction of organic materials in the absence of oxygen to produce char, gas and oil (Bain et al., 1998). However, if the process occurs in the limited presence of air or oxygen, it is called gasification process. Giltrap et al., 2003 describes thermochemical gasification as a process for converting solid fuels into gaseous form.

The basic principles of gasifier technology have been studied and developed since the early 19th century. While usage of solid fuels for internal combustion engines was developed and extensively used in European countries during World War II (FAO Forestry Department, 1986). Producer gas, the product of gasified biomass, can replace fossil fuels in a number of applications. These applications can be divided into three main categories. These are direct heat, large scale and shaft power applications.

In direct heat application, the producer gas produced from the gasifier is burnt directly in a furnace to fire boilers for steam generation. Currently, all oil and gas-fired equipment can be converted by simply removing the existing burner and replacing it with a producer gas burner. In large scale applications, the producer gas produced by gasifier is used to generate electricity using gas turbines. The Biomass Integrated Gasifier/Gas Turbine (BIG/GT) technology for cogeneration or stand-alone power applications in many instances looks promising in being able to produce electricity at a lower cost than most alternatives. In shaft-power applications, the producer gas produced from the gasifier is used directly in internal combustion engine to generate power for electricity generation. Currently, this application can be found in rural areas where grid electricity is either expensive or unavailable.

There are large numbers of variables affecting gasification based process designs. The main important variables are gasifying agent, gasifier operating pressure and reactor type (Bain et al., 1998). The classifications of the gasifiers are made based on their approach and fuel characterization. The three main types of gasifier are fixed bed gasifiers, fluidized bed gasifiers and entrained flow gasifiers.

In entrained flow gasifier, the particles of fuel are suspended for a certain period of time to react with gasifying agent. Previously, the technology has been developed for coal gasification. Entrained flow gasifier need fine biomass fuel (<0.1 – 0.4 mm) (Mckendry, 2002b). Cyclone gasifier is one example of this technology. However, the previous studies on this gasifier are very limited in term of theoretical and experimental investigation.

Cyclone gasification system is a process intensified system acting as a gasifier to generate combustible gases and also as a gas cleaner to separate unburned particles from the gas flow (Fredriksson, 1999). Generally other gasification systems which deal with small particles as fuels needed a cyclone separator to remove large particles. Cyclone gasification system eliminates this and operates as a single unit operation and thus reduces the operating cost for the overall system.

In utilizing sawdust as biomass fuel, cyclone gasification system has several advantages compared to other conventional gasification systems. Cyclone gasifier is capable of gasifying smaller size particles of less than 1mm in diameter directly into the gasification system without needing extra pretreatment on the fuels and the reaction may take place at atmospheric pressure (Fredriksson, 1999). Cyclone gasifier also generally operates at relatively moderate temperature. Therefore the volatile matters will be released and the fixed carbon will be gasified without having to face problems such as ash melting or ash vaporization. The corrosive ash will remain as solid in char particles which will be then collected in the ash bin.

Development of biomass utilization technologies has been increasingly needed towards prevention of the global greenhouse effect and creation of the recycling-oriented society. Biomass gasification can increase options for combination with various power generation systems using gas engines, gas turbines, fuel cells and/or others to enhance power generation efficiency, and also can open the door to examining power generation system configurations meeting site conditions, such as kinds of collectable biomass, plant capacity, etc. Feasibility study on various power generation systems combined with gasification of various kinds of biomass inevitably requires application of adequate study on the performance and characteristics of the gasifiers and the gasification processes.

A cyclone gasifier is specifically developed at School of Mechanical Engineering, Universiti Sains Malaysia to gasify fine biomass material such as sawdust for the purpose of power generation. Thus, it is important to study the performance and characteristics on the existing design. The experimental work consists of biomass fuel characteristics, investigation on fuel feeding and injection system, temperature profiles in cyclone chamber and analysis of producer gas. Furthermore, during the experimental conduct, the important parameters such as fuel feed rate, air flow rate and equivalence ratio will be determined in order to obtain stable and optimum gasification process condition. Therefore, study on performance and a characteristic of the cyclone gasifier is essential for proving the workability of the system.

Sawdust is chosen as the biomass fuel in this project because compared to other materials sawdust is easily and abundantly available as waste and generally disposed in landfill areas, since there is a cheapest way to manage it. In addition, it is locally available at the surrounding areas of the university especially at the Furniture Industrial Area, Sungai Baong, Jawi, Pulau Pinang. Sawdust is readily available in dry pulverized form which can be used directly without pretreatment process.

The use of sawdust from wood based industries must be carefully analyzed to offer the best technical, economic and environmental alternative. The characterization (quantity, type, chemical and energetic analysis) of the residues generated is essential to determine which technology is more suitable.

Objectives and Scope of Study

The main objective of this research is to elucidate experimentally the performance and characteristics of the cyclone gasifier using sawdust as biomass fuel and thereby proposing a stable and optimum condition for design and operation of the cyclone gasifier. The scopes of the study are:

1. Design and fabrication of cyclone gasifier system.
2. Characterize the sawdust as biomass fuel in terms of size distribution, ultimate analysis, proximate analysis, moisture content and heating value determination.
3. Determine the temperature profiles of the producer gas and wall temperature profiles inside the cyclone chamber with respect to the effect of different sawdust size distribution, effect of air flow rate, fuel feed rate and equivalence ratio.
4. Analyze the producer gas in terms of the gas composition and calorific value, the flow rate of the producer gas, thermal output from the cyclone gasifier and mass conversion efficiencies with different range of equivalence ratio.
5. Perform thermodynamics analysis on the cyclone gasifier such as the enthalpy balance, enthalpy of input and output, enthalpy of the combustible gases, sensible heat of producer gas and enthalpy of the char.
6. Perform mass balance calculation and evaluate the separation process of the cyclone gasifier.
7. Carry out calculation on cyclone gasifier efficiency
8. To identify the necessary future work in this research field.

PROJECT SUMMARY

The research activities to be undertaken in this project have been classified in Table 2 below:

Table 2: The implementation Period (months) of the research activities

	M 1-2	M 3-4	M 5-6	M 7-8	M 9-10	M 11-12	M 13-14	M 15-16	M 17-18	M 19-20	M 21-22	M 23-24
Study the separation and gasification/combustion process for pulverized biomass fuel in cyclone gasifier												
Study the entire factors that affect the performance of the system												
Study the power generation from producer gas												
Study the characteristics of the pulverized biomass fuel												
Study the gas cooling and cleaning system for I.C. engine												
Design the test rig												
Fabricate the test rig												
Commissioning of the fabricated rig												
Carry out the experiments/experimental investigation												
Analysis of the experimental results												
Optimize the parameter that affect the performance of the gasifier												
Designing the control system												
Evaluate the performance of the process												
Report							*					*

The theoretical study covers the needed background knowledge to appraise the performance and characteristics of a typical cyclone gasifier which areas as follows:

I. Cyclone Gasifier Design and Operation
II. Fuel Characterization
III. Chemistry of Gasification Process

IV. Temperature Profiles of the Cyclone Gasifier
V. Quality Analysis of the Producer Gas
VI. Thermodynamics Study of Gasification Process
VII. Pressure Drop in Gasifier
VIII. Gasifier Efficiency and Thermal Output of Gasifier
IX. Practical Operation of Cyclone

The experimental work comprised of design, construction the experimental set-up, planning, performance and evaluation of test series. A cyclone gasifier system has been developed at University Science Malaysia, fabricated and installed in Bio-energy Laboratory, School of Mechanical Engineering. Currently, there are no present commercial cyclone gasifier available in the market, thus the present cyclone gasifier was designed based on the work by Fredriksson, 1999 with some modifications. An outline of the experimental set-up can be seen in Figure 1 while Plate 1 shows a picture of the cyclone gasifier. The cyclone gasifier was designed to gasify sawdust at the required rate which was 200 kW_T output and at the lowest possible temperature. The cyclone must be produced combustible gaseous and the process should be stable with high efficiency and low pressure losses.

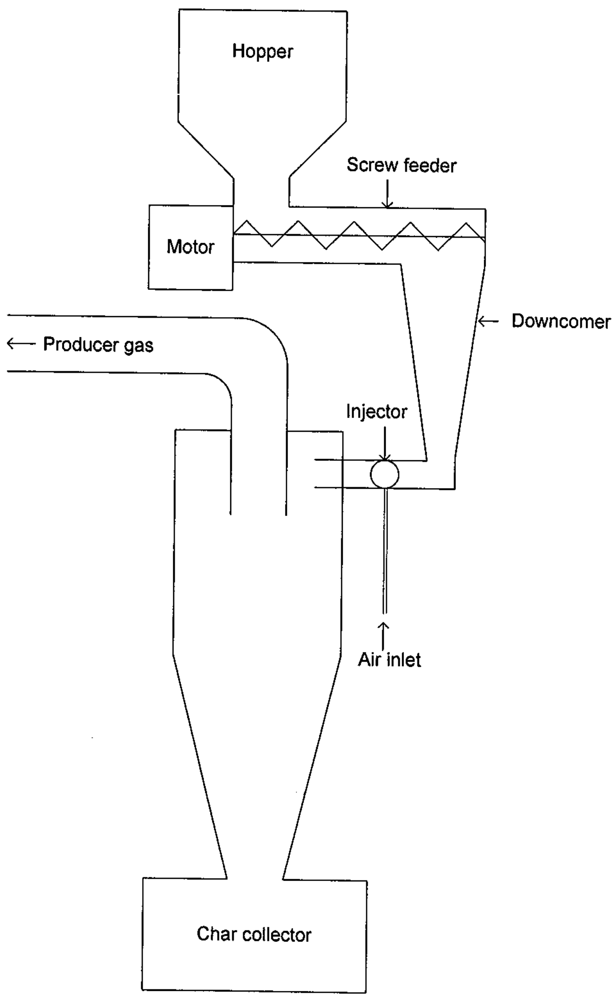

Figure 1: A Schematic Diagram of Cyclone Gasifier System

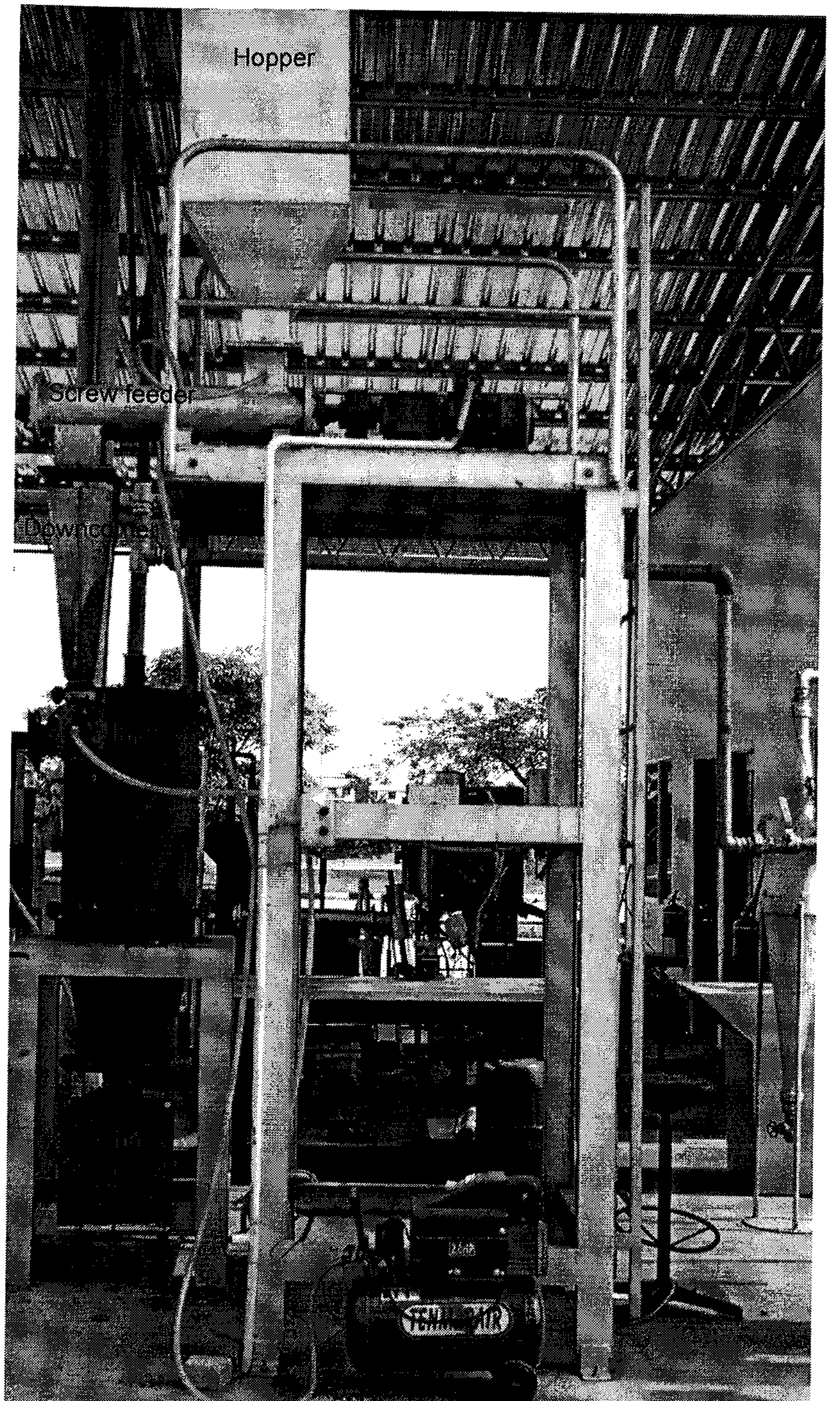

Plate 1: Cyclone Gasifier System in Open Laboratory USM Engineering Campus

The system consists of five main parts: fuel feeding system, cyclone gasifier unit, injector system, heat up system and removing compartment. These parts are easily dissembled for modification or repair, because in research the possibility is there. The feeding system consists of a hopper, screw feeder and downcomer. The biomass fuel (sawdust) is stored at the hopper and further it will be transferred to the downcomer by a screw feeder. Then, sawdust is injected into the cyclone tangentially with air driven injector into the cyclone chamber. Gasification air will be supplied to the cyclone together with the sawdust using air compressor. The injector directs the fuel/air mixture entering the cyclone chamber in a tangential direction, which generates swirl flow in the cyclone. The swirl will force the incoming sawdust particles to follow the trajectory close to the cyclone wall. Producer gas exits the cyclone via a vortex finder, while the char fall downwards toward the bottom outlet into ash collector.

A cyclone is a mechanism that used to separate solid materials from gases or liquids. All cyclone separators are based on centrifugal separation of particles in an induced vortex within the gas flow. When the fluid, with the dispersed particles in suspension injected tangentially through the inlet pipe into the cyclone, then due to the specially designed geometrical feature of the cyclone, the fluid acquires a spiraling motion, which first descends along an outer spiral and then ascends through an inner spiral. When the vertical motion, spiraling reached the conical section, the centrifugal forces can be several times greater than gravity contributing to particle separation. The dispersed particles, which have a different density to their carrying fluid, are driven by the centrifugal acceleration to move perpendicular to the fluid motion. The relatively larger particles possess a larger inertia and therefore acquire a stronger centrifugal acceleration. When the centrifugal acceleration is sufficiently large, then the particles drift towards the sidewall and finally they are separated at the bottom of the cyclone.

The cyclone gasifier is the common returned flow type cyclone with tangential inlet. The design was based on a combination of dust separator and cyclone combustor principles. Dust separator used angular momentum fluxes to separate dust while, cyclone combustor use an internally generated high centrifugal force fields, secondary flows and well stirred reactor conditions to mix fuel and air which support good gasification characteristics. The geometric swirl number for the present designed cyclone gasifier was S_{gT}=12 as suggested by Fredriksson, 1999. The cyclone gasifier was designed to gasify sawdust at the required rate and at the lowest possible wall temperature, 400 - 600°C. The operation of the cyclone should be stable and the gas produced must be combustible.

The cyclone gasifier unit consists of conical and cylindrical parts which together form the body of the cyclone. The gasifier body is made of Mild Steel plate with 6mm thickness. The cylindrical body has a 472 mm internal diameter and 1262 mm height and the conical part connected with a char collector at the bottom. The inlet of the cyclone is mounted tangentially on to the sidewall of the cylindrical part of the cyclone body, 170 mm from the top of the cyclone. The exit tube usually called the vortex finder or the vortex tube is fixed on the top of the cyclone and it protrudes 160 mm in to the body of the cyclone. Part of the internal diameter is insulated with 75 mm refractory cement and 50 mm calcium silicate to minimize heat loss. Gasification air was supplied to the cyclone together with the sawdust via Injector. The Injector directed the air/fuel mixture to enter the cyclone in a tangential direction, which generate a swirl flow in the cyclone. The swirl will force the incoming sawdust particles to follow the trajectory close to the cyclone wall. The product gas leaves through the top outlet of the cyclone. Figure 2 shows a schematic diagram of cyclone gasifier unit.

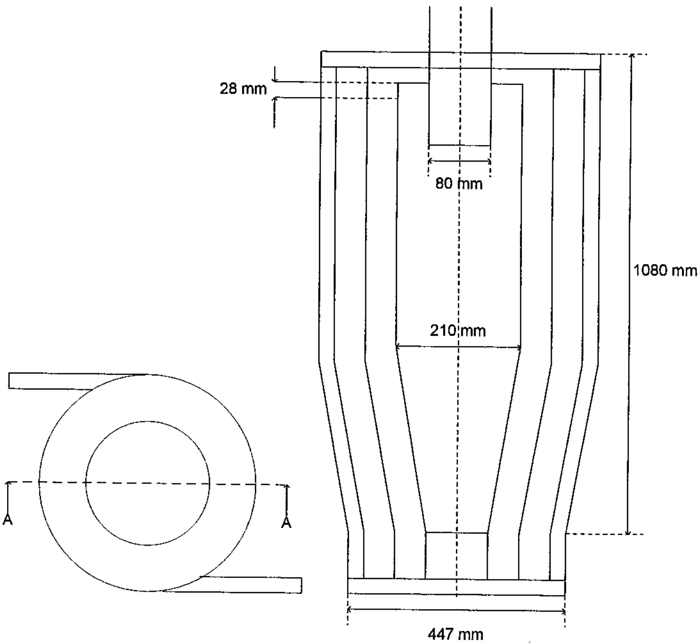

Figure 2: Cyclone Gasifier Unit

The feeding system consists of hopper and screw feeder. Hopper is used to store sawdust before being fed by screw feeder. The diameter of helical screw and tubular shaft is 147mm and 50 mm, while the size of pitch is 120 mm. The fully specification of screw feeder can be seen in Appendix A. Sawdust will flow towards the screw feeder by gravity. The hopper designed applies funnel flow where the fuel flows through the core. The degree of inclination of the tapered side is 45° from vertical wall to make sure the hopper provide mass flow effect properly. The hopper can store maximum 30 kg of sawdust and sawdust stored in hopper manually. Screw feeder is used to feed sawdust from hopper to downcomer. The rotation of screw feeder was controlled by motor while the rotation of the motor is controlled by Micro Inverter which is shown in Plate 2.

