PERFORMANCE AND CHARACTERISTICS OF A CYCLONE GASIFIER

by

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Thesis submitted in fulfillment of the requirements for the degree of Master of Science

NOVEMBER 2006

ACKNOWLEDGEMENTS

Alhamdulillah through His Blessing my study was completed. I am deeply grateful to my loving wife (Rasida Tuddina binti Abdullah), children (Nurulain Azmah & Muhammad Ammar) and parent of their continuous support all the time, morally and financially and to all my friends, thank you for being there.

I would like to express my highest appreciation to my supervisor Associate Professor Zainal Alimuddin Zainal Alauddin, for his guidance, advice and assistance throughout my Master of Science Programme. I would also like to thank Universiti Sains Malaysia for providing me the opportunity to pursue my study.

I would like to thank all technicians in charges, especially En. Zalmi and En. Abd. Latif for their assistant and help me technically and morally.

I greatly appreciate to En Mat Isa from Zilanza Furniture Sdn. Bhd. for your supply of sawdust and all who have helped me in my efforts.

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LIST OF SYMBOLS

Symbol	Description	Units
a	Igniting time of the Bomb Calorimeter	minute
b	Time at 6/10 from maximum temperature	minute
c	Time to reach the maximum temperature	minute
cp	Specific heat capacity	kJ/kg K
AF	Air fuel ratio	
H	Enthalpy input for gasification process	MJ
h	Specific energy	J/kg
m_{WC}	Mass water in cylinder	g
m_{WEC}	Mass water in equivalent calorimeter	g
T_{corr}	Temperature correction	^{o}C
T_a	Temperature at igniting	^{o}C
T_b	Temperature at b time	^{o}C
T_c	Temperature at the maximum	^{o}C
T_f	Temperature film	^{o}C
T_s	Surface temperature of biomass	K
W	Mass of water per kilogram of feed	
X	Molar concentration of gasified product	
ΔH	Heat of formation	kJ/mole
ϕ	Equivalence ratio	
η	Efficiency	
ΔT	Temperature difference	K
λ	Latent heat of vaporization	kJ/kg
ρ_{wood}	Density of wood	Kg/m^3
$\dot{V}$	Volumetric flow rate	m^3/h
$\dot{m}$	Mass flow rate	kg/h

LIST OF ABBREVIATION

A	Weight Fraction of Ash
C	Weight Fraction of Carbon
GC	Gas Chromatograph
H	Weight Fraction of Hydrogen
HHV	High Heating Value
kW_e	kilo Watt electricity
kW_T	kilo Watt thermal
LHV	Low Heating Value
MC	Moisture Content
N	Weight Fraction of Nitrogen
O	Weight Fraction of Oxygen
S	Weight Fraction of Sulfur
TDC	Thermal Conductivity Detector
LPG	Liquefied Petroleum Gas
S_g	Geometric Swirl Number
S_{gT}	Non-isothermal Geometric Swirl Number

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LIST OF AWARDS

Bronze Medal
Invention, Innovation, Competition, Expo Science & Technology 2004 (MOSTI 2004), 27-29 August 2004, Kuala Lumpur, Malaysia.
Product: Cyclone Gasifier for Sawdust
Researchers: M.A. Miskam and Z.A.Z. Alauddin

Sanggar Sanjung Award 2004
Universiti Sains Malaysia
Product: Cyclone Gasifier for Sawdust
Researchers: M.A. Miskam and Z.A.Z. Alauddin

PRESTASI DAN PENCIRIAN PENGGAS SIKLON

ABSTRAK

Melihat isu-isu global mengenai tenaga lestari dan pengurangan gas-gas rumah hijau, tenaga biojisim merupakan satu sumber penting tenaga lestari yang semakin mendapat perhatian sebagai sumber tenaga yang berpotensi di masa hadapan. Penggasan biojisim adalah suatu proses untuk menukarkan bahan api pepejal kepada gas boleh bakar yang mengandungi nilai pemanasan 3 – 5 MJ/m^3. Ciri-ciri bahan api biojisim adalah parameter rekabentuk penting apabila memilih sesuatu sistem penggasan. Habuk kayu adalah bahan api biojisim halus yang terdapat dengan banyaknya di Malaysia boleh digunakan sebagai satu sumber tenaga untuk menghasilkan tenaga yang berguna. Walaubagaimanapun, penggunaan habuk kayu dihadkan oleh masalah-masalah yang disebabkan oleh saiz zarah di dalam bahan api tersebut. Penggas siklon telah direkabentuk dan dibina di Universiti Sains Malaysia untuk menggaskan bahan api biojisim berbentuk halus dengan saiz zarah yang kurang daripada 500 mikron. Sistem tersebut mengaplikasikan teknik baru untuk menggas habuk kayu melalui konsep pergerakan secara siklon.

Kajian ini melibatkan kerja teori dan eksperimen untuk memahami operasi dan juga prestasi dan ciri-ciri penggas siklon menggunakan habuk kayu sebagai bahan api biojisim. Objektif kajian ini adalah untuk: (i) mencirikan habuk kayu sebagai bahan api biojisim untuk penggas siklon, (ii) menentukan profil suhu gas keluaran dan profil suhu di dalam kebuk siklon, (iii) analisa gas keluaran, (iv) melakukan analisa termodinamik dan (v) mendapatkan kecekapan penggas dan keluaran haba penggas siklon. Hasil yang didapati di dalam kajian ini dibandingkan dengan pengkaji lain.

Habuk kayu yang dikisar daripada industri perabut digunakan sebagai bahan api dengan 80% daripada agihan saiz berjulat dari 0.25 ke 1 mm. 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 mengubah nisbah kesetaraan daripada 0.19 ke 0.53. 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 rendah tertinggi bagi gas terhasil adalah 3.9 MJ/m^3 dengan kadar aliran isipadu 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.

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ABSTRACT

With respect to global issues of sustainable energy and reduction in greenhouse gases, biomass energy as one of the key sources of renewable energy is getting increased attention as a potential source of energy in the future. Biomass gasification is a process to convert solid fuel into combustible gases of typically 3 – 5 MJ/m^3. The characteristic of biomass fuel is the key design parameters when selecting a gasifier system. Sawdust is a fine biomass fuel abundantly available in Malaysia that can be utilized as a source of energy to produce power. However, the utilization of sawdust is limited by problems caused by the size of particle in the fuel. A cyclone gasifier has been designed and developed at Universiti Sains Malaysia to gasify pulverized biomass fuel with particle size of less than 500 microns. The system applied a novel technique to gasify sawdust through cyclonic motion concept.

The study involved both theoretical and experimental work to understand the operation as well as the performance and characteristics of a cyclone gasifier using sawdust as a biomass fuel. The objectives of the study are to: (i) characterize the sawdust as biomass fuel for cyclone gasifier, (ii) determine the temperature profiles of the producer gas and wall temperature profiles inside the cyclone chamber, (iii) analyze the producer gas, (iv) perform thermodynamics analysis and (v) obtain gasifier efficiency and thermal output of the cyclone gasifier. The results found in this study were compared to other workers.

Ground sawdust from furniture industries is used as a fuel with 80% of the size distribution ranging from 0.25 to 1 mm. 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 from 0.19 to 0.53. 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 low heating value of producer gas was 3.9 MJ/m^3 with volume flow rate of 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.

CHAPTER 1
INTRODUCTION

1.0 General 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.

1.1 Sawdust as a Source of Biomass Fuel

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. In plant photosynthesis, the reaction can be written as follows (Donald & Jean, 1988):

$$CO_2 + 6H_2O + \text{light energy} = C_6H_{12}O_6 + 6O_2 \quad (1.1)$$

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 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 1.1 shows the biomass resources potential in term of power generation in Malaysia for the year 1999.

Table 1.1: 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.

1.2 Biomass Energy Conversion Process

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 of the material in a furnace. Direct burning is an exothermic process that produces combustion products such as carbon dioxide, nitrogen oxides, and particulate matter. Many types of furnace are available for the combustion of biomass such as refractory-lined furnaces, water-wall furnaces and boilers. Typically it involves the oxidation of biomass with excess air, giving hot flue gases, which are then used to produce steam in the heat exchanger sections of boilers which can then be used for process heating, drying or electricity generation (Bain et al., 1998). Large biomass power generation systems have comparable efficiencies to those of fossil fuel systems, but this comes at a higher cost due to the moisture content of biomass. However, by using the biomass in combined heat and electricity production systems (or cogeneration systems), the economics are significantly improved. Cogeneration is viable where there is a local demand for both heat and electricity (Ayhan, 2001).