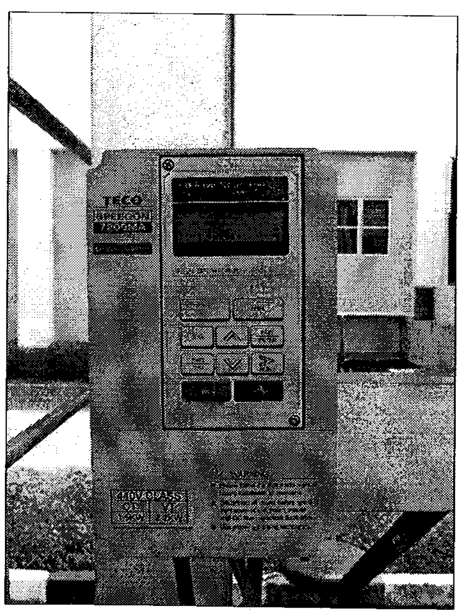

Plate 2: TECO SPEECON 7200MA Micro Inverter

The feeding rate of sawdust can be determined by calibrating the screw feeder with different speeds of the motor. Figure 3 is the chart showing the relationship of the biomass fuel feed rate and frequency of the micro inverter.

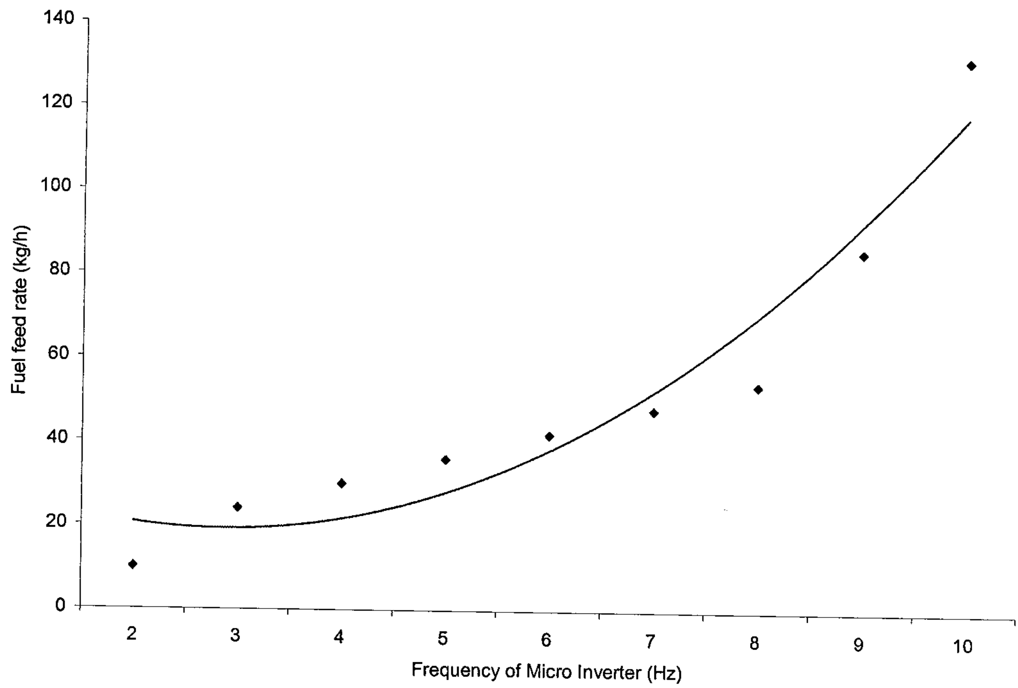

Figure 3: Relationship of Fuel Feed Rate and Frequency of Micro Inverter

The trend shows that the fuel feed rate increases with the increase in frequency of the micro inverter. From the result, the minimum fuel feed rate that can be fed by screw feeder is about 10 kg/h. Therefore, in this study the minimum amount of sawdust that will be fed to the hopper is limited to 10 kg. The amount will be increased with increasing the frequency of micro inverter. However, the maximum amount of sawdust that can be injected by the injector through tangential inlet is about 40 kg/h. Therefore, the frequency of Inverter should be varying from 2 Hz to 6 Hz.

The injector system consists of a downcomer and a fuel injector. The fuel injector is used to supply air and inject sawdust in to the cyclone chamber, while the downcomer connects the fuel injector and the screw feeder. The fuel injector consists of air ejector and air supply nozzle. The air nozzle will force the sawdust, whilst air ejector will induce the air/fuel mixture into the cyclone chamber. Figure 4 shows the schematic drawing of an injector system. Plate 3 shows the air supply nozzle, while Plate 4 shows the air ejector.

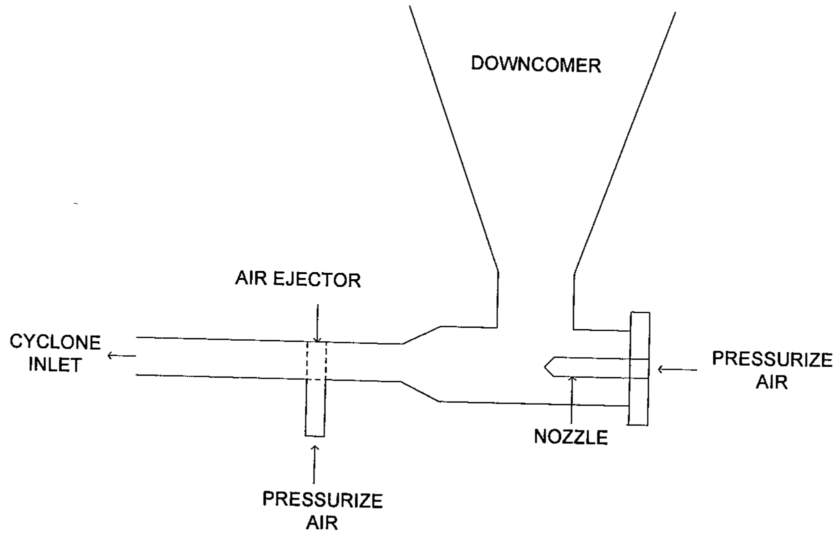

Figure 4: Schematic Drawing of Injector System

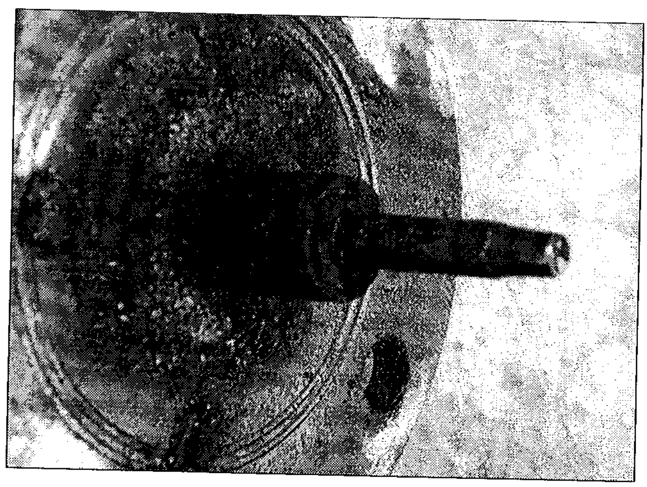

Plate 3: Air Nozzle Located at Injector System

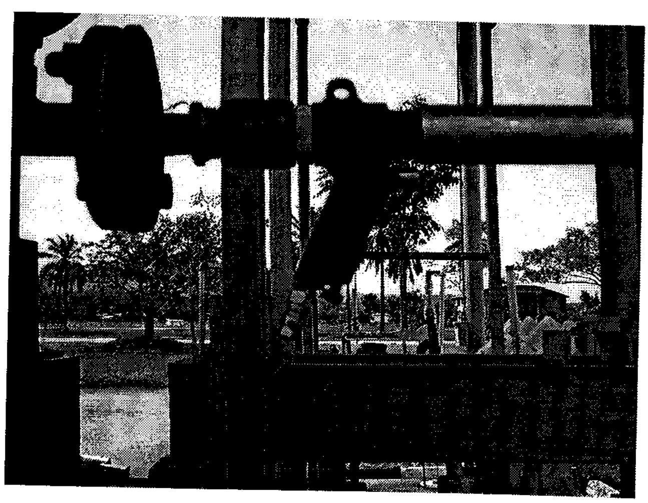

Plate 4: Air Ejector for Fuel Injector System

The air nozzle is made of brass with diameter of the nozzle 1 mm while the air ejector has a diameter 3 cm. The injector system is located at the cyclone inlet, tangentially to the cyclone chamber. The air is supplied to the gasifier through the injector system by an air compressor. Plate 5 shows the air compressor used in this system.

The cyclone chamber needs to be heated up before the injection process. Diesel burner or LPG burner were used for heating process. Burner inlet is located tangentially to ensure good heat distribution inside the chamber. Plate 6 shows the commercialize diesel burner.

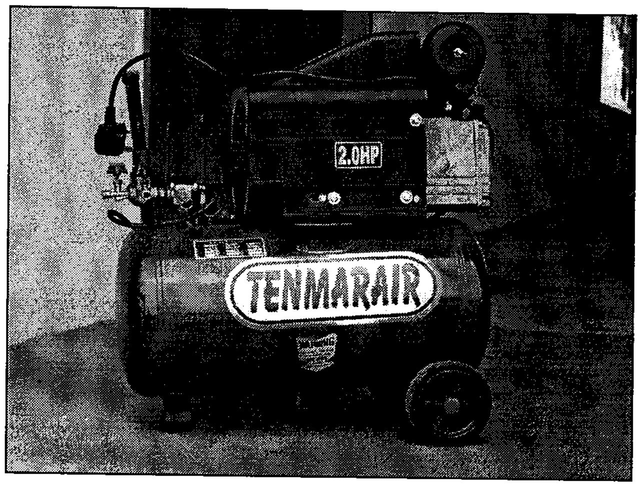

Plate 5: Air Compressor to Supply Air through the Injector

The commercialize diesel burner is capable to act as a heat back up for immediate heat up to the cyclone chamber in case any problem occur in the feeding system or during reloading the biomass fuel in the hopper. However, the maintenance of the diesel burner is quite high because of the tar produced from the process deposited in moving part and spray nozzle of the burner and thus creating problems.

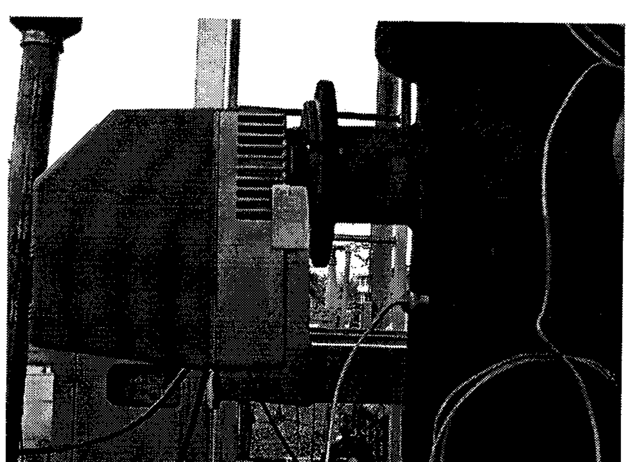

Plate 6: Commercialize Diesel Burner Located Tangentially with Cyclone Chamber

Following the problems with the diesel burner an LPG burner was designed and fabricated at USM. To ignite the burner, the LPG gas and air supply should be adjusted to acquire proper flame. The system is free maintenance and easy to operate. However, the time required to heat up is longer than commercialize diesel burner.

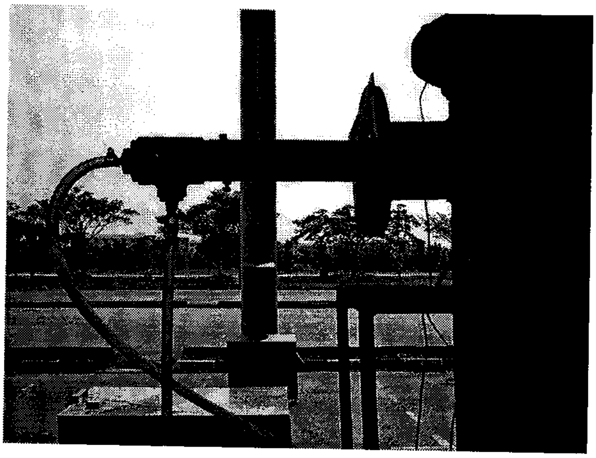

Plate 7: LPG Burner

The main measurement apparatus are used to measure temperature, air flow rate, pressure, weight of fuel and gas composition. Type K thermocouple, rotameter, anemometer, differential pressure meter and gas chromatography (GC) are the main measurement apparatus. Type K thermocouples were used to measure the temperature inside the gasifier chamber. There were 4 type-K thermocouples located at different location to investigate the thermal effect and temperature distribution inside the cyclone chamber. One thermocouple was placed at cyclone outlet, the other two placed at the cylindrical body (top and middle) and last thermocouple located at the body of the conical section. Plate 8 shows the thermocouples located at different locations of cyclone chamber while Figure 5 shows schematic drawing of thermocouples position for temperature monitoring.

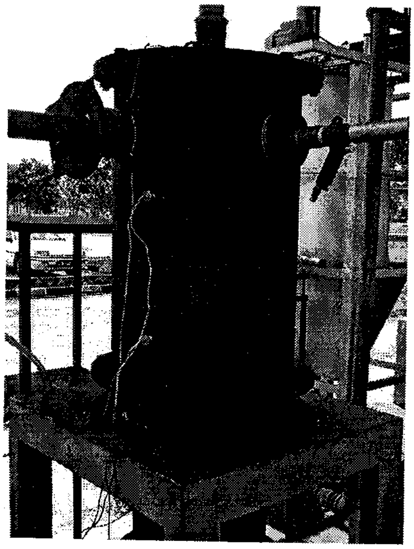

Plate 8: Four Thermocouples Located at Different Locations

All thermocouples were connected to the data logger which is then connected to a computer. Scan link software recorded the temperatures for every 4 seconds. The data obtained then graphically plotted to illustrate temperature profiles over the period of time during the test. Thermocouple one measured the temperature level of producer gas located at 50 mm from the top gasifier unit. Thermocouple two, measured the temperature at the top of cylinder part located at about 100 mm from the inlet. Thermocouple three, measured the temperature at the bottom of cylinder part located at about 300 mm from the inlet while the thermocouple four, measured the temperature at cone part located at about 500 mm from the inlet. The thermocouple probe tips should be clean and polish regularly with tar remover to remove any layer of tar to avoid measurement error.

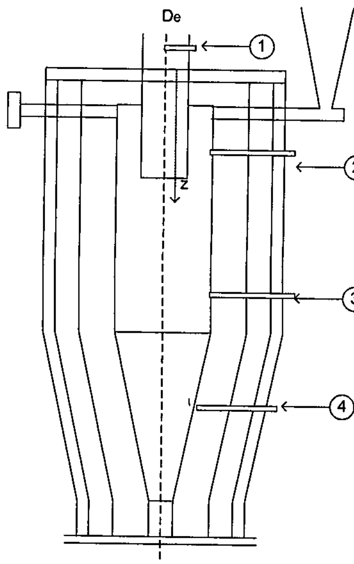

Figure 5: Schematic Drawing of Thermocouples Locations

DIGI-SENSE scanning Thermometer with 12 channel thermocouple scanner Model 69202-30 was used to log the temperatures during the tests. The data logger is capable of logging the temperatures for every 4 second. Plate 9 shows the data logger.

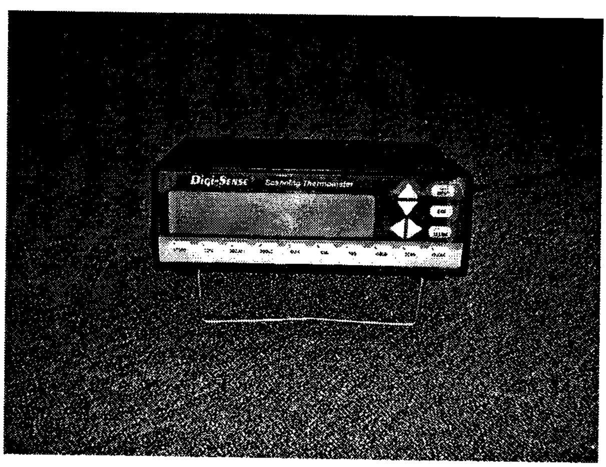

Plate 9: Thermocouple Data Logger

The gasification air was supplied through an injector by an air compressor. The flow rate of air was measured by a rotameter. The rotameter is capable of measuring up to 400 liter/min. In addition, the air flow rate of producer gas was measured by Mini Thermo-Anemometer Model 45118 from Extech Instrument. Plate 10 shows the rotameter while Plate 11 shows the anemometer. Pressure drop across cyclone gasifier unit was measured by using Differential Pressure meter. Plate 12 shows the differential pressure meter model PM-80 from Digitron.

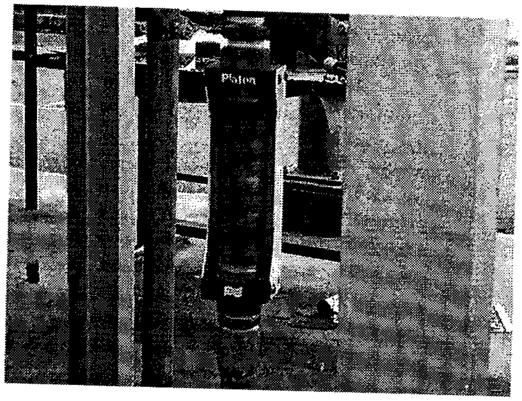

Plate 10: Rotameter

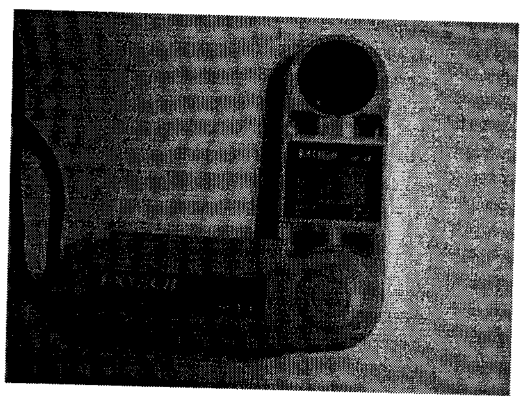

Plate 11: Mini Thermo Anemometer

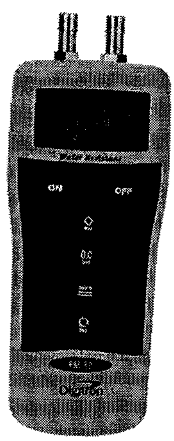

Plate 12: Differential Pressure Meter

Gas chromatograph was used to analyze the composition of producer gas which is expected to consist of hydrogen, carbon monoxide, carbon dioxide, methane, nitrogen and oxygen. The producer gas was collected by gas sampling bags. The brass tube with 5 mm diameter and 2 m length is used as a simple tubing system is installed at the cyclone outlet to reduce the temperature and to transfer the producer gas through gas sampling train into the gas sampling bag. A gas sampling train was used to clean a producer gas because the gas from the cyclone is dirty and wet and could cause damage the gas chromatograph. The gas samples were analyzed as soon as possible in gas chromatograph in order to avoid any contamination or diffusion of gases into or out of the bags. Plate 13 shows the gas chromatograph (GC) used to analyze the producer gas.

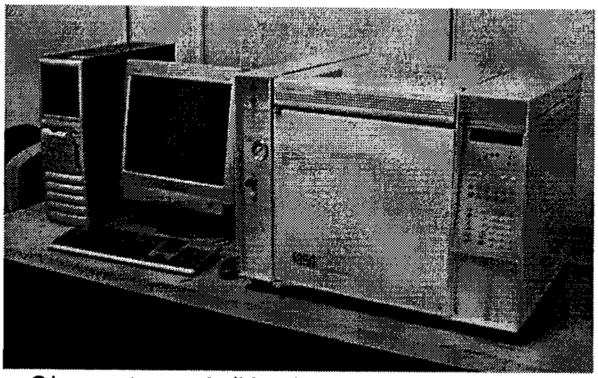

Plate 13: Gas Chromatograph (Hewlett Packard Module 4890)

In this analysis, helium was used as a carrier gas. Generally gas chromatograph consists of an injection port and separation part contain of column, detector and recorder. Two columns (Propack-Q and Molecular Sieve) were used in order to identify the gases. The Propack-Q column was used to detect CO_2 and the Molecular Sieve was used to detect the other gases (CO, CH_4, H_2, O_2 and N_2) using thermal conductivity detector (TCD). The results are explained in term of retention times and areas of the peaks.

The test and analysis have been performed on the sawdust in order to study its characteristics (moisture content, bulk density, particle size, calorific value and chemical composition via proximate and ultimate analysis) to cater for the design requirement of the cyclone gasifier. This biomass waste was collected from Zilanza Furniture Sdn. Bhd. at the Furniture Industry Area, Jawi Nibong Tebal, Pulau Pinang. The raw sawdust was produced by cutter, sawing, sieve and sanding. The types of species of wood sawn timber used by the factory were Meranti (Dark Red, Light Red and Red).

The size distribution of the fuel particles is very important because it determines the particle flow in the downcomer, the injector and the cyclone chamber. The size distribution also influences the time required for gasification and the carry-over particles with the product gas. The raw sawdust was characterized using sieve shaker and pre-treated using a grinder. Plate 14 shows the disk mill used for grinding the raw sawdust. The disk mill is capable of grinding and sieve with three different mesh sizes (3.5 mm, 1.2 mm and 0.6 mm). The size distribution was determined by automatic sieve shaker. Plate 15 shows the automatic sieve shaker located at School of Material and Mineral Resources.

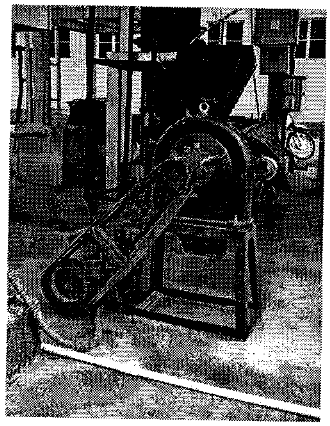

Plate 14: Disk Mill for Grinding the Raw Sawdust from Furniture Industry

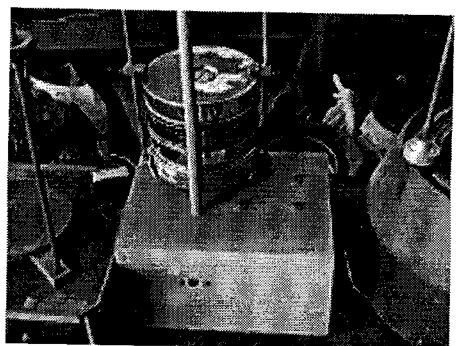

Plate 15: Automatic Sieve Shaker

Bomb calorimeter was used to determine the heating value of the sawdust. The test was done at Thermodynamic Lab, School of Mechanical Engineering. The sample was wrapped and tied by nickel wire before placing it in the crucible. Then, the crucible with the sample was placed in the bomb filled with oxygen. Then, the bomb was immersed in water. The outer jacket was kept at a constant temperature while the calorimeter water in the inner vessel changed. The changes were measured until it stops. The experiment was done in almost 15 minutes. Plate 16 shows the bomb calorimeter.

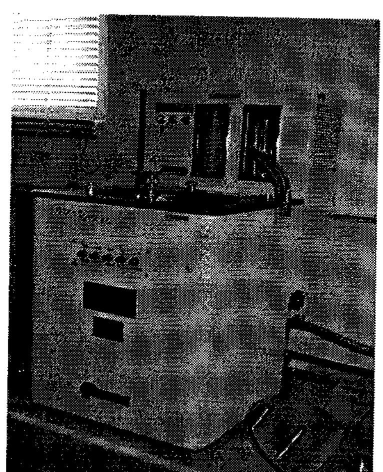

Plate 16: Bomb Calorimeter for Measuring Calorific Value of Sawdust

The ultimate analysis was conducted on the sample ground sawdust in order to determine its chemical composition using PE 2400 Elemental Analyzer located at School of Chemical Engineering. Proximate analysis was carried out using TGA7 together with TG controller. The TGA system interfaced to a microcomputer for data acquisition and control task. Plate 17 shows the PE 2400 Elemental Analyzer and Plate 18 shows TGA7 system with TG controller.

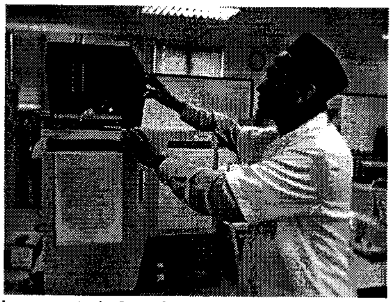

Plate 17: PE 2400 Elemental Analyzer

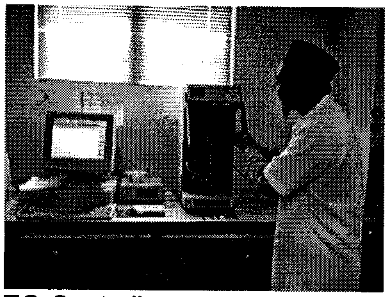

Plate 18: TGA7 with TG Controller

To test the performance of the cyclone, a number of experiments were conducted in which the cyclone was operated at different conditions. Different operating conditions were achieved mainly by changing the equivalence ratio in the cyclone. Fuels with slightly different size distributions have also been tested. The experimental procedures of cyclone gasifier using sawdust as a fuel are as follows:

1. Prepared the sawdust and weigh about 10 kg for batch feeding. Place the sawdust manually into the hopper. The raw sawdust should be ground and sieved to the desired size distribution of the biomass fuel.
2. Connect and switch on the data logger before heating the cyclone chamber.
3. Heat up the cyclone chamber with diesel burner or LPG burner until the wall temperature reached 400°C – 600°C.
4. Turn on the air compressor and open the air compressor valve for supplying air inside the chamber through the injector.
5. Set with appropriate frequency at the Micro Inverter and then switch on the screw feeder. The sawdust is transferred to the injector via screw feeder and downcomer.
6. As long as the sawdust is injected to the cyclone chamber, the combustion occurs. Allow the combustion process steadily about 1 to 2 minutes then switch off the burner.
7. When the process is running smoothly, the producer gases are collected using gas sampling bag and then quickly tested in the gas chromatograph.
8. During the process the flow rate of producer gas and pressure is measured by anemometer and pressure gauge.
9. Fuel feed rate and air flow rate should be varied to get optimum process.
10. The process should reach stable conditions and running smoothly.

11. Once the experiment was completed, switch off the air compressor and screw feeder.
12. Open the char collector and weigh the collected char and determine the energy content in the char.

Problems Encountered During the Test

There were many problems encountered during the running process that can be solved and some could not. Generally the gasifier worked successfully. The most significant problem was the fuel feeding system. The sawdust from the hopper falls down to the screw feeder by gravity effect. Because of bulky nature of the fuel, certain sawdust jammed at the throat of the hopper. As a result, an air ejector was installed at the throat to gurgle the sawdust. This works and the sawdust will continuously flow. In early stages of the test, the sawdust also stuck at the downcomer and injector when the fuel feed increased but the problems was fixed by changing the designed of downcomer and installing the air ejector to induce the mixture of fuel and air. Much work also has been done to overcome the fluctuation of the fuel feeding system using different kind of injector systems.

At first, the heat up process cannot be done using available gas LPG torch. The gas blew in the gasifier several times during the heat up process forcing the modification to be made on the heating port and quest for another type of burner to be used instead of the current one. Diesel burner is considered and the heating port modified. However, diesel burner needed high maintenance. After several tests, the diesel burner must be serviced and repaired due to particles and tar clogging the spray nozzle. As a result, newly developed LPG burner was designed and installed for heating process. The LPG burner is free maintenance and easy to handle but the time for heat up process increased because the LPG burner operated at minimum condition due to the limitation of the air compressor. The LPG burner was ignited manually by adjusting the LPG and air compressor valves to obtain good mixture and produce blue flame.

A disk mill was operated with minimum load (25 kg/h) of raw materials due to the limitation of the motor. Therefore, the preparation of sawdust for the test required spending much time. In the test, a large amount of sawdust was needed, thus the disk mill must be carefully maintained. The sieve must be cleaned continuously to prevent clogging and could cause damage to the motor.

RESULTS AND DISCUSSION

Experimental work to study the performance and characteristics of the cyclone gasifier has been conducted at the School of Mechanical Engineering, USM. In this chapter the results of all experimental work done are presented as follow:

I. Fuel characterization: size distribution of raw and ground sawdust, ultimate and proximate analysis and heating value of sawdust
II. Temperature profiles: producer gas temperature and wall temperature profiles inside the cyclone chamber i.e. effect of different size distribution, effect of air flow rate and effect of equivalence ratio
III. Analysis of producer gas: gas composition and calorific value, the flow rate of the producer gas, thermal output from the gasifier and mass conversion efficiencies
IV. Thermodynamics of gases: enthalpy balance, enthalpy of input, output, combustible gases, sensible heat of producer gas and enthalpy of char
V. Mass balance and separation process of the gasifier
VI. Pressure drop in cyclone gasifier
VII. Gasifier efficiency

All the results are then discussed in order to obtain the most practical condition in gasifying sawdust through a cyclone gasifier.

Fuel Characteristics

Experimental studies were carried out on three different types of size distributions of sawdust. Different types of size distributions of sawdust were tested in order to study the effect of size distribution on gasification process in cyclone gasifier. Mean size distributions of the fuels were determined using different size of sieves. The conditions of the test were stated in Table 3 while the result of the size distributions of raw sawdust and ground sawdust from the sieving process are as shown in Figure 6.

Table 3: The Conditions of Sieve Test

Type of fuel	A	B	C	D
Sources	Furniture Industries	Furniture Industries	Furniture Industries	Furniture Industries
Grinder	Raw	Disk Mill	Disk Mill	Disk Mill
Meshing Size	N/A	3.5 mm	1.2 mm	0.6 mm

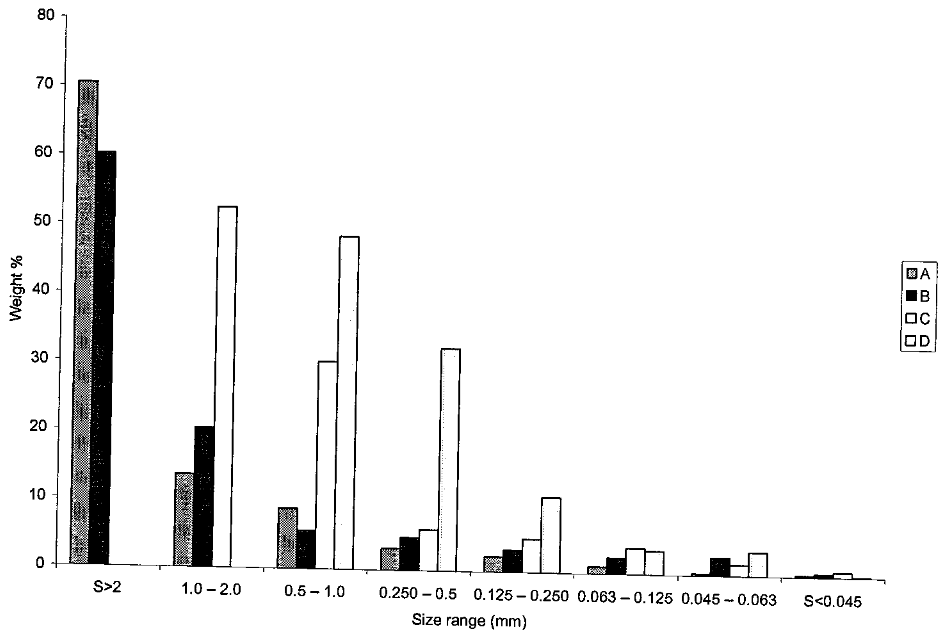

Figure 6: Size distributions of Sawdust

From the results, Fuel A and B consist of about 80% for size more than 1 mm while Fuel C consist of about 50% in the same region. In addition for size ranging from 0.25 – 1.0 mm, Fuel C and D consist of about 40% and 80% respectively. From previous study, Fredriksson, 1999 using commercialize Swedish wood powder, the largest percentage of size distribution is in the range of 0.25 – 0.5 mm which is about 38%. Gabra et al., 2001b using different types of sugar cane residue and the largest percentage of size distributions is in the range of 0.25 – 1 mm which is about 50% to 70%.

Flow Test and Spray Test

The objective of flow test is to determine the continuity of the flow in the feeding system while spray test is used to prove the workability of the injector system. In spray test, spray length and spray width were measured to verify the spray system ability to eject the particles and reach the wall of the cyclone chamber. All the tests were done outside cyclone chamber in an isothermal and ambient condition. The test was done using the lowest fuel feed rate and air flow rate which was about 10 kg/h and 120 liter/min respectively.

In the first attempt, Fuel A was used and it was observed that, the flow of Fuel A stopped instantly after screw feeder was switched on because the incoming sawdust was block by accumulated fuel at the injector inlet. The blockage was caused by an inhomogeneous of size and shape of raw sawdust particles. Therefore, Fuel A is unsuitable to be used directly in the cyclone gasifier.

A flow test was continued for ground sawdust, Fuel B, C and D. The result showed that, the fuel flowed smoothly and continuously through the feeding system without any interruption. However for Fuel D, after about 15 minute the amount of sawdust that has been fed by the screw feeder became slower. It was found that, at the hopper or fuel storage bin, the flow of fuel was only at the core while at the surrounding the fuel was stagnant. This is because the flow at the hopper works by gravity effect. So, to assist a better fuel flow at the hopper, a system such as vibrator, stirrer or air injector should be installed to fix the problem. Thus, a simple and low cost air injector system was introduced at the exit of the hopper to force the fuel into the screw feeder.

The ground sawdust showed good results in term of eliminating the problems associated with feeding process compared to the raw sawdust. Options available are to grind the raw sawdust or by separating the sawdust particles to the intended size distribution by physical means such as sieving. However the latter process is tedious and uneconomical for practical usage in the operation of cyclone gasifier. The former process is a better option.

Table 4 shows the spray length and maximum width for Fuel A, B, C and D. The result shows that Fuel B, C and D have spray length and width in the range of 60 cm to 100 cm and 10 cm to 20 cm respectively. Therefore, the minimum air flow rate is strong enough to carry the fuel particles to reach and hit the cyclone wall with considering the diameter of the cyclone chamber is measured at 210 mm.

Table 4: Spray Size for Different Sawdust Size Distribution

Type of fuel	Length (cm)	Maximum width (cm)
A	N/A	N/A
B	60	10
C	80	15
D	100	20

The test was further extended to investigate the effect of the injector to inject the sawdust with increasing fuel feed rate. Fuel B, C and D were used with maximum air flow rate which is 360 liter/min. It was found that, the fuel flowed smoothly and continuously through the feeding system without any interruption as long as the frequency of Micro Inverter set below 6 Hz. Therefore, the maximum fuel feed rate can be inject by the injector is about 40kg/h.

Ultimate and Proximate Analysis

The ultimate analysis determines the weight percentage of carbon, hydrogen, nitrogen, oxygen and sulphur. The raw sawdust from locally furniture industry was tested where the type of species of wood sawn timber used by the factory was Meranti (Dark Red, Light Red and Red). The result of the ultimate analysis is as shown in Table 5.