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. The best known process is the conversion of sugar to alcohol (ethanol). The alcohol produced is often termed 'bio-ethanol' or a 'bio-fuel'. Ethanol can be produced from certain biomass materials which contain sugars, starch or cellulose (Ayhan, 2001). Bio-ethanol can be combined with petrol and burned as a fuel in spark-ignition engines. 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 (Ayhan, 2001). The gas produced is called 'biogas'. Animal manure, sewage, crop residues, and industrial waste can all be used in digesters to produce biogas. The gas can be used for heat or power production.

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 chemical energy of the solid fuel is converted into both the thermal and chemical energy of the gas. The chemical energy contained within the gas is a function of its chemical composition. Thus the chemical composition of the product gas determines its quality as a fuel. High concentration of combustible gases such as H_2, CO and CH_4 increase the combustion energy of the product gas.

1.3 Conventional Gasification Technology

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, producer gas can replace fossil fuels in a number of applications (FAO, Forestry Department, 1986). 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.

1.3.1 Fixed Bed Gasifiers

There are three types of fixed bed gasifiers depending on the direction of air flow. The gasifiers are classified as updraft, downdraft and cross-flow (Mckendry, 2002b). The simplest type of fixed bed gasifier is the updraft gasifier. The biomass is fed at the top of the reactor and moves downwards as a result of the conversion of the biomass and the removal of ashes. The air intake is at the bottom and the gas leaves at the top. The biomass moves in counter current to the gas flow, and passes through the drying zone, the distillation zone, the reduction zone and the hearth zone. The updraft gasifier has the advantage of using high amount moisture content biomass and the overall efficiency of the process is high but this configuration produces a producer gas with high content of tar and particulates (Mckendry, 2002b).

In a downdraft reactor biomass is fed at the top and the air intake is also at the top or from the sides. The gas leaves at the bottom of the reactor, so the fuel and the gas move in the same direction. Downdraft gasification produces a low tar gas (0.1 kg/kg feed) and a low particulate but not tolerate with high moisture content biomass but the overall energy efficiency is low due to the high heat content carried over by the hot gas (Mckendry, 2002b).

Cross-flow gasifier is adapted for the use of charcoal. Charcoal gasification results in very high temperatures (1500^{o}C and higher) in the hearth zone which can lead to material problems. Advantages of the system lie in the very small scale at which it can be operated. In developing countries installations for shaft power under 10 kW_e are used. This is possible due to the very simple gas-cleaning train (cyclone and a bed filter). The process produce low overall energy efficiency and a producer gas contain high tar content (Mckendry, 2002b).

1.3.2 Fluidised Bed Gasifiers

Fluidised bed gasification is originally developed to overcome the operational problems with fixed bed gasification of fuels with high ash content, but is very suitable for the larger capacities (larger than 10 MW_T) in general. Compared to fixed bed gasifier, the gasification temperature is relatively low 750^{o}C-900°C (Mckendry, 2002b). The fuel is fed into a hot (sand) bed which is in a state of suspension, bubbling or circulating. The bed behaves more or less like a fluid and is characterized by high turbulence. Fuel particles mix very quickly with the bed material, resulting in a fast pyrolysis and a relatively large amount of pyrolysis gases. Because of the low temperatures the tar conversion rates are not very high.

1.3.3 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.

1.4 Cyclone Gasification Technology

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.

1.5 Background of the Study and Problem Statement

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 this 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.

1.6 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.

1.7 Overview of the Thesis

The literature review on previous researches on cyclone gasifier is presented in Chapter 2. The theoretical study is elaborated in Chapter 3. Chapter 4 describes the detail design of the experimental setup and experimental study. Results and discussion of the experiments is discussed in Chapter 5. Results are presented in the form of graphs and tables for easy evaluation. Finally, in Chapter 6, conclusions and recommendations for further work in this area are drawn for future developments.