Table 5: Ultimate Analysis of the Sawdust

Element	Dry weight, %
C	42.38
H	5.27
N	0.14
O	42.41
S	0.00

The result shows that the weight percentage of carbon, hydrogen, nitrogen, oxygen, and sulphur (dry basis) are consistent with typical wood analysis reported in the literature. However, the percentage of nitrogen and carbon of the sawdust used are relatively lower compared to processed biomass materials such as plywood which normally gives higher carbon and nitrogen value at above 48% and 1% respectively (Reed, 1998). The low nitrogen and carbon value is nevertheless consistent with the analysis obtained for unprocessed wood. This may reflect the quality of the sawdust obtained from the local furniture industry which is comparable to the unprocessed wood.

Referring to the data (Appendix B), the proximate analysis for 5 mg sample of ground sawdust is summarized in Table 6.

Table 6: Proximate Analysis of the Sawdust

Proximate Analysis	**Dry weight, %**
Moisture Content	8.25
Volatile Matter	76.23
Fixed Carbon Content	14.04
Ash Content	1.49

From the result shown above, the fixed carbon content is 14.04%, the volatile content is 76.23% and the ash content is 1.49%. The amount of ash content is much lower compared to rice husk, another potential biomass fuel for application in a cyclone gasifier, which has the typical ash content at 20% (Yusoff, 2006). The selection of sawdust as the biomass fuel appear to be the right choice since ash content is very important parameter affecting the composition and calorific value of producer gas. The lower the amount of ash content the better the fuel.

According to the above proximate analysis, moisture content of sawdust is around 8.25%, a typical value for sawdust. This moisture content is relatively higher compared to other types of biomass fuel used by other researchers using cyclone gasification technique. Other researchers agreed that the moisture content will affect the performance of the gasifier and thus they adopt a pre-treatment process to reduce the moisture content of their biomass fuel to give the optimum operating condition. The typical maximum amount of moisture content of wood acceptable for gasification process is in the range of 30% to 60% depending on types of gasifier design. However effect of different moisture content of sawdust and other biomass fuels on the cyclone gasifier are beyond the scope of this study since assumption has been made that any extra pre-treatment process on the sawdust will render the cyclone gasifier to be impractical and uneconomical and direct use of the sawdust with the typical moisture content is still within acceptable value for smooth operation. Extra caution has been made for the sawdust used in this study to be in the dry condition as-it-is basis. Table 7 shows the moisture content of various type biomass fuels used in similar cyclone gasifier.

Table 7: Comparison of Biomass Fuel Moisture Content

Researchers	**Biomass fuel**	**Type of gasifier**	**Moisture content (% dry basis)**
Gabra et al. (2001)	Ground bagasse	Cyclone gasifier	5.9
Gabra et al. (2001)	Sugar cane trash	Cyclone gasifier	6
Fredriksson (1999)	Commercialize wood powder	Cyclone gasifier	5.6

Heating Value of Sawdust

The high heating value (HHV) of sawdust was found to be about 18.23 MJ/kg using a Bomb Calorimeter (see Appendix C) with moisture content 8.25%. The low heating value (LHV) was about 16.54 MJ/kg. The result determined was in the range of various type of wood which is between 15.3 MJ/kg and 21.2 MJ/kg on dry fuel basis (Negi and Todaria, 1993). Low heating value (LHV) is used in the calculation for gasification rather than high heating value (HHV) because the final product from the gasifier is in the gaseous form.

Temperature Profiles in the Gasifier

A large number of tests were taken to characterize the cyclone gasifier. The tests used ground sawdust with three different size distributions (Fuel B, C and D). To characterize the gasification process in the cyclone gasifier, the tests used a wide range of fuel feed rates and three different air supply flow rates resulting in different equivalence ratios. All tests are operated to reach stable steady state condition.

Dynamic temperature profiles are important to assist in the understanding of the gasification process in terms of the thermochemical phases. But more importantly, it also can be used as a process control indicator inherently measuring disturbances occurring in the feed rate and the air flow rate. A process controller scheme may be devised to control the gasification process utilizing the temperature response in the temperature profiles. In order to measure the temperature, three thermocouples were placed at different positions along the cyclone gasifier. One thermocouple was placed at exit point to record producer gas temperature. The characterization exercise was extended to cover the temperature profile of exit gas temperatures because the determination is important for the purpose of examining the economical and potential application in an external combustion system such as boiler, gas turbine etc. or in an internal combustion system. Table D.1 summarizes the condition of tests taken (see Appendix D).

It is difficult to differentiate the thermochemical phases in the cyclone gasifier through the temperature profiles since the numbers of thermocouples were not sufficient. Figure 7 shows the typical wall temperature profiles and gas temperature in the gasifier. Looking at the temperature at T2, it can be concluded that the drying and devolatilisation zones are minimal and the fuel oxidized almost instantly. The drying and devolatilisation zones can be said to co-exist theoretically but experimentally it is difficult to be determined. This is caused by the nature of the fuel used. The sawdust is in the particle form so when it was injected into the chamber, it reacted almost as gaseous fuel. Meaning that sawdust can be considered to react and combust with the same behavior like gaseous fuel and does not undergo drying and devolatilisation processes. It went straight to combustion. This phenomenon is contrary to other gasifiers and is an exclusive characteristic of a cyclone gasifier.

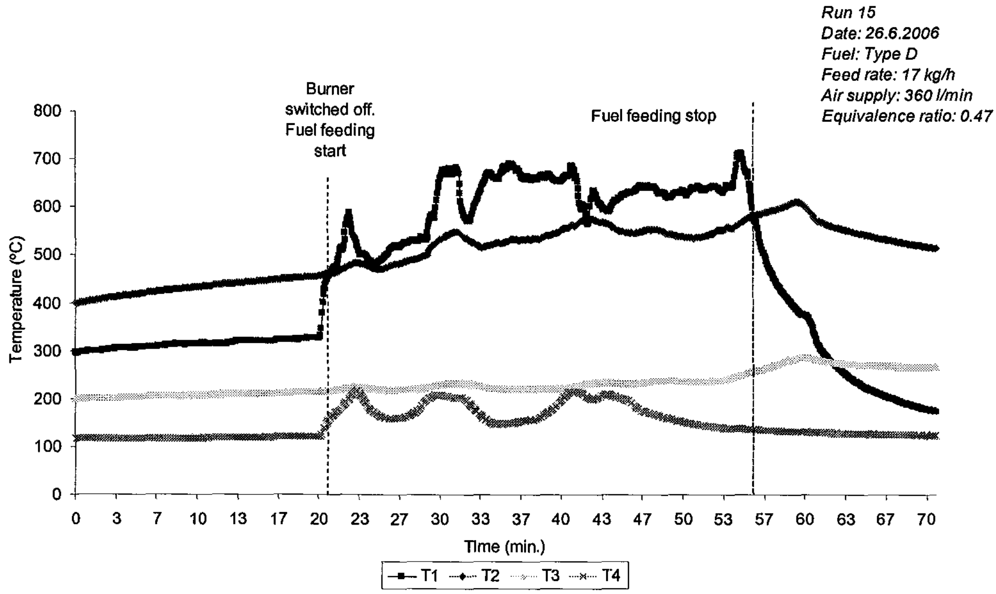

Figure 7: Temperature Profiles in the Gasifier

The temperatures level at T4 almost lower than T3. However at some run (see Appendix E) appeared to be giving higher temperature compared to the T3. This could be caused by oxygen presence at the ash collector and thus reacted with the char at the zone. However it can also be attributed to the difference in the fluid dynamics properties at the conical and cylindrical section. At the cylinder section the swirling flow has a bigger diameter while in the conical section the diameter is reduced thus increasing the swirling velocity. An upward flow forced vortex was formed as the result and flowed to the vortex finder and exiting the gasifier. In that region, from the fluid dynamics perspective, the velocity increased with the increasing pressure drop and then the gas is slightly compressible to create an upwards forced vortex flow and hence resulted in a slight temperature increase.

It is also interesting to see that the exiting temperatures were higher than T2 temperatures. At T2, some of the fuel was combusted resulting in high temperature flow. The flow temperatures getting lower at T3 since the oxygen is limited hence the oxidation process comes to a halt resulting in a char gasification process which should give lower temperatures. However, exiting temperature was much higher than temperature at T2. This could possibly caused by exchange of heat between the upward vortex flow and the downward swirling flow at T2. The upward vortex flow is in lower temperature and the downward swirling flow is in higher temperature and the vortex finder made from mild steel. The high temperature flow heated the low temperature flow and when exiting the gasifier, the producer gas is considerably in higher temperature than in the lower region which provides a better condition to react with the oxygen present at the exit point. This phenomenon may as well serves as the explanation on the temperature losses between T2 and T3. This is another important characteristic of a cyclone gasifier. If the quality of the producer gas sought i.e. for internal combustion, then a cooling system is needed at the exiting point and the design aspects of the vortex finder should be looked into to prevent the unnecessary heat exchange. However if the temperature of the producer gas is sought i.e. for external combustion, then this characteristic will be an added advantage for the cyclone gasification technique.

Effect of Using Different Size Distribution of Sawdust on the Temperature Profiles of the Gasification Process

The size distribution of sawdust particle is one of the important factors to be considered when running cyclone gasifier. Three types of fuel was used those are Fuel B, C and D specified in the section 5.1.1. The condition of the run was fixed for all three run. The air supply was fixed at 120 liter/min and the fuel feed rate was fixed at 15 kg/h. Figure 5.3, 5.4 and 5.5 show the results of the temperature profiles of each types of fuels used.

Figure 8 shows wall temperature profile of run conducted using Fuel B.

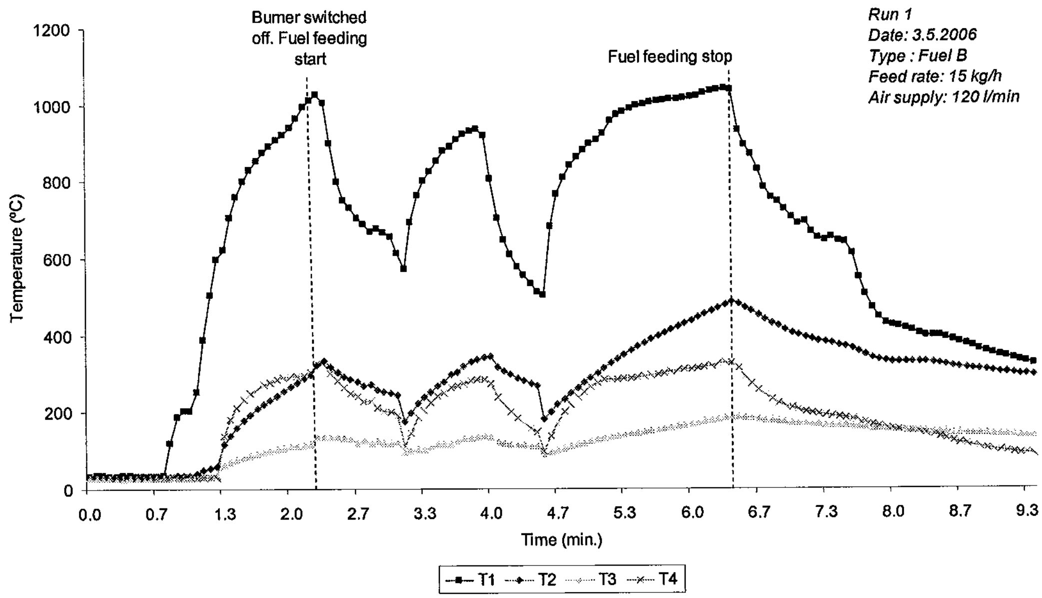

Figure 8: Temperature Profiles for Test Run using Fuel B.

Air was supplied through an injector that was located at the cyclone inlet, 170 mm from the top of cyclone gasifier unit. The test was carried out when the gasifier was cold. The test starts with heating up the gasifier using diesel burner with maximum capacity (fully open air valve). The result shows that, when the cyclone chamber was heated up, the gas temperature rose rapidly to 1000°C. The pattern followed by the wall temperature at T2 and T3 rose to 300°C in about two minute but the wall temperature at the T4 is relatively low which is about 130°C.

The result shows that the gasification process initiated as the sawdust was injected but the gasification process cannot be maintained except for about 6 minute. When the fuel was first injected, the wall temperature at all thermocouple decreased rapidly to about 100°C in only less than one minute before later on the temperature fluctuated for several minute and decreased further because the sawdust particle was unable in sustaining the gasification process. The reason is believed to be caused by the size distribution of particle which is relatively larger and cannot be suspended long enough in the chamber to enable the gasification process to occur. Hence, Fuel B was found unsuitable for this cyclone gasifier because the gasification process cannot be maintained in the cyclone chamber.

Figure 9 shows the wall temperature profile at cyclone chamber using Fuel C.

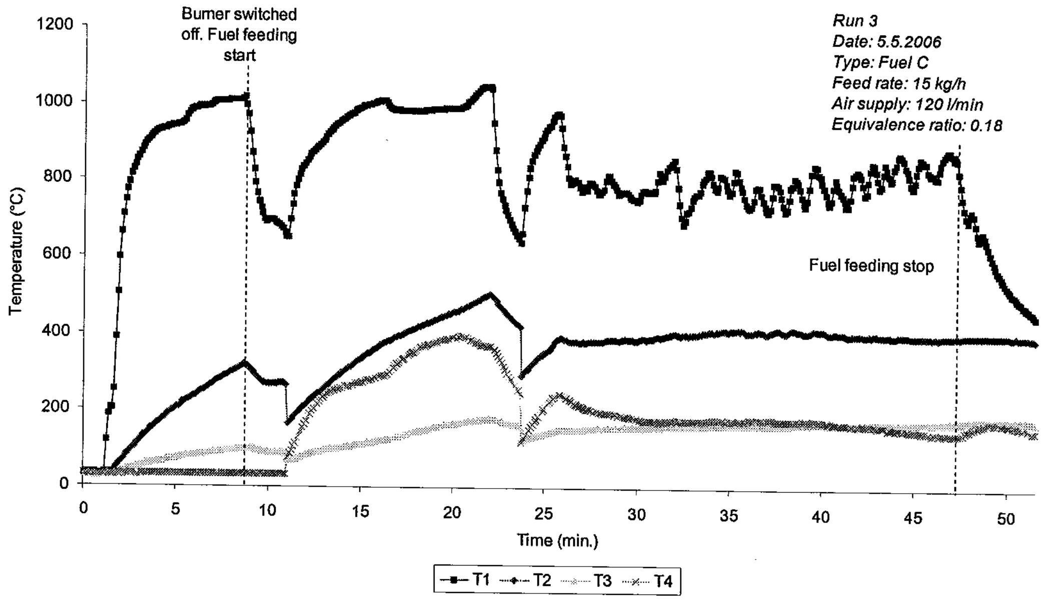

Figure 9: Temperature Profiles for Test Run using Fuel C.

The wall temperature profile at all thermocouple showed similar pattern with Fuel B during the heated up process. However, when fuel was injected the gas and wall temperatures fluctuated for about 10 minute before stabilizing until the end. The maximum wall temperature recorded at T2 was about 500°C but along the running process, the wall temperature recorded was maintaining a mean value of 380°C. Therefore, the wall temperature at T2 which was about 400°C was high enough to gasify Fuel C and the gasification process capable to sustain for long period of time. The wall temperature profile at T3 and T4 fluctuated at early stage but after 30 minute, the wall temperature at T3 and T4 began to rise at a point where the wall temperature at T3 and T4 met at the end. This showed that in steady state condition, the wall temperature at T3 and T4 should be maintained at the same value. Even though, Fuel C can be gasifying in cyclone gasifier, the gasification process took long time to reach steady state condition because the effect of particles size distribution. Therefore, for fuel C the heated process should be prolonged to further increase the wall temperature before injecting the fuel to enable the gasification process to occur steadily in early stage of running but the process seems uneconomical in term of fuel burner usage.

Figure 10 shows the wall temperature profile at cyclone chamber using Fuel D.

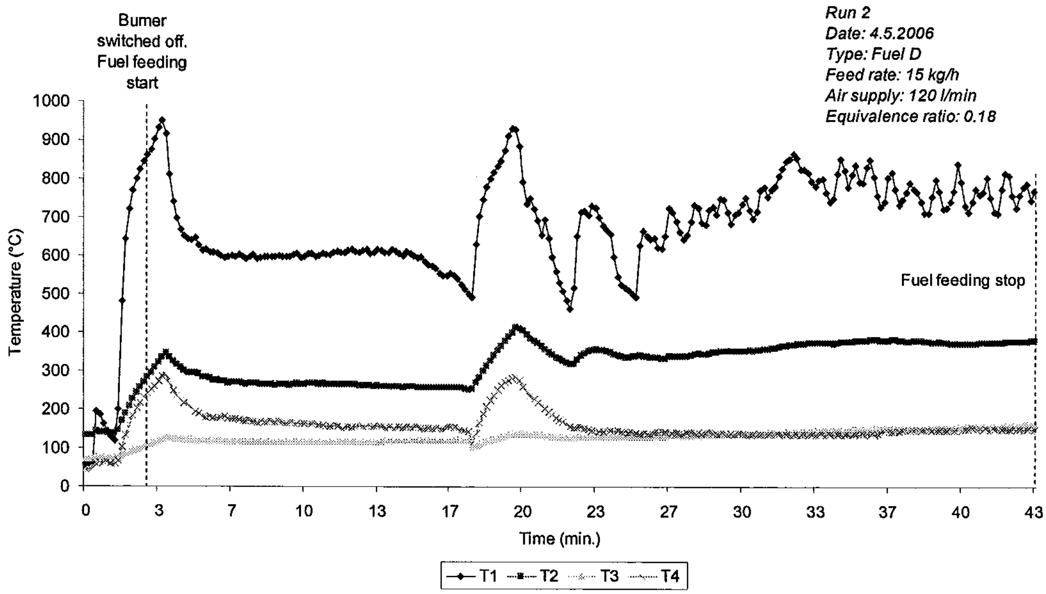

Figure 10: Temperature Profiles for Test Run using Fuel D.

From the figure, there is a significant different in the wall temperature profile inside the cyclone chamber especially just after fuel was injected. As long as the sawdust was injected inside the cyclone chamber the gasification process occurred steadily and the gasifier running smoothly. However after 15 minute the wall temperature at all zone start fluctuated for about four minute because of the problem of fuel flow at hopper, but the wall temperature increase further towards the end of the process when the injector located at hopper was switched on for only about one minute. The gas temperature profile followed the similar pattern along the test. The temperature profile at T2 generally increased and maintain steadily at a mean value 430°C. The temperature profiles at T3 and T4 maintained at about 200°C. As a result, the gasification process occurred steadily and the gasifier running smoothly when Fuel D was used.

These three wall temperature profiles of the gasification process using different sizes distribution of sawdust is presented in a single graph in which all thermocouples located are shown to assist in looking into the general trend of the profiles. Figure 11 shows the mean value temperature against fuel type for thermocouple T1, T2, T3 and T4.

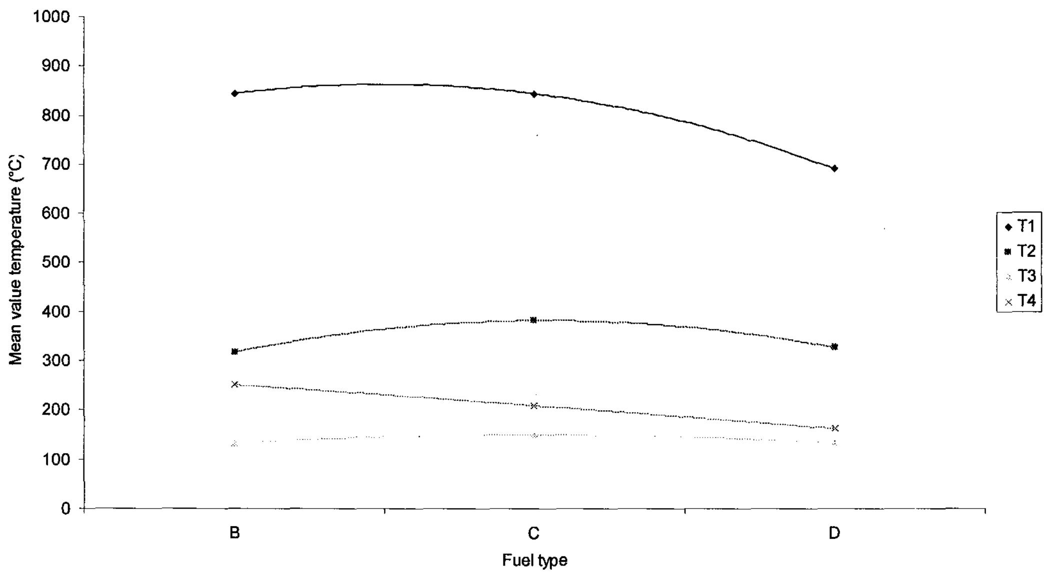

Figure 11: Mean Value Temperature versus Fuel Type

As discussed earlier Fuel B was not successfully gasified where the gasification process stopped after 7 minutes. Fuel C gave the higher temperature at all thermocouple (T1, T2, T3 and T4) compared to Fuel D. The temperature difference of both Fuels was about 150°C, 60°C, 20°C and 50°C respectively. It appears that the finest size distribution of sawdust will gave lower temperature profile at all thermocouple. This is possibly due to the rate of conversion process. The finest sawdust size distribution means the conversion process from one phase to another phase occurred very fast thus the main value temperature profile reduced. However too large a particle will results in instability in the gasifier and found unsuitable such as in Fuel B.

Effect of Using Different Air Flow Rates on the Temperature Profiles of the Gasification Process

Only Fuel D is used to examine the effect of using different air flow rates on the gasification process in cyclone gasifier chamber. This is because the gasification process reached steady condition fastest than other type of fuel (B and C), thus the process seems economical in term of fuel burner usage. In addition, Fuel D gave lowest temperature profile at all thermocouple position. The condition of the run was fixed for all three run. The fuel feed rate was fixed at 15 kg/h and the air supply flow rate was varied which were 120, 240 and 360 liter/min. Figure 5.7 and 5.8 show the results of the wall temperature profiles for air flow rate 240 and 360 liter/min respectively.

Figure 12 shows temperature profiles for tested using air flow rate equal to 240 liter/min. During the heating up process, the temperature increased slowly at all thermocouple positions because the LPG burner used was operated at minimum capability due to limitation of air compressor. The gas temperature profile at exit shows continuous increment but fluctuated extremely from start to the end with a mean value 530°C. The wall temperature profile at T2 increased gradually from 300°C to 500°C. The wall temperature profiles at T3 and T4 fluctuated with mean values 130°C and 150°C respectively. As a result, with increasing the air flow rate to 240 l/min, the temperature profile at T2 was higher than run used air flow rate 120 l/min.

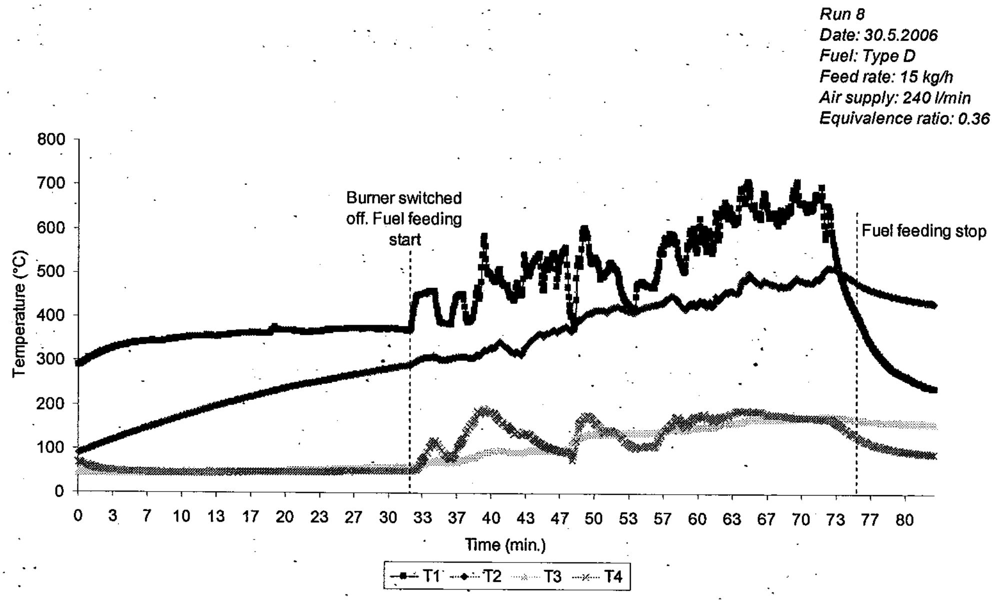

Figure 12: Temperature Profiles for Air Flow Rate 240 l/min

Figure 13 shows temperature profiles at cyclone gasifier chamber using air flow rate about 360 liter/min.

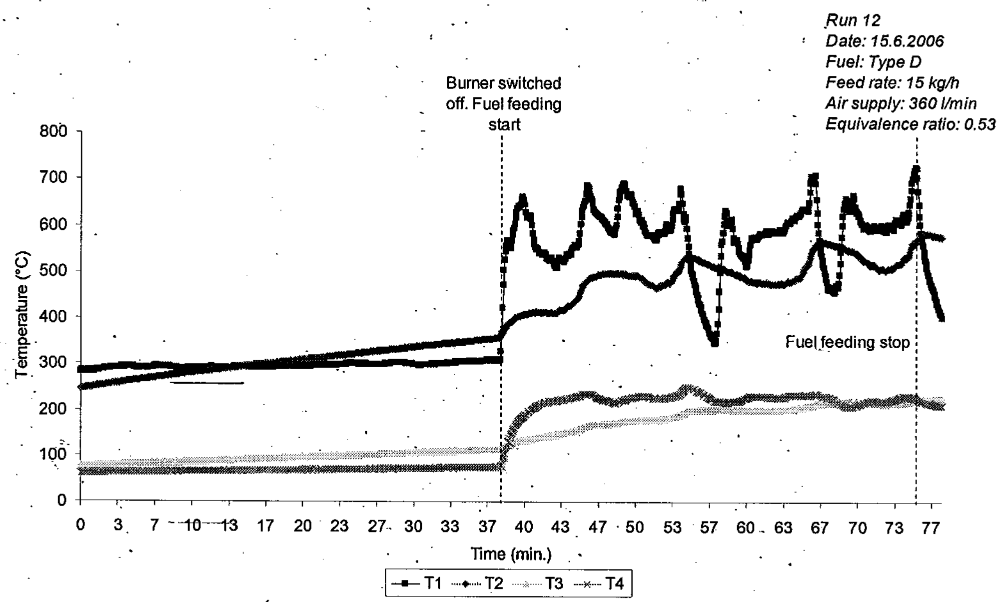

Figure 13: Temperature Profiles for Air Flow Rate 360 l/min

The gas temperature profile at the exit fluctuated frequently along the process with a mean value 580°C. This pattern followed by the wall temperature profile at T2 where there was a gradual increase with a mean value 390°C but fluctuated more compared to low air flow rate. The wall temperature at T3 was lower than thermocouple at T4 with a mean value 150°C and 220°C respectively.

These three wall temperature profile of the gasification process using different air flow rate is presented in a single graph in which all thermocouples located are shown in Figure 14 to assist in looking into the general trend of the profiles. The wall temperature profiles at T2 increased with increasing air flow rate. It appears that the higher air flow rate will gave higher temperatures at T2. This is due to the amount of available oxygen. A higher air flow rate means more oxygen was supplied to the gasifier and hence more oxidation occurred thus increased the temperature. The lowest temperature profiles at T1, T3 and T4 was run with air flow rate 240 l/min. The wall temperature at T4 was higher than T3, possibly due to turbulence flow at conical section that was disturbed the swirling flow when forming the upward forced vortex.

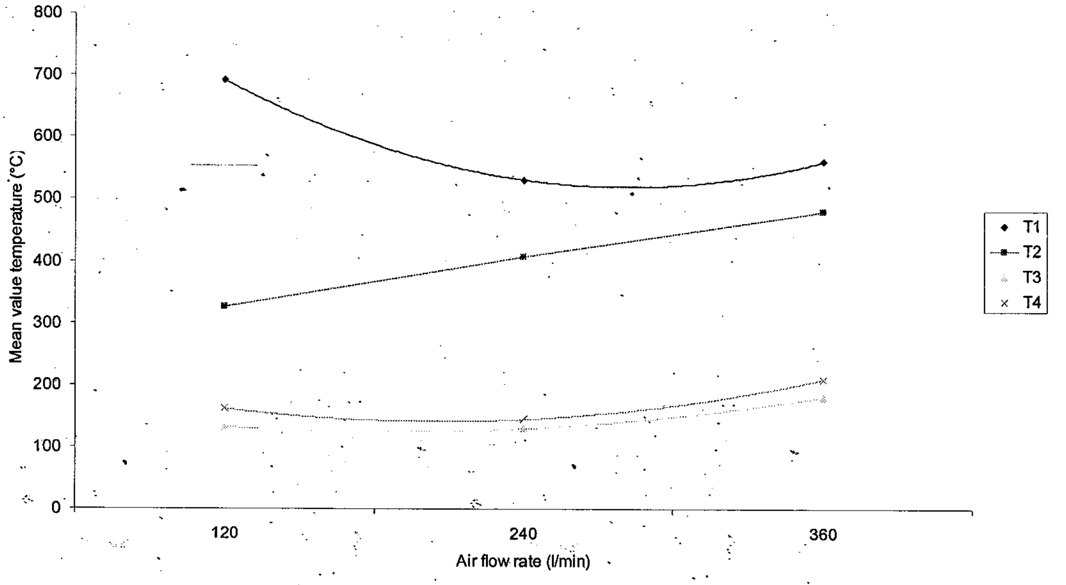

Figure 14: Mean Value Temperature versus Air Flow Rate

Effect of Using Different Feed Rate on the Temperature Profiles of the Gasification Process

Again only type Fuel D was used to examine the effect of using different fuel feed rates on the gasification process in cyclone gasifier chamber. The condition of the run was fixed for all run. The air supply flow rate was fixed at 240 liter/min while the fuel feed rates were varied: 17, 20, 22 and 28 kg/h.

Figure 15 shows the temperature profiles of tested using fuel feed rate 17 kg/h.

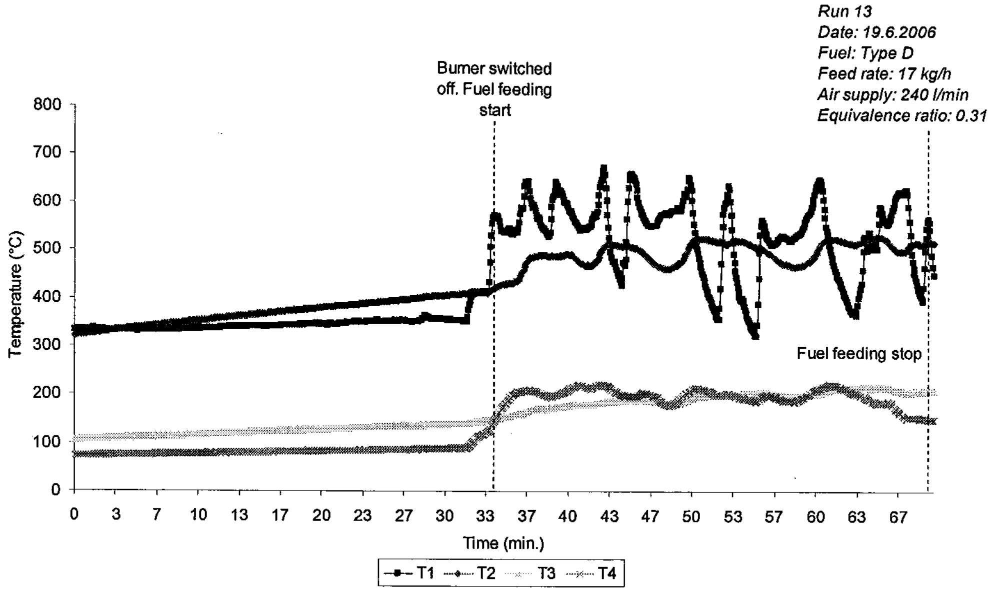

Figure 15: Temperature Profiles using Fuel Feed Rate 17 kg/h

The producer gas temperature profile at T1 fluctuated with a mean value 530°C. The wall temperature profile at T2 is relatively high with a mean value 500°C and at T3 and T4 the wall temperature mean values were about 200°C.

Figure 16 shows temperature profiles for cyclone gasifier at fuel feed rate 20 kg/h. From the graph, the gas temperature gradually decreased with the increase in time after the fuel was injected up to about 25 minutes and then increases, thus gave lower mean value about 470°C. The wall temperature at T2 was slightly increased in time with a mean value 470°C. Therefore, the mean value gas temperature is equal to mean value wall temperature for fuel feed rate 20 kg/h. In addition, the wall temperature at T4 is higher than T3 with a mean value of 240°C and 210°C respectively.

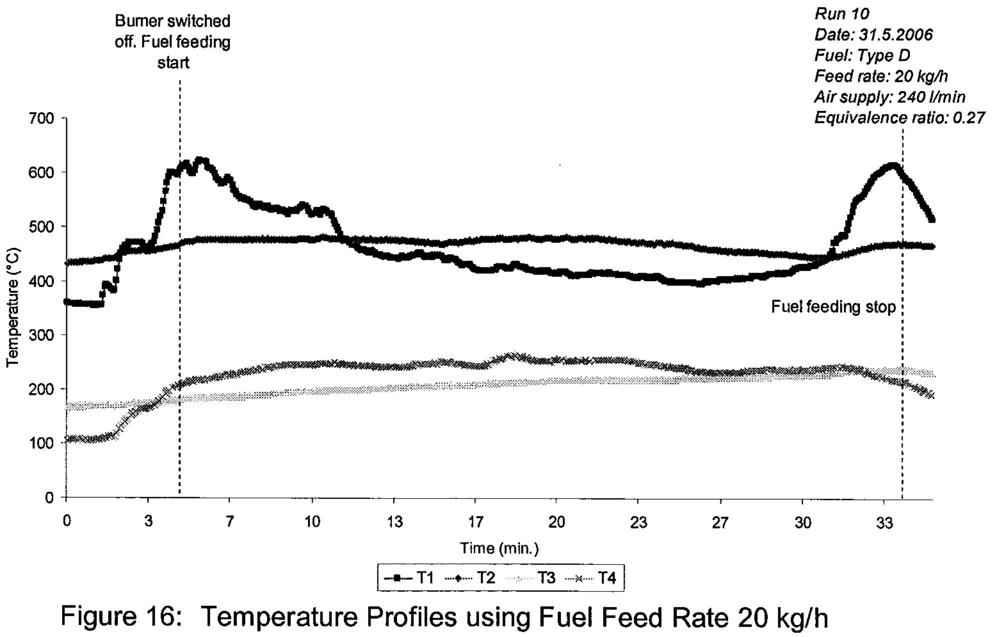

Figure 16: Temperature Profiles using Fuel Feed Rate 20 kg/h

Figure 17 shows temperature profiles for cyclone gasifier at fuel feed rate 22 kg/h.