CHAPTER 2
LITERATURE REVIEW

2.0 Introduction

Cyclone is the most widely used separation technique to clean gas stream from solid or liquid particles and extensive works have been reported on this separating technique. Furthermore, the used of cyclone as a combustor system is well known and there are many types of commercialize cyclone combustor available in the market. However, the use of cyclone combustor is generally limited to burn liquid and gaseous fuel. In addition they are also cyclone combustor designed to burn pulverized coal. Hence, the idea of using cyclone to gasify biomass fuels was first studied by Kjellstrom, 1993 at the Royal Institute of Technology in Stockholm. Since, then only few studies including practical work have been reported in the literature on using cyclone as a gasifier.

2.1 Earlier Study Associated to Cyclone Gasifier Design and Operation

Design and operation of the cyclone gasifier was earlier studied and published by three researchers in the cyclone gasification areas namely by Fredriksson (1999), Gabra et al. (2001a) and Syred et al. (2004). Here their cyclone gasifier designs and operation especially relevant to this study are reviewed and discussed.

2.1.1 Two Stage Atmospheric Gasification/Combustor Design and Operation

A schematic diagram of a two stage atmospheric gasification/combustor which was developed by Fredriksson, 1999 and Gabra et al. (2001) is shown in Figure 2.1.

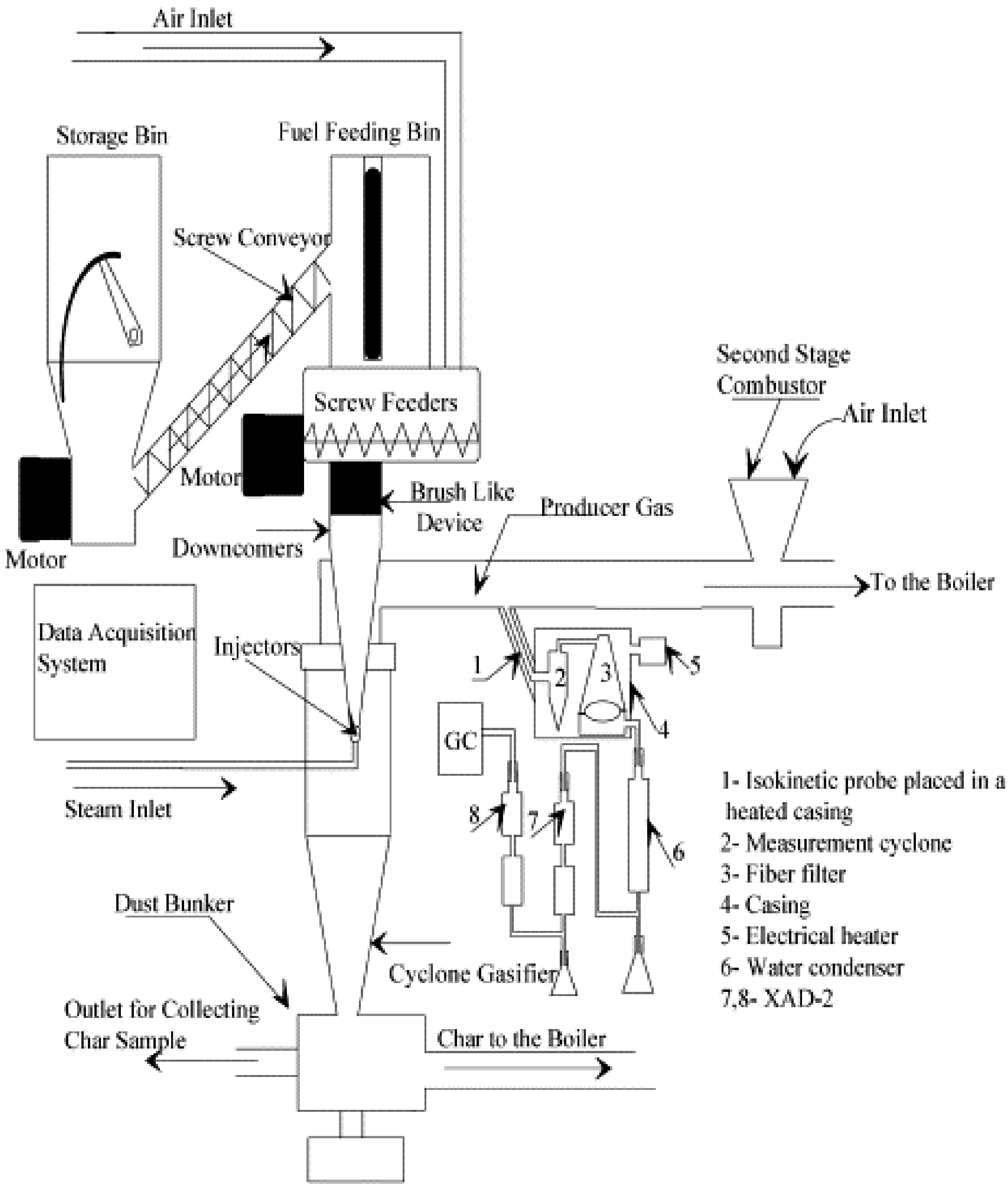

Figure 2.1: Schematic Diagram of a Two Stage Atmospheric Gasification
Resources: Gabra et al., 2001

The first stage is a cyclone gasifier while the second stage is a combustor. The system consists of fuel feeding system, an injector system, cyclone gasifier unit and combustor at second stage. The fuel is transferred from storage bin to the fuel feeding bin by single screw feeder and from fuel feeding bin to the injector by double screw feeders. The fuel is blown into the cyclone chamber by two opposite injectors entering the cyclone by tangential direction. The injector is also used as suction pumps to suck the air for gasification process. Char is separated and collected on a square dust bunker located at the bottom of the gasifier. The producer gas leaves through the top outlet of the cyclone, which is connected to the secondary combustor. The cyclone gasifier unit is made of temperature-resistant stainless steel with a volume of 0.046 m^3. There are two tangential inlets with circular cross-section.

Fredriksson (1999) discussed the experimental and theoretical studies of cyclone gasifier. The experiments were carried out with commercial Swedish wood powder as a biomass fuel where the producer gas was used as a gas fuel for gas turbine operation. The cyclone gasifier developed by Kjellstrom had been used with some modifications on cyclone geometry to improve the performance of the cyclone. However, the modifications that were made affected only the gas temperature but did not seem to change the gas composition. It was found that the temperature at cyclone outlet increased slowly to about 820^oC with increasing equivalence ratio. The calorific value of producer gas was about 4.4 MJ/m^3 with H_2 concentration of 8%.