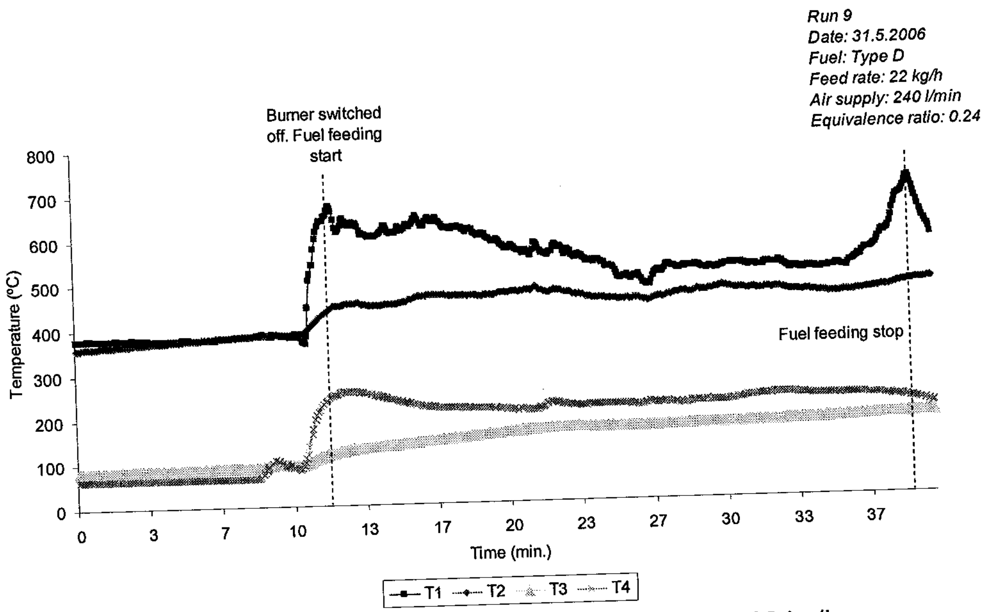

Figure 17: Temperature Profiles using Fuel Feed Rate 22 kg/h

From graph, the gas temperature profile, T1 follows the pattern of fuel feed rate at 20 kg/h which is gradual decrease with mean value 560°C. The wall temperature profile at T2 increased slightly and steadily maintain at the middle towards the end with a mean value 460°C. As usual the wall temperature at T4 is higher than T3 with a mean value 220°C and 160°C respectively.

Figure 18 shows the temperature profiles of cyclone gasifier system running at 28 kg/h. From the graph shown, the system attains steadiness quickly and has less fluctuation compared to the lower fuel feed rate previously. The gas temperature is high and maintained at a mean value 690°C. The wall temperature at T2 is relatively lower compared to the lower fuel feed rate which is at a mean value 210°C. The mean value of wall temperatures at T3 and T4 are 150°C and 91°C respectively.

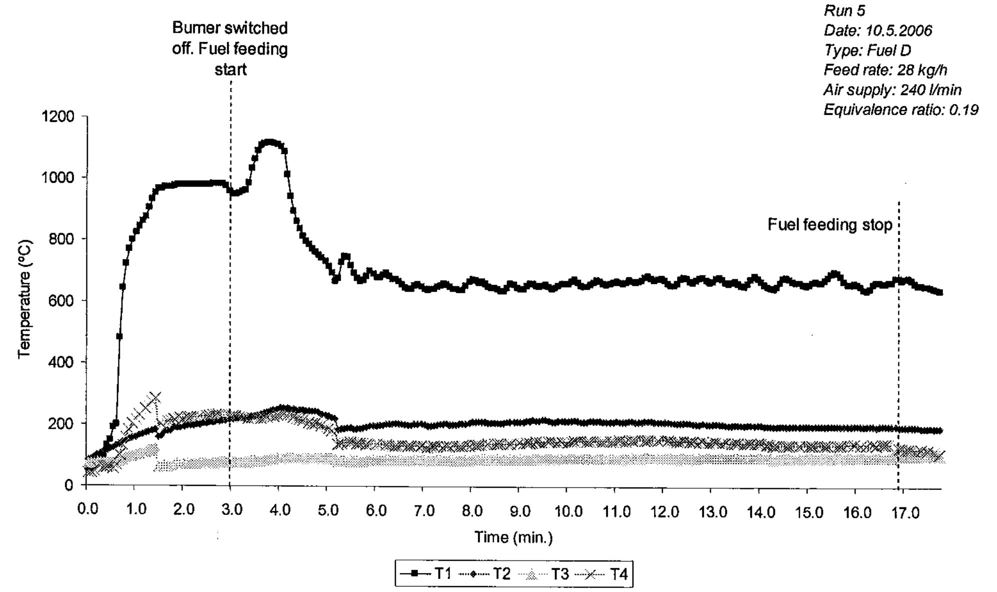

Figure 18: Temperature Profiles using Fuel Feed Rate 28 kg/h

These four temperature profiles of the gasification process using different fuel feed rate is presented in a single graph in which all thermocouple are shown to assist in looking into the general trend of the profiles. Figure 19 shows the mean value temperature versus fuel feed rate. The gas temperature increases with the increase in fuel feed rate. This is due to the amount of available fuel. A higher feed rate means more fuel was fed to the gasifier. However, the pattern was different in T2 where the wall temperature decreases with the increase in fuel feed rate. The lowest fuel feed rate gave higher wall temperature at T2. The wall temperature at T3 and T4 generally decrease with the increase in fuel feed rate. The temperature profile does not vary much with 2 kg/h difference.

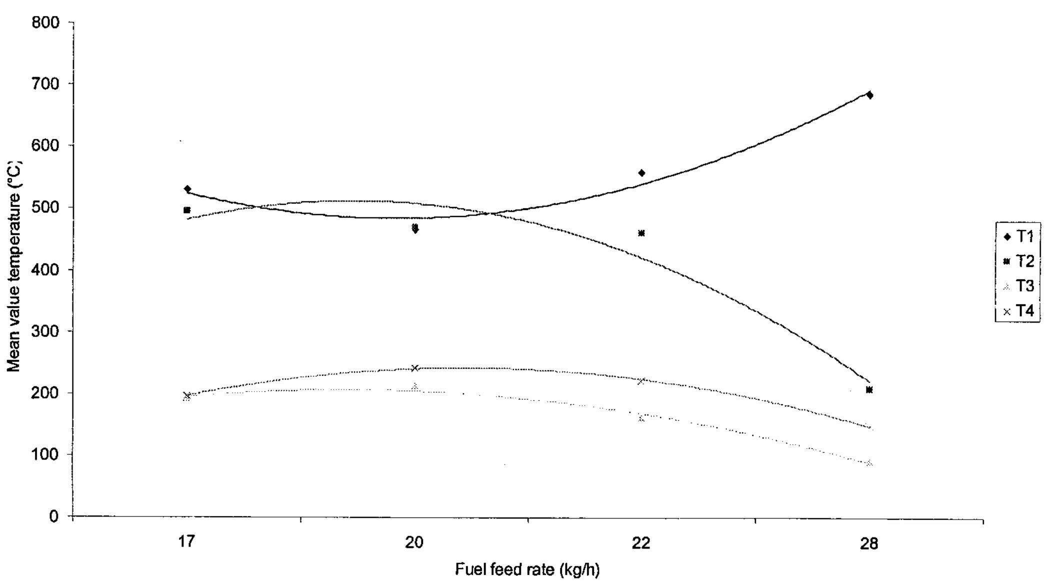

Figure 19: Mean Value Temperature versus Fuel Feed Rate

Effect of Using Different Equivalence Ratio on the Temperature Profiles of the Gasification Process

The range of equivalence ratio is 0.19 to 0.43. However, the range of equivalence ratio was extended up to 0.53 to investigate the temperature profiles. Fuel D was used with the equivalence ratio selected. As a result, the measured mean values of gas outlet and wall temperature were plotted against equivalence ratio for gasification with air as injection medium is shown in Figure 20. The temperature of producer gas decreases with the increase in equivalence ratio up to about 0.31 and then increases. The highest mean value of producer gas temperature was 700°C with equivalence ratio of 0.19. The wall temperature at T2 increases with the increase in equivalence ratio up to about 0.41 and then decreases. The highest mean value temperature at T2 was 560°C with equivalence ratio 0.41. The wall temperatures at T3 and T4 increase with the increase in equivalence ratio. However, the wall temperature at T4 is seen slightly higher than T3.

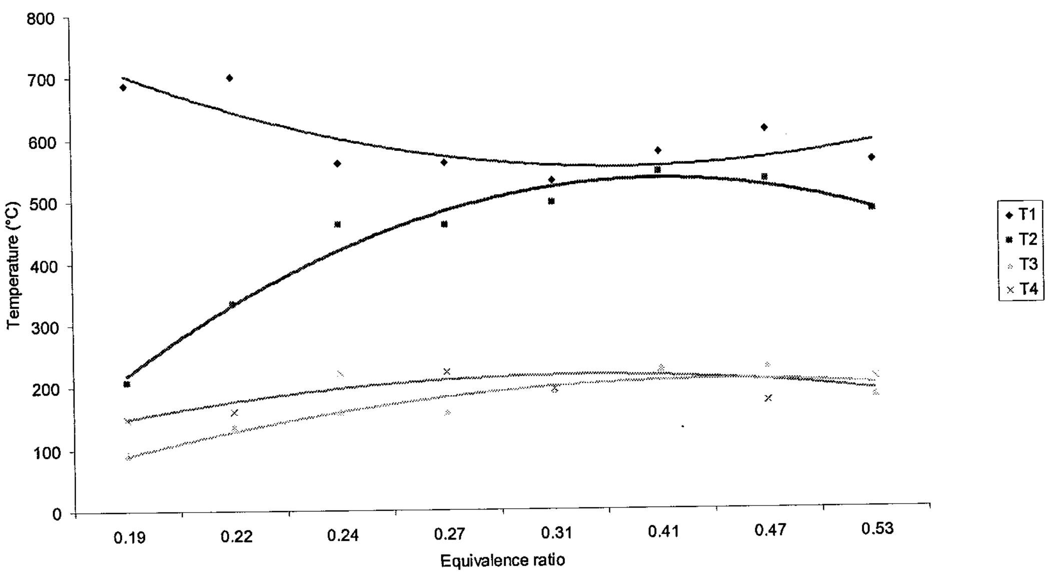

Figure 20: Temperature Profiles with Equivalence Ratio

Char Separation

The amount of char that is separated and collected at the bottom of the cyclone for Fuel D is plotted against equivalence ratio and is shown in Figure 21.

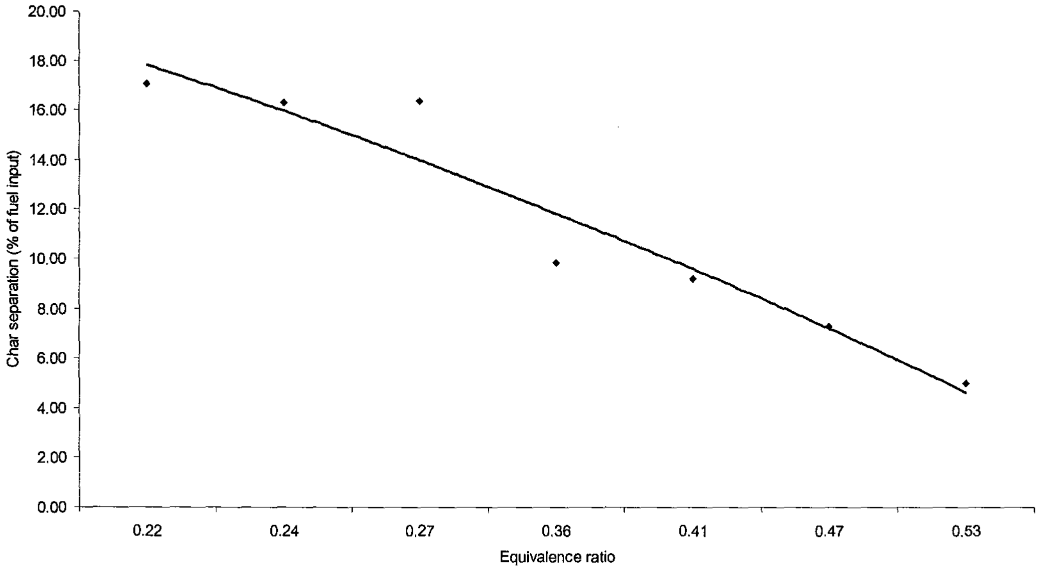

Figure 21: Char Separation versus Equivalence Ratio

Figure 5.16 shows that the char separation decreases with the increase in equivalence ratio. The amount of separated char decreased from 17% to approximately 7% when equivalence ratio was increased from 0.22 to 0.47. The general trend in gasification process is that the char formation increased as fuel feed rate increased. However it should be remembered that the temperature in the cyclone was also increased by increasing the equivalence ratio in the cyclone. Thus most of the char has reacted and the reaction rate of the char is seen to be much higher at the higher temperature compared to the formation of char as equivalence ratio increased.

Pressure Drop and Flow Rate of Producer Gas

The static pressure drop inside the cyclone chamber has been measured between the inlet and the outlet of cyclone gasifier. The measured pressure drop was about 60 to 80 Pa for the entire test. The pressure drop found is lower than those found by other researchers. Fredriksson, 1999 found that the pressure drop was between 100 and 200 Pa. However, the overall efficiency of the gasifier is not dependent on the pressure drop alone.

The flow rate of producer gas can be determined from the exhaust gas velocity. The flow rate of producer gas against the equivalence ratio is shown in Figure 22. From the results, the flow rate of producer gas decreases with the increase in equivalence ratio up to about 0.41 and then increases. The equivalence ratio increases with decrease in the mass of the fuel for a given air supply and duration of the run. As a result the combustible gas also reduces. This explains the reason for decreasing trend of producer gas flow rate. The higher producer gas flow rate was $0.01664 m^3/s$ with equivalence ratio is equal to 0.22.

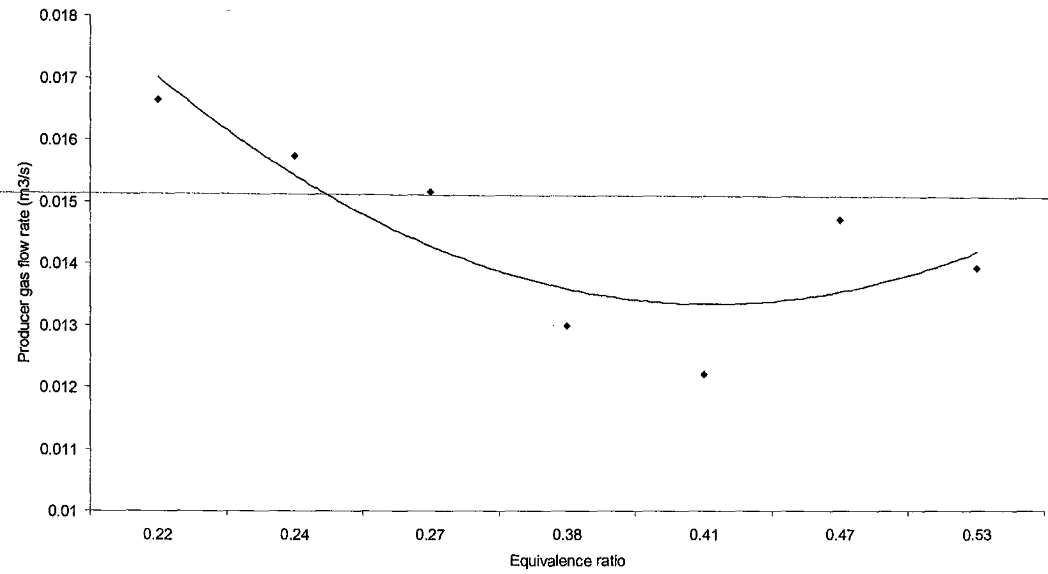

Figure 22: Flow Rate of Producer Gas versus Equivalence Ratio

Performance of the Cyclone Gasifier

The producer gas produced from the cyclone gasifier can be used as an indicator to determine the performance of the gasifier. The important parameters are gas composition, calorific value of the producer gas, the cold gas and the mass conversion efficiencies. The amount of char collected in the char collector located at the bottom of cyclone gasifier is also important to be a sign of overall fuel utilization.

The characteristic of biomass fuel (sawdust) such as moisture content, the size distributions, the cyclone gasifier design, the air flow rate, the injector and the gasifying agent used (air, oxygen or steam) are some factors that affect the quality of producer gas. Because the end product from the gasifier is a mixture of combustible gases, the calorific value of the producer gas is the main important parameter in defining the gasification process. Therefore, the design focus of any gasifier is to increase the concentration and quality of the producer gas as much as possible. During the tests carried out, several samples of producer gas were taken and analyzed using gas chromatograph (GC).

Characteristics of Gas Composition

An analysis of producer gas was performed to evaluate the quality of the fuel gas produced. Several samples of producer gas were taken during the run at time interval around 15 minutes after the gasifier reach stable condition and running smoothly. The gas samples were stored in gas sampling bag before being analyzed using a gas chromatograph. The sample gas was taken at a sampling point located at about 10 cm from the exit of the gasifier. A simple connector made from brass pipe with length about 2 m is used. A gas sampling train was used to clean a producer gas because the gas from the cyclone is dirty and wet and could cause damage the gas chromatograph. The combustible gases, produced from the gasifier are H_2, CO, and CH_4, while the noncombustible gases include N_2, O_2 and CO_2. Appendix F shows method of GC used while Appendix G shows sample of output from GC for run 10. Figure 23 shows the percentage of the components of the producer gas against the equivalence ratio.

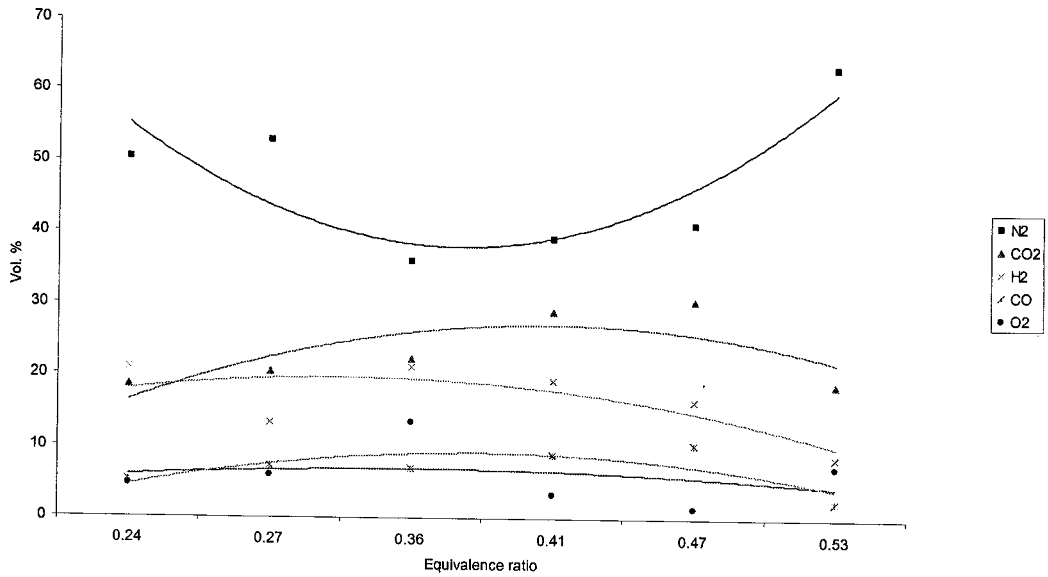

Figure 23: Variation of Gas Concentration with Equivalence Ratio

The percentage of nitrogen, N_2 decreases with the increase in equivalence ratio up to about 0.41 and then increases. The highest amount of N_2 concentration is about 53% at equivalence ratio of 0.27. The percentage of N_2 is lower to those reported by other researchers. Gabra et al., 2001 found that the percentage of N_2 was about 60% at equivalence ratio 0.25. Syred et al., 2004 found that the percentage of N_2 was about 68% at equivalence ratio 0.27.

The percentage of carbon dioxide, CO_2 increases with the increase in equivalence ratio. The highest amount of CO_2 concentration is about 31% at equivalence ratio of 0.47. The concentration of CO_2 is higher than reported by other researchers. Gabra et al., 2001 and Syred et al., 2004 found that the highest concentration of CO_2 was about 18%. The decrease in the percentage of CO_2 shows better conversion into CO in the gasification process.

The percentage of hydrogen, H_2 decreases with the increase in equivalence ratio. It was found that, the lowest concentration of H_2 was 16% whilst the highest concentration was 21%. The concentration of H_2 is the most significant contributor to the calorific value of producer gas because LHV of H_2 is higher than CO. Thus it is desirable to increase its concentration in order to increase the calorific value of producer gas. The concentration of H_2 is higher than other researchers. Gabra et al., 2001 found that the concentration of hydrogen was about 8%. The reason is probably due to the moisture content of sawdust which is higher than bagasse, thus increasing the reaction of water vapor with char. The methane formed was also unstable, thus reacting with water vapor to form more concentration of hydrogen.

The percentage of carbon monoxide, CO increases with the increase in equivalence ratio up to about 0.47 and then decreases. The highest amount of CO concentration is about 11% at equivalence ratio of 0.47. The concentration of CO is lower than other researchers. Syred et al., 2004 and Gabra et al., 200la found that the concentration of CO was in the range of 7% to 15%.

The percentage of oxygen, O_2 decreases with the increase in equivalence ratio up to about 0.47 and then increases. The highest percentage of O_2 is about 13% with equivalence ratio 0.36. The lowest percentage of O_2 is about 1% at equivalence ratio

0.47. The percentage of O_2 is found to be slightly higher to those reported by Syred et al., 2004 which is about 1% to 2%. The average gas composition is shown in Figure 24.

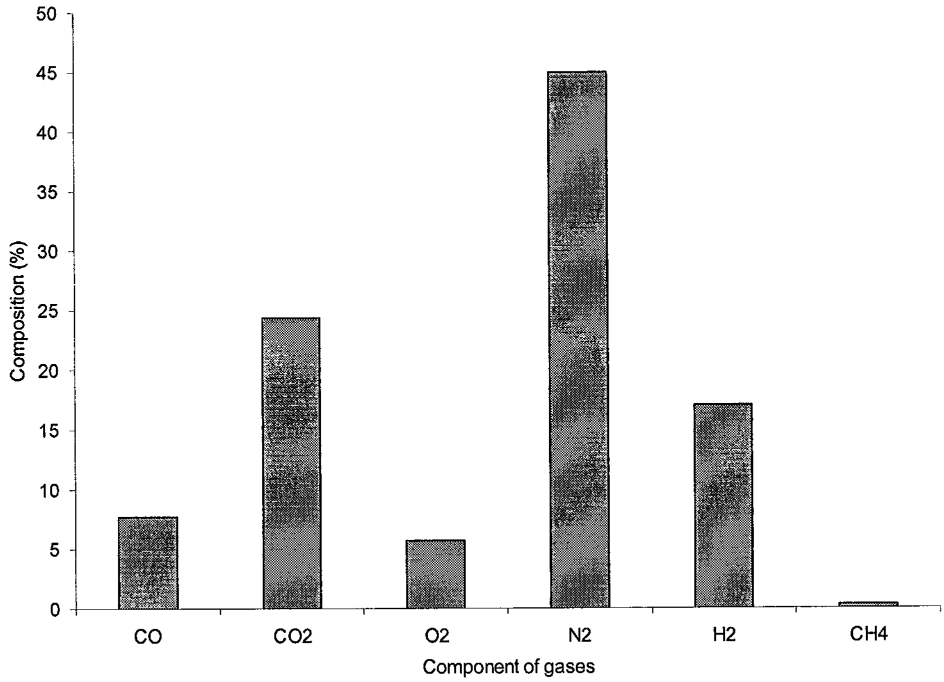

Figure 24: Compositions of Producer Gas.

Calorific Value of Producer Gas

The calorific value of producer gas against the equivalence ratio is shown in Figure 25.

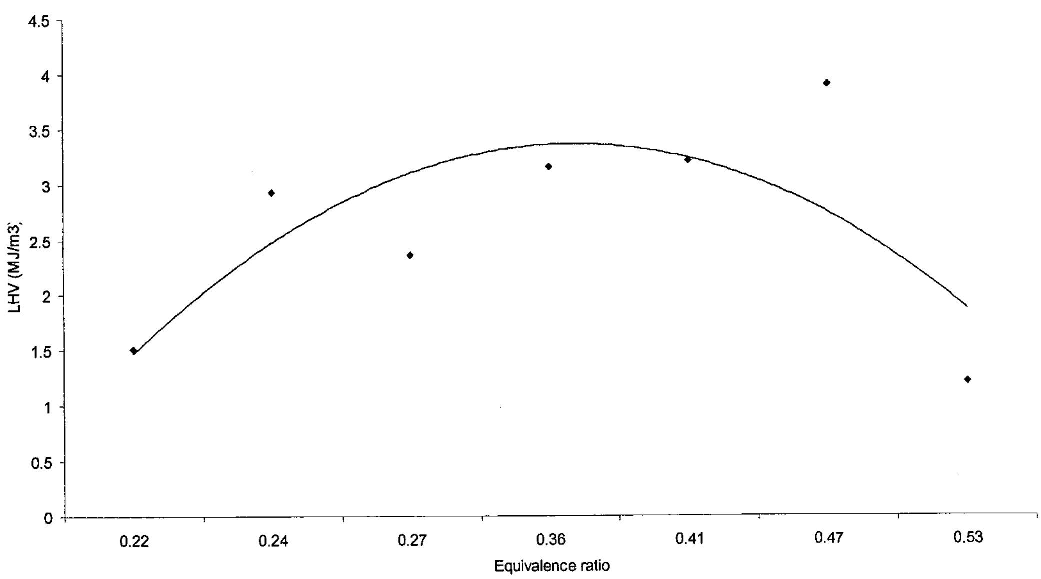

Figure 25: Calorific Value of Producer Gas versus Equivalence Ratio

It was found that, the steadier and consistent calorific values were obtained in the middle of each run and these are the values used in Figure 5.20. The calorific value increases with the increase in equivalence ratio. The increase in calorific value is due to the increase in the percentage of CO and H_2. The highest calorific value, LHV of the producer gas is calculated from the concentration of the combustible components and had an average of 3.90 MJ/m^3. The trend of calorific value is in confirmation with Figure 5.19 for CO and H_2 respectively. Other researchers have also observed a similar trend. Gabra et al., 2001 found that the LHV increased from 2 to 4 MJ/m^3 with the increased in equivalence ratios. Syred et al., 2004 found the LHV increased from 2.99 to 4.26 with the increased in equivalence ratios. Fredriksson, 1999 found the LHV was about 4.4 MJ/m^3 with assumption the H_2 was about 8 vol. % due to failure of a measuring cell in gas analysis equipment.

Thermal Output of the Gasifier

Figure 26 shows the thermal output of cyclone gasifier against equivalence ratio.

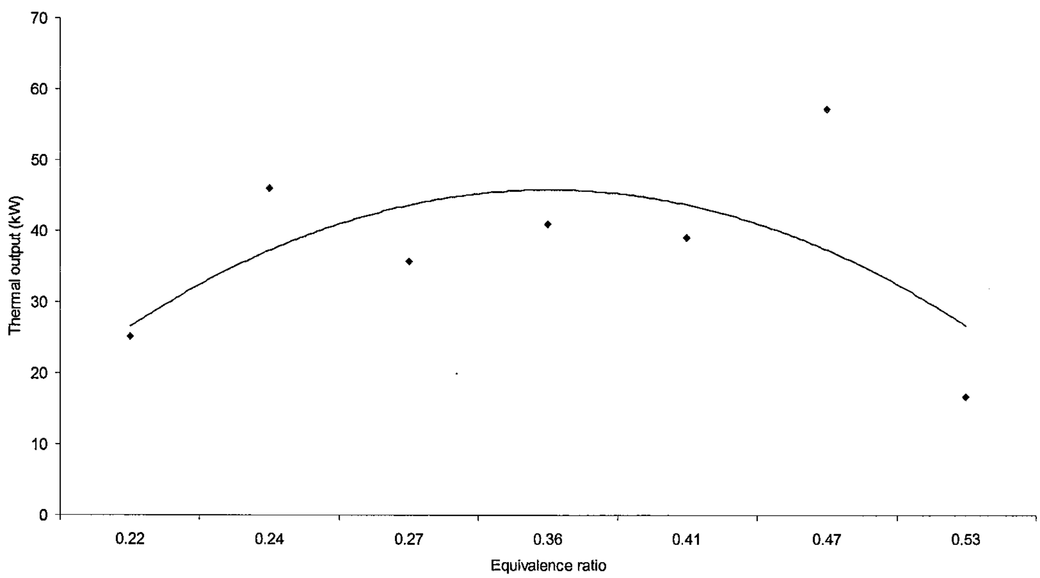

Figure 26: Thermal Output of Cyclone Gasifier versus Equivalence Ratio

From the results, the thermal output increases with the increase in equivalence ratio up to about 0.47 and then decreases. The highest thermal output from the cyclone gasifier was found to be 57.35 kW_T at equivalence ratio equal to 0.47.

Mass Conversion Efficiency

Figure 27 shows mass conversion efficiency against equivalence ratio. Appendix H shows a sample calculation in determining the mass conversion efficiency for run 15.

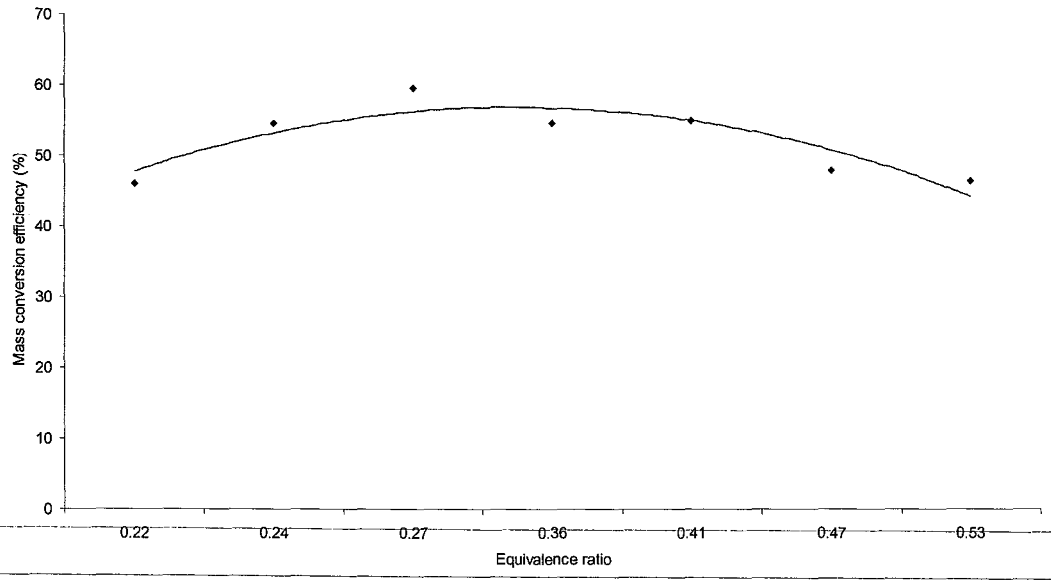

Figure 27: Mass Conversion Efficiency versus Equivalence Ratio

The mass conversion efficiency increases with the increase in equivalence ratio up to a peak value at an equivalence ratio of 0.27 before it starts to decrease. The highest mass conversion efficiency was found to be about 60%. The result obtained is lower than other researchers because the water vapour was not condensed and ash particle cannot be determined because the cooling and cleaning system was not installed.

Enthalpy Balance of Cyclone Gasifier

Appendix I shows the sample of a complete calculation in determining the enthalpy balance for run 15. The law of conservation energy states that enthalpy input into the system must equal the enthalpy output from the system. Otherwise, the enthalpy is loss from the system. Enthalpy input into the gasifier includes the enthalpy from the wood, the moisture in the air and the enthalpy from the air compressor that supplies the air into the gasifier. Enthalpy of wood is given by product of its low heating value (LHV) and mass of the wood. Heating value for wood is 16.54 MJ/kg and about 10 kg fuel was used. Enthalpy of the air is the enthalpy of the moisture in the air due to the latent heat of vaporization. Often this value is neglected in the calculation but when compressed air is used in the process than the amount should be considered which is equal to 2.16 MJ. The enthalpy from the air compressor was calculated from power specification of the air compressor times the duration time of the experiment, which is about 34 minutes. Thus the enthalpy of air compressor was found to be 9.13 MJ. Hence, the total enthalpy input is equal to 176.59 MJ.

Enthalpy output are the enthalpy of the combustible gases, the sensible heat of the producer gas, the enthalpy of the remaining char in the gasifier, the enthalpy of tar which has not been cracked in the gasifier and the enthalpy of the water vapor present. The enthalpy of the producer gas was found to be 117.01 MJ and the sensible heat of producer gas about 37.52 MJ. The amount of char remained in gasifier is 0.7 kg, thus enthalpy for char was found to be 13.23 MJ. Hence, total enthalpy output was found to be 167.76 MJ. Therefore, the enthalpy balance was found to be 94.9 %.

The enthalpy balance against equivalence ratio is shown in Figure 28. From the results, the enthalpy balance increases with the increase in equivalence ratio up to about 0.47 and then decreases. The highest enthalpy balance was about 98%.

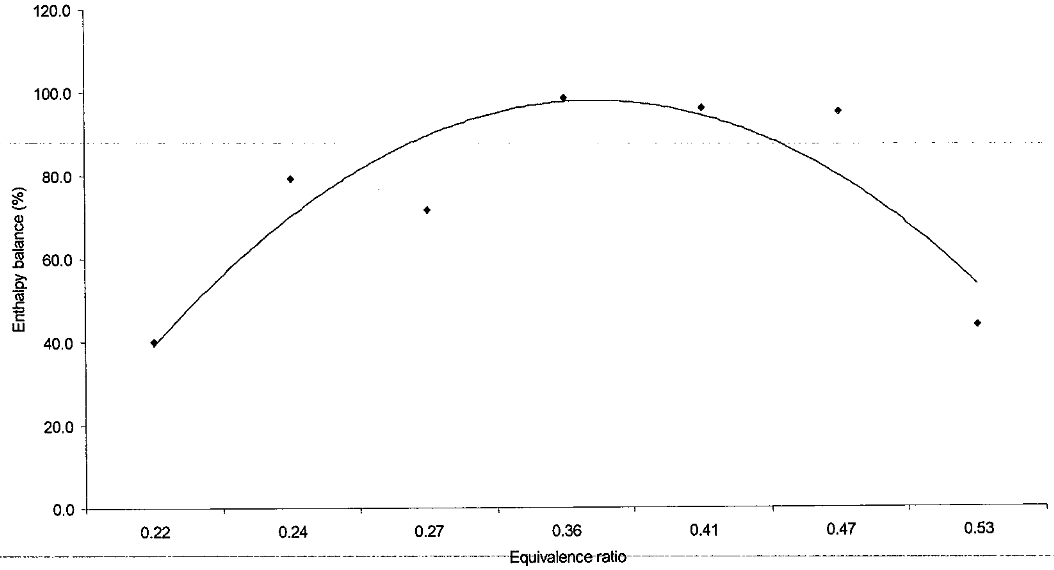

Figure28: Enthalpy Balance versus Equivalence Ratio

Cyclone Gasifier Efficiency

Figure 29 shows the variation of cyclone gasifier efficiency against the equivalence ratio. The detailed calculation of cyclone gasifier efficiency was presented in Appendix J.

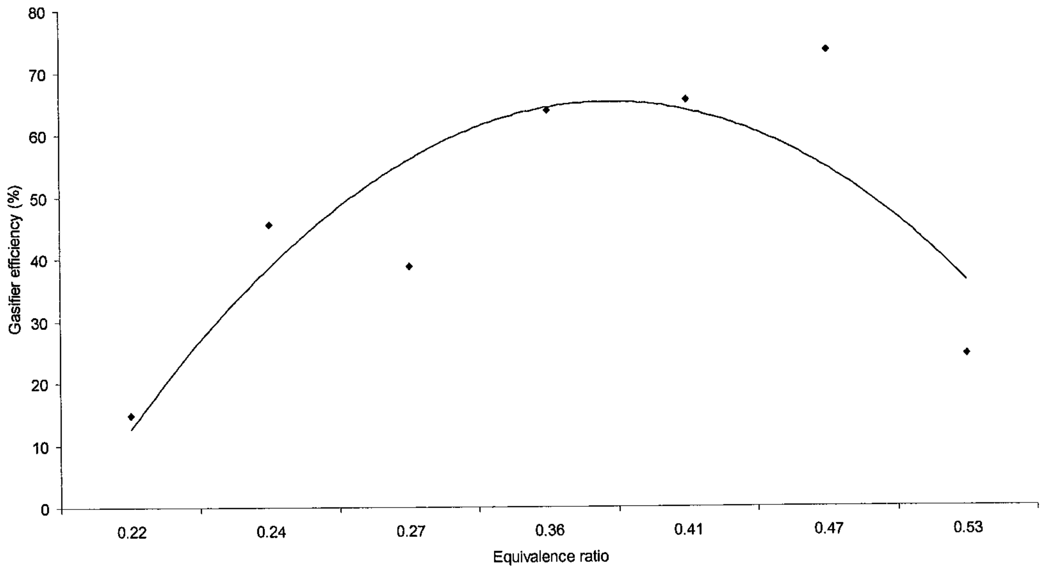

Figure 29: Cyclone Gasifier Efficiency versus Equivalence Ratio

As a result, the efficiency of cyclone gasifier increases with the increase in equivalence ratio up to about 0.47 and then decreases. The highest efficiency of cyclone gasifier obtained was about 73.4%. The cyclone gasifier efficiency obtained is comparable with other researchers. Syred et al., 2004 found that the inverted cyclone gasifier efficiency was about 36% to 76% with respect to different types of fuel and equivalence ratio from 0.17 to 0.27.