Gabra et al. (2001a) discussed the performance of a cyclone gasifier for gasification of sugarcane residue (bagasse). In this study, cyclone gasifier was tested using crushed bagasse and ground bagasse pellets, while the injection medium used is steam. The crushed bagasse were palletized and then grounded to improve the characteristics of the fuel and to eliminate the feeding problems. The moisture content of the tested fuel is 5.90 (wt %).

Gabra et al. (2001b) also have studied the performance of a cyclone gasifier using sugar cane trash in the same cyclone gasifier for operation of gas turbine. In this study, air is used as an injection medium. The gasification tests were made with two feeding rates, 39 kg/h and 46 kg/h at two equivalence ratios of 0.25 and 0.20 and the gas temperature is in range between 820^{o}C to 850^{o}C. It was found that the heating value of the producer gas is in the range of 4.5 – 4.8 MJ/m^3.

Gabra et al. (2001c) also discussed the comparison of alkali separation using bagasse in a fluidized bed and cyclone gasifiers. The baggase were palletized and then grounded to improve the characteristics and eliminate the feeding problem, and the bulk density therefore increased from 128 to 485 kg/m^3. In the cyclone gasifier, the fuel injection was started when the gas temperature reached 850^{o}C. The fuel feed rate was fixed to 39 kg/h, while the air flow was adjusted to vary the equivalence ratio. The equivalence ratio for stable operation of the cyclone gasifier is in the range of 0.25 to 0.21. The system reached stable conditions and run smoothly after 15 minutes of fuel injection.

2.1.2 Inverted Cyclone Gasifier

Syred et al. (2004) designed an inverted cyclone gasifier to gasify pulverized biomass as shown in Figure 2.2. The main system consists of fuel feeding system, ignition system, cyclone gasifier unit and residual bin. An inverted cyclone gasifier was developed to enable larger sizes of fuel particles to be used with size distribution extending from 2 to 3 mm. The gasifier was designed with a vortex collector pocket (VCP) and central collector pocket (CCP). The purpose of VCP and CCP are to promote particle and ash separation from the flow. Two VCPs were used and placed at different locations, at the top and at the exit sections while CCP was located at ash bin section. The fuel feeding system consists of a screw feeder and venturi tube while the ignition system applied premixing of natural gas and air from fan located at the inlet.