CONCLUSION AND RECOMMENDATION

The experimental work that has been done in this study is to develop the technique to gasify sawdust and to characterize the performance of a cyclone gasifier using sawdust as a fuel. Therefore, this chapter will conclude the findings from the study and suggest some recommendations for future work.

The main objective of this study is to characterize the performance of a cyclone gasifier which was designed and fabricated at School of Mechanical Engineering, USM using sawdust as a biomass fuel. Experimental study at atmospheric pressure showed that it was possible to generate a combustible gas when injecting the ground sawdust from furniture industries with air as a gasifying agent. Most of the runs were performed using ground sawdust with particle size distribution in the range from 0.25 – 1 mm comprising about 80%. The raw sawdust is not possible to be used directly in the cyclone gasifier because it contains different sizes and shapes of particles thus blocking the flow at feeding and injector system.

The low heating value of sawdust was found to be about 16.54 MJ/kg with moisture content of 8.25%. Sawdust is suitable to be used for gasification process and from proximate and ultimate analysis the result show that sawdust contained high volatile matter and low ash content that were about 76.23% and 1.49% respectively while the percentage of carbon content (dry basis) was about 42.38% and it is consistent with other biomass wood fuels.

The temperature profiles of producer gas and inside the cyclone chamber are significant to understand the phenomena taking place for this cyclone gasifier system. It has shown in Chapter 5 that the temperature levels in the gasifier affect the gas compositions and the calorific value of the producer gas. Consequently, the knowledge of the temperature profiles is necessary in optimizing the performance of the gasifier. The producer gas temperature profiles clearly make known that the fuel feeding system fluctuated thus affect the gas composition of producer gas. Good heating up process in the initial stage results in the minimum wall temperature for initiating gasification process found to be about 400°C at T2 region. In addition, the average temperature of producer gas was about 600°C while at T3 and T4 region was about 200°C.

The highest average low heating value (LHV) of the producer gas was 3.9 MJ/kg with flow rate about 0.01471 m^3/s. The highest thermal output from the cyclone gasifier was 57.35 kW_T. The highest value of mass conversion efficiency was about 60 % while enthalpy balance was found to be 98 %. As a conclusion, the efficiency of cyclone gasifier increases with increasing equivalence ratios in the range of 0.19 to 0.47 and the maximum efficiency of the gasifier obtained was about 73.4%. The gasifier efficiency obtained is comparable with other researcher which is 36 – 76%.

The development of cyclone gasifier system was subjected to constant modifications throughout the research to overcome various problems unforeseen initially until the experiments were carried out. Unfortunately, the experiences and problems encountered in design and fabrication by other worker were not mentioned in their paper. Finally, it is hope that this work can contribute with a relevant part to the research and development work on the technical concept of pulverize biomass fuel gasification with a cyclone gasifier and serve as a basis for future work in this field.

Recommendations for the Future Work

One of the objectives of this study was to identify areas where more research work is needed in order to realize this technique for power generation. During the course of the work presented here, several areas have been identified where more research work is needed.

Temperature measurements inside the cyclone would be of great assistance to be able to understand the process. Therefore, more thermocouples can be placed along the gasifier to determine the temperature profiles. The maximum capacity of the gasifier was 60 kg/h of pulverized biomass fuel; fed through two tangential inlets but for this experiment only single inlet was used because of the limitation in fuel feeding system. It is suspected that the performance of the system will increase when the maximum capacity of the gasifier is used to ensure a longer run and sustain a longer gasification condition.

There is more work that can be discerned which are accounted for in the following:

1. Computer simulation on temperature and flow in the cyclone
2. Gas cooling and cleaning system performance
3. Engine performance

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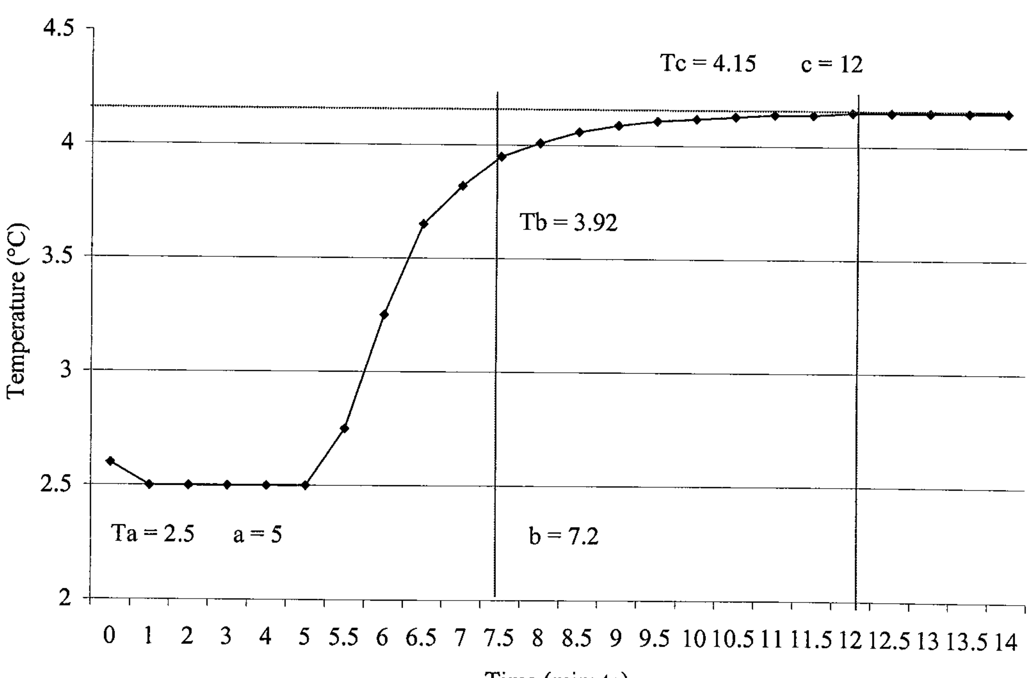
BOMB CALORIMETER TEST

Test result:

Weight of specimen : 1 gram
Water quantity of inner cylinder : 2100 ml
Length of wire before experiment (Lo) : 12.1 cm
Length of wire after experiment (Lt) : 4.60 cm
Diameter of Nickel wire : 0.125 mm
Temperature of room : 21 °C
Temperature of water : 27.5 °C

Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	2.60	8.5	4.06
1	2.50	9	4.09
2	2.50	9.5	4.11
3	2.50	10	4.12
4	2.50	10.5	4.13
5 (Ignited)	2.50	11	4.14
5.5	2.75	11.5	4.14
6	3.25	12	4.15
6.5	3.65	12.5	4.15
7	3.82	13	4.15
7.5	3.95	13.5	4.15
8	4.01	14	4.15

Base on the table above from the bomb calorimeter test, graph temperature versus time can be plotted to calculate the high heating value of the sample sawdust.



Formula:
$$T_{corr} = T_c + r_2 (c-b) - [T_a + r_1 (b-a)]$$

$$HHV_{Wood} = (m_{ECW} + m_{WC})x\frac{T_{Corr}}{m_S}x\,Cp_W x\,4.1868$$

Where:

Tcorr	= Correction temperature (°C)
Ta	= Temperature at igniting (°C)
Tb	= Temperature at b time (°C)
Tc	= Temperature at the maximum (°C)
a	= Time at igniting (min)
b	= Time at 6/10 from maximum temperature (min)
c	= Time to reach the maximum temperature (min)
r_1	= Temperature rate 5 minutes before igniting (° C/min)
r_2	= Temperature rate 5 minutes after maximum temperature (° C /min)
HHV	= Higher heating value (MJ/kg)
m_{WEC}	= Mass water in equivalent calorimeter (g)
m_{WC}	= Mass water in cylinder (g)
m_S	= Mass of sample (g)
Cp_W	= Specific heat of water (cal/g °C)

Where:

Specific heat of water	=1 cal/g ° C
1 cal/g	= 4.1868 kJ/kg
Water in equivalent calorimeter	= 604 g

Base on the data and graph above can be determined these values:

Ta	= 2.5 ° C
Tb	= 3.92 ° C
Tc	= 4.15 ° C
a	= 5 min
b	= 7.2 min
c	= 12 min
r1	= 0.02
r2	= 0

Calculation of Tcorr as follow:

Tcorr = 4.15 + 0 (12 – 7.2) – [2.5 + 0.02 (7.2 – 5)]
= 1.61

HHV_{Wood} = [604 g + 2100 g] x (1.61 °C/1 g) x 1 cal/g ° C x 4.1868 (kJ/kg)
= 18.23 MJ/kg (dry wood basis)

With the moisture content 8.25% and the high heating value of the sawdust is 18.23 MJ/kg, hence the high heating value of the wet sawdust basis is:

$$HHV_{Wood} = \frac{(100 - 8.25)}{100} \times 18.23$$

HHV_{Wood} = 16.73 (MJ/kg) (wet wood basis)

With latent heat of vaporization (λ = 2.260 MJ/kg) and moisture content 8.25%, hence the low heating value ((LHV) of the sawdust is:

HHV_{Wood} = LHV + W λ

LHV_{Wood} = HHV_{Wood} – W λ
= 16.73 (MJ/kg) – (2.260 x 0.0825)
= 16.54 MJ/kg

Mass Balance for Run 15

$$\rho_{producer\ gas} = \sum(\rho * x)_{constituent\ gas}$$

$\rho_{\ producer\ gas}$ $= (\rho\ H_2 \text{ x } 16.34\%\ H_2) + (\rho\ CH_4 \text{ x } 2\%\ CH_4) + (\rho\ CO \text{ x } 10.43\%\ CO)$

$+ (\rho\ CO_2 \text{ x } 30.59\%\ CO_2) + (\rho\ N_2 \text{ x } 41.22\%\ N_2) + (\rho O_2 \text{ x } 1.42\%\ O_2)$

$= (0.0408\ kg/m^3 \text{ x } 0.1634) + (0.335\ kg/m^3 \text{ x } 0.02) + (0.5687\ kg/m^3 \text{ x } 0.1043) + (0.941\ kg/m^3 \text{ x } 0.3059) + (0.5688\ kg/m^3 \text{ x } 0.4122) + (0.6498 \text{ x } 0.0142)$

$= 0.604\ \ kg/m^3$

Mass of producer gas $= V_g \text{ x } \rho g \text{ x running duration}$

$= 0.014707 m^3/s \text{ x } 0.604\ kg/m^3 \text{ x } 2040\ s$

$= 18.12\ kg$

Mass output = Mass of gas + Mass of char and ash

$= 18.12\ kg + 0.5\ kg$

$= 18.62\ kg$

Mass of air $= V_a \text{ x } \rho_a \text{ x running duration}$

$= 0.006\ m^3/s \text{ x } 2.3\ kg/m^3 \text{ x } 2040\ s$

$= 28.15\ kg$

Mass input =Mass of wood + Mass of air

$= 10\ kg + 28.15\ kg$

$= 38.15\ kg$

$$\text{Mass Balance} = \frac{\text{Mass output}}{\text{Mass input}} = \frac{18.62\ kg}{38.15\ kg}$$

$= 49\%$

ENTALPY BALANCE

Enthalpy input into the gasifier

$$H_{input} = H_{wood} + H_{blower} + H_{air}$$

Enthalpy of wood:

$$H_{wood} = m_{wood} \times (LHV)_{wood}$$

$$= 10 \text{ kg} \times 16.54 \text{ MJ/kg}$$

$$H_{wood} = 165.4 \text{ MJ}$$

Enthalpy of air compressor:

Duration time of the blower is 34 min

$$H_{ac} = 1492 \text{ watt}$$

$$= 1492 \text{J/s} \times 2040 \text{ s}$$

$$=3.044 \text{ MJ}$$

Two air compressor used, H_{ac} = 9.13 MJ

Enthalpy of moisture in air:

By using this formula and the table at the bottom:

$$h_{air} = c_{pa}\, t + x\, [c_{pw}\, t + h_{we}]$$

Where:

c_{pa} =specific heat capacity of air at constant pressure (kJ/kg.°C)

t = air temperature (°C)

c_{pwv} = specific heat capacity of water vapor at constant pressure (kJ/kg.°C)

h_{we} = evaporation heat of water at 0°C (kJ/kg)

Mass flow rate of producer gas can be calculated as follow:

$$\dot{m}_{producergas} = \dot{V}_{producergas} \, x \rho_{producergas}$$

$$\dot{m}_{producergas} = 0.014707 \, m^3/s \times 0.604 \, kg/m^3$$

$$= 31.98 \, kg/h$$

The sensible heat of producer gas can be determined from the equation above:

$$H_{\text{sensible heat of producer gas}} = 31.98 \, kg/h \times 3.345 \times (500\text{-}154) \times 2040 \, s$$

$$H_{\text{sensible heat of producer gas}} = 31.98 \, kg/h \times 3.345 \times 619 \times 2040 \, s$$

$$H_{\text{sensible heat of producer gas}} = 37.52 \, MJ$$

Enthalpy of Char

The amount of char remained is 0.5kg and assuming LHV of char about 18.9 MJ/kg (Jorapur, 1994), hence the enthalpy of the char can be calculated using this formula:

$$H_{char} = LHV_{char} \times M_{char}$$

$$H_{char} = 18.9 \, MJ/kg \times 0.7 \, kg$$

$$H_{char} = 13.23 MJ$$

The total output of the gasifier is:

$$H_{output} = H_{PG} + H_{SH} + H_{char}$$

$$H_{output} = 117.01 \, MJ + 37.52 \, MJ + 13.23 \, MJ$$

$$H_{output} = 167.76 \, MJ$$

Therefore the enthalpy balance is found to be 94.9%

The enthalpy of humid air at 25°C with specific moisture content x = 0.019826 kg/kg, can be calculated as:

h_{air} = 1.005 (kJ/kg.°C) 25°C + 0.019826 (kg/kg) [1.864 (kJ/kg.°C) 25°C + 2,547 (kJ/kg)]

h_{air} = 25.125 (kJ/kg) + 51.421 (kJ/kg)

h_{air} = 76.546 (kJ/kg)

The flow rate of air supplied is 0.006m³/s and density of compressed air is 2.3 kg/m³. Hence the enthalpy of moisture in air is:

$$H_{air} = \dot{V}_{air} \times \rho_{air} \times h_{air} \times \text{duration time}$$

$$H_{air} = 0.006 m^3/s \times 2.3 kg/m^3 \times 76.546 kJ/kg \times 2040 s$$

$$H_{air} = 2.16 MJ$$

Hence the total enthalpy input into the gasifier was found to be about:

$$H_{input} = H_{wood} + H_{blower} + H_{air} = 165.3 MJ + 9.13 MJ + 2.16 MJ = 176.59 MJ$$

Enthalpy Output of the Gasifier

Enthalpy out of producer gas:

$$H_{output} = H_{PG} + H_{SH} + H_{char}$$

Enthalpy of producer gas:

With LHV of the combustible gas was found 3.9 MJ/m³., hence the enthalpy of the producer gas:

$$H_{PG} = \dot{V}_{PG} \times (LHV)_{PG} \times \text{Time}$$

$$H_{PG} = 0.014707 m^3/s \times 3.9 MJ/m^3 \times 2040 s$$

$$H_{PG} = 117.01 MJ$$

Sensible Heat of Producer Gas

The actual enthalpy of the wood gas should also take into the account the sensible heat loss in reducing the temperature of the wood gas from 500°C to 154°C. Sensible heat of producer gas is given by:

$$H_{\text{sensible heat of producer gas}} = \dot{m}_{\text{producer gas}}\, cp_{\text{producer gas}}\, \Delta T \times \text{Time}$$

$cp_{\text{producer gas}}$ can be calculated as:

$$cp_{\text{producer gas}} = \Sigma(cp^{*}x)_{\text{constituent gas}}$$

Where:

x = gravimetric concentration of the producer gas and the properties of gas was determined at temperature film T_f ($T_f = \frac{500+154}{2}$ =327°C) =600K

$cp_{\text{producer gas}}$ = ($cp\ H_2$ x 16.34% H_2) + ($cp\ CH_4$ x 2% CH_4) + (cp CO x 10.43% CO) + ($cp\ CO_2$ x 30.59% CO_2) + ($cp\ N_2$ x 41.22%) +($cp\ O_2$ x 1.42% O_2)

= (14.537 kJ/kgK x 0.1634) + (3.482 kJ/kgK x 0.02) + (1.0870 kJ/kgK x 0.1043) + (1.0761 kJ/kgK x 0.3059) + (1.0751 kJ/kgK x 0.4122) + (1.0032 x 0.0142)

$cp_{\text{producer gas}}$ = 3.345 kJ/(kg.K)

and:

$$\rho_{\text{producer gas}} = \Sigma(\rho^{*}x)_{\text{constituent gas}}$$

$\rho_{\text{producer gas}}$ = ($\rho\ H_2$ x 16.34% H_2) + ($\rho\ CH_4$ x 2% CH_4) + (ρ CO x 10.43% CO) + ($\rho\ CO_2$ x 30.59% CO_2) + ($\rho\ N_2$ x 41.22% N_2)+ (ρO_2 x 1.42% O_2)

= (0.0408 kg/m^3 x 0.1634) + (0.335 kg/m^3 x 0.02) + (0.5687 kg/m^3 x 0.1043) + (0.941 kg/m^3 x 0.3059) + (0.5688 kg/m^3 x 0.4122) + (0.6498 x 0.0142)

= 0.604 kg/m^3