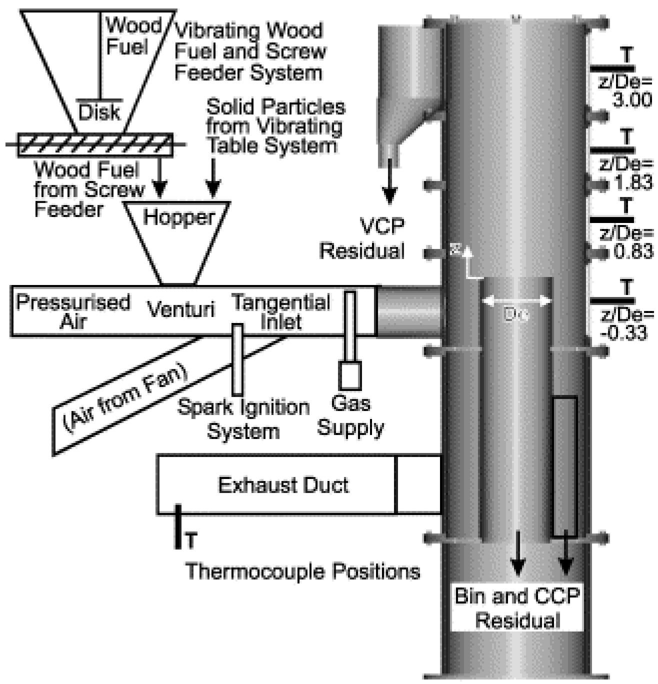

Figure 2.2: Inverted Cyclone Gasifier
Resources: Syred et al., 2004

In the study, the inverted cyclone gasifier was coupled to a cyclone combustor in series for small gas turbine application. The experimental studies were carried out on Commercial Austrian sawdust (Fuel A) and Commercial Swedish wood powder (Fuel S) with the size distribution between 0.063 and 3 mm. The inverted cyclone gasifier developed is suitable for gasifying biomass under a range of conditions with varying equivalence ratio between 0.19 and 0.24. Table 2.1 shows the gasification conditions investigated.

They stated that, the exhaust gas temperature increased from 850^{oC} to 1250^{o}C when the air flow rate was increased from 550 to 880 liter/min, however exhaust gas temperatures above 1000^{o}C do not represent realistic gasification condition, regardless of the mixture ratio. The highest composition of the producer gas was achieved with test 4 which was 9% H_2, 18% CO and 3% CH_4. A good quality producer gas was produced with maximum calorific value of 5.91 MJ/m^3.

Table 2.1: Gasification Conditions

Test No.	**1**	**2**	**3**	**4**
Fuel type	Fuel A	Fuel A	Fuel S	Fuel S
Total air flow rate (l/min)	550	660	550	660
Wood fuel feed rate (kg/h)	26	37	26	40
Equivalence ratio	0.243	0.205	0.243	0.190

Resources: Syred et al., 2004

2.2 Remarks on Literature Review

As a result, from the literature review discussed above, the different areas that will be covered in this study are as follows:

I. Cyclone Gasifier Design

The design and development of cyclone gasifier is based on work by Fredriksson (1999) with some modifications on cyclone geometry, fuel feeding system and injection system. The cyclone use in the design is a common returned flow type cyclone separator with one tangential inlet. This type of cyclone separator has been studied and developed for many years and has been proven to work to separate the particles from the air flow. In addition, the sawdust chosen as the source of the biomass fuel for this study does not require complex inverted cyclone design.

II. Biomass Fuel

Sawdust as a waste from local furniture industries was used in the study as a biomass fuel to characterize the cyclone gasifier with different size distribution.

III. Heat up process

The heat up process was varied using different types of burner which is commercialize diesel burner and LPG burner.

IV. Practical Operation of Cyclone Gasifier

The different ranges of operating parameters for successful cyclone gasification such as temperature profile and equivalence ratio will be perform.

CHAPTER 3
THEORETICAL STUDY

3.0 Introduction

This theoretical study covers the needed background knowledge to appraise the performance and characteristics of a typical cyclone gasifier, and the areas cover are 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 Gasifier

3.1 Cyclone Gasifier Design and Operation

The cyclone used in the study was the common returned flow type cyclone separator with tangential inlet as shown in Figure 3.1. This type of cyclone has been developed for many decades and a lot of works has been done since 1949 (Syred et al., 2004). The cyclone is used to clean a gas from solid or liquid particles. In addition, the use of cyclones as combustor for solid fuels such as to burn high ash coals was well developed where the works were done as early as 1920 (Syred et al., 2004). However, only a few studies related to cyclone as a gasifier have been reported in the literature (Gabra et al., 1998, Fredriksson, 1999, Gabra et al., 2001a and Syred et al., 2004).

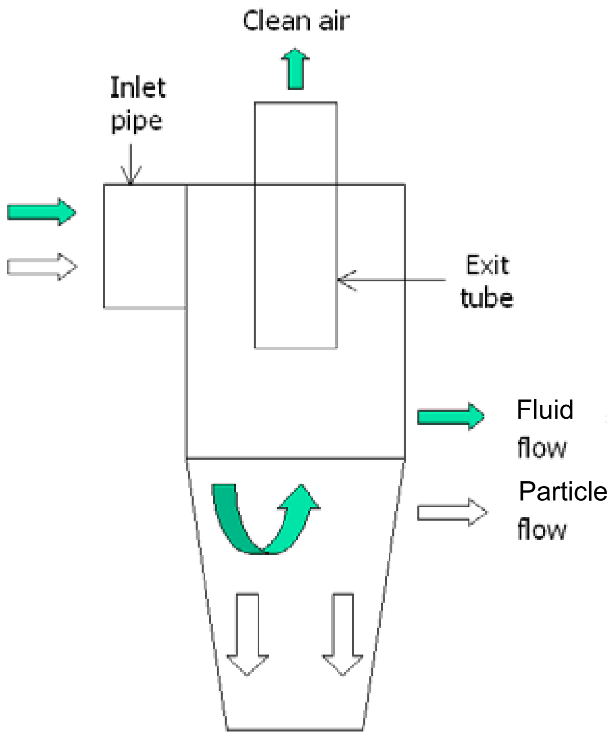

Figure 3.1: Returned Flow Type Cyclone Separator with Tangential Inlet

3.1.1 Particle Separation and Pressure Drop

A cyclone separator was developed to separate the particles from turbulent gas flow via centrifugal force induced by a swirling flow inside the gasifier. The particles entering the cyclone were subjected to two radial forces which were centrifugal force due to the curved path and the drag force due to the radial flow. To ensure that the particles move towards the wall and can be collected in the bin, the centrifugal force must be larger than the drag force. If the drag force is larger than centrifugal force, the particles will escape together with outgoing gas (Shephred and Lapple, 1939).

The pressure drop is an important variable to evaluate the performance of the cyclone. The pressure drop was defined as the different between the mean total pressure at the inlet and outlet. About 80% of pressure drop caused by pressure losses inside the cyclone due to rotational turbulent flow and the remaining 20% are caused by contraction of the fluid flow at the outlet, expansion at the inlet and fluid friction on the cyclone wall surface. There is a pressure drop of 100 to 300 Pa in the cyclone gasifier depending on the geometry of its outlet pipe (Fredriksson, 1999). The desire to minimize the pressure drop is conflicts with the wish to maximize the separation efficiency. The lower the pressure drop, the lower the separation efficiency.

3.1.2 Cyclone Performance at High Temperature

The separation efficiency decreases with an increase in temperature (Bohnet, 1995). Furthermore, pressure drop also decreases with an increase in temperature. When the temperature was increased, the density decreased while the wall friction and viscosity increased thus lowers the pressure drop and separation efficiency. However, the results were based on the conditions where the inlet velocity was constant for all test.

3.1.3 Gasification in Cyclone

Pulverized biomass fuels contained high fraction of volatiles. Therefore, the fuel will be converted to gas immediately upon rapid heating. The volatile gas then reacts with the oxygen presents. Thus, pulverized biomass fuel will behave like a gaseous fuel (Najim et al., 1981). The particles will react immediately at the entrance region of the cyclone. The producer gas with lower density and high temperature moves towards the centre and outlet pipe while the partially burn products and air with higher density and lower temperature move towards the wall thus suspended in the cyclone long enough to be completely burned.

The swirling flow in cyclone gasifier can be characterized by non-isothermal swirl number for swirl burners as follow (Syred and Beer, 1974).

$$S_{gT} = S_g x \frac{T_{inlet}[K]}{T_{outlet}[K]} \tag{3.1}$$

$$S_g = \frac{\pi . D_e . D}{4.a.b} \tag{3.2}$$

From the equation, the swirl number decreases with increasing temperature. A typical swirl number for a cyclone combustor is between 8<S<20. However, if producer gas form cyclone is discharged into open air, the swirl number should be higher than 0.6 (Syred and Beer, 1974).

3.2 Fuel Characterization

The characteristics of the biomass fuel have a significant effect on the performance and key design parameters when selecting the gasifier system. All the gasifier will operate satisfactory within the range of fuel properties which the most important parameters are:

- Particle size distribution
- Ultimate and proximate analysis i.e. moisture content, volatile matter and ash
- Energy content

3.2.1 Particle Size Distribution

The particle size of biomass fuel and the size distribution affects the pressure drop across the gasifier and power output produced from the gasification process. Large pressure drops reduces the particle separation in the cyclone gasifier, resulting in low temperature inside the gasifier chamber. Excessively large sizes of particles reduce reactivity of fuel, causing start-up problem and poor gas quality. Theoretically, the smaller biomass fuel the faster is the gasification reaction. For example fluidized bed gasifiers accept size in the range of 1 mm diameter while fixed bed gasifiers accept in the range of 100 mm diameter. Thus for pulverized biomass fuel, with particle size below 1 mm, cyclone gasifier is introduced which utilizes cyclonic motion concept to suspend the particles for initiating the gasification process occurred in the chamber.

The size distribution of sawdust is a very important parameter because it affects the flow of particles in the downcomer, the injector and in the cyclone chamber. The low bulk density and cohesive characteristics of sawdust can cause accumulation of fuel in the feeding system, creating the difficulties to flow towards the cyclone chamber. The build up amount of sawdust along the flow channel can break off the fuel flow, thus compacted into a solid structure and leads to a blockage in the discharge. Furthermore, the size distributions determine the time required for initiating and maintains gasification process and determine amount of particles carried out of the cyclone gasifier chamber with the producer gas.

3.2.2 Ultimate and Proximate Analysis

Biomass fuels are characterized using the ultimate and proximate analysis. The ultimate analysis gives the composition of the biomass in weight percentage of carbon, hydrogen and oxygen as well as sulfur and nitrogen. This analysis will show the elemental composition differences between sawdust and other biomass fuels. The composition variations among biomass fuels are large, but as a class biomass has substantially more oxygen and less carbon than other fuels. Less obviously, nitrogen, chlorine, and ash vary significantly among biomass fuels. Generally, biomass has relatively low sulfur compared to other fuels.

The proximate analysis gives the moisture, the volatiles, the fixed carbon and the ash contents in the biomass fuel. From the analysis, the quality of biomass fuel for usage in the gasifier is determined. The significance of the volatiles and fixed carbon is that they provide a measure of the ease with which the biomass can be ignited and subsequently gasified or oxidized, depending on how the biomass is to be utilized as an energy source (Mckendry, 2001a). For example, a volatile content of the wood of about 80% is higher compared to a charcoal with volatile content of only 30%. This is good for initiating the combustion in the oxidation zone but too high means creating problems associated with tar formation because the formation of tar is proportional to the volatile content.

3.2.3 Moisture Content

The moisture content of biomass fuel affects the heating value of producer gas. In thermal conversion processes, it is necessary to reduce the moisture content of biomass fuel. High moisture contents contribute to low gas heating value. This is because, dry biomass burns at higher temperature and thermal efficiency than wet biomass. High moisture contents will reduce the thermal efficiency since the heat is used for drying purposes. Besides, flame temperature is directly related to the amount of heat necessary to evaporate the moisture contained in the biomass fuel. The concentration of CO reduces with increase of moisture (reaction between CO and steam) while the concentration of CO_2 increases. In addition, the reaction between carbon and hydrogen will increase the concentration of CH_4.

Moisture content can be determined on a dry basis as well as on a wet basis. Moisture content is defined as:

$$MC_{\text{dry basis}} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \text{x}100\% \qquad (3.3)$$

Alternatively, the moisture content on a wet basis is defined as: