DEVELOPMENT AND CHARACTERIZATION OF BIOMASS GASIFIER-COMBUSTOR SYSTEM FOR HOT AIR PRODUCTION

by

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In the name of Allah, the most beneficent, the most merciful

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LIST OF SYMBOLS

		Units
a	Igniting time of the bomb calorimeter	Minute
A	Surface area	m^2
Acs	Cross flow area (pressure drop calculations)	m^2
Ai	Air inlet area (pressure drop calculations)	m^2
Ap	Area of the pipes inlet or outlet (pressure drop calculations)	m^2
Aw	Window area (pressure drop calculations)	m^2
b	Time at 6/10 from maximum temperature (bomb calorimeter)	Minute
c	Time to reach the maximum temperature (bomb calorimeter)	Minute
C	Heat capacity rate	W/K
C*	Heat capacity ratio	_
Cv_{pg}	Heating value of the producer gas	J/kg
Cv_{wood}	Energy content for wood	J/kg
Cp	Specific heat capacity	J/kg.K
di	Pipe inner diameter	m
do	Pipe external diameter	m
Dh	Hydraulic diameter	m
e	Surface roughness magnitude	mm
F	Correction factor (MTD design method)	_
f	Friction factor (pressure drop calculations)	_
GMW	Gram molecular weight of the pollutant	gram

Gt	Mass flow rate per unit area	$kg/m^2.s$
h	Enthalpy	J/kg
h_s	Heat transfer coefficient for the tube side	$W/m^2.K$
h_t	Heat transfer coefficient for the shell side	$W/m^2.K$
Ka	Thermal conductivity of the air	W/m.K
k_c	Compression pressure drop factor in the pipe bank inlet (pressure drop calculations)	_
k_e	Expantion pressure drop factor in the pipe bank outlet (pressure drop calculations)	_
Kg	Thermal conductivity of the combustion gases	W/m.K
Kw	Thermal conductivity of the pipe wall	W/m.K
L	Total length of the heat exchanger	m
$\dot{m}$	Mass flow rate	kg/s
$\dot{m}_a$	Air mass flow rate	kg/s
$\dot{m}_{ca}$	Air mass flow rate for combustion	kg/s
$\dot{m}_{cg}$	Mass flow rate of the combustion gases	kg/s
$\dot{m}_{output}$	Output air mass flow rate	kg/s
$\dot{m}_{pg}$	Producer gas mass flow rate	kg/s
$\dot{m}_W$	Wood fuel mass flow rate	kg/s
Mp	Measured weight of the pollutant	mg
Ncs	Number of pipes in the cross area (pressure drop calculations)	_
Np	Number of pipes for one pass (heat exchanger design)	_
Nt	Total number of pipes (heat exchanger design)	_
Nu	Nusselt number	_
Nw	Number of pipes in the window area (pressure drop calculations)	_
P1	Temperature effectiveness for first fluid (heat exchanger design)	
P	Pressure	bar
P_r	Relative pressure (ideal brayton cycle calculations)	_
Pr	Prandtl number (heat exchanger design)	_
Pt	Distance between two pipes (heat exchanger design)	mm
Q	Power	Watt
R1	Heat capacity rate ratio for first fluid (heat exchanger design)	_
Re	Reynolds Number (heat exchanger design)	_
Rfa	Fouling resistant for air	$m^2.K/W$
Rfg	Fouling resistant for combustion gases	$m^2.K/W$
S	Entropy	J/kg.K

uc	Flow speed in the cross area (pressure drop calculations)	m/s
uw	Flow speed in the window area (pressure drop calculations)	m/s
U	Over all heat transfer coefficient	$W/m^2.K$
ω	Wetted perimeter of the fluid flow passage	m
ρ_{gas}	Combustion gases density (pressure drop calculations)	kg/m^3
ρ_{in}	Air density at the inlet of heat exchanger (pressure drop calculations)	kg/m^3
ρ_m	Air mean density (pressure drop calculations)	kg/m^3
ρ_{out}	Air density at the exit of heat exchanger (pressure drop calculations)	kg/m^3
µa	Viscosity of air inside heat exchanger	Pa.s
µg	Viscosity of combustion gases in the shell side of the heat exchanger	Pa.s
Δpcs	Ideal pressure drop per cross section (pressure drop calculations)	Pa
ΔPs	Pressure drop in the shell side (pressure drop calculations)	Pa
ΔPw	Pressure drop in the window area (pressure drop calculations)	Pa
ΔT	Temperature difference	°C
ΔT_{lm}	Log-mean temperature difference	°C

LIST OF ABBREVIATION

AF	Air Fuel Ratio
BIGGT	Biomass Integrated Gasification/ Gas Turbine Cycle (Direct Firing)
BIGICR	Intercooled/ Recuperated Biomass Integrated Gasification/ Gas Turbine Cycle (Direct Firing)
DFGT	Direct Fired Gas Turbine
EFGT	Externally Fired Gas Turbine
g/Nm^3	Gram of Pollutant per Normal Cubic Meter (Measured at standard Pressure and Temperature)
HE	Heat Exchanger
HHV	High Heating Value
ICEFGT	Intercooled Externally Fired Gas Turbine
kWe	Kilowatt Electrical
kWt	Kilowatt Thermal
LHV	Low Heating Value
LPG	Liquid Petroleum Gas
LMTD	Log-mean Temperature Difference
MC	Moisture Content

MTD	Mean Temperature Difference Design Method
NTU	Number of Transferred Units
ppm	Parts Per Million
rpm	Revolution Per Minute
SS	Stainless Steel

LIST OF APPENDICES

LIST OF PUBLICATIONS & SEMINARS

1. Alattab K. A., Zainal Z. A., 2006. Externally fired turbo charger based gas turbine using biomass fuel. The Sixth Mechanical Engineering Research Colloquium, July 11-13, 2006, Engineering campus, USM, Nibong Tebal, P. Pinang, Malaysia.

2. Alattab K. A., Zainal Z. A., 2006. Externally Fired Gas Turbine for Small Scale Power Unit / Hot Air Production Unit for Drying Processes Using Biomass Fuel. International Conference on Energy and Environment, August 28-29, 2006. University Tenaga Nasional, Kuala Lumpur, Malaysia.

3. Alattab K. A., Zainal Z. A., 2007. Performance of High Temperature Heat Exchanger in Externally Fired Gas Turbine System Using Biomass Gasifier-Combustor with Full Air Recuperation. Submitted on 1st Feb 2007, for review in the biomass & Bioenergy journal, Elsevier Science Limited.

PEMBANGUNAN DAN PENCIRIAN SISTEM PENGGAS-PEMBAKAR BIOJISIM UNTUK PENJANAAN UDARA PANAS

ABSTRAK

Bahan api merupakan subjek utama dalam bidang pengajian, terutamanya untuk tenaga boleh diperbaharui, disebabkan oleh kekurangan bahan api fosil. Biojisim merupakan salah satu tenaga boleh diperbaharui yang penting untuk penjanaan kuasa, terutamanya di Malaysia di mana banyak biojisim boleh didapati dan ia berpotensi yang besar untuk digunakan sebagai bahan api. Pengeringan merupakan salah satu proses yang penting di dalam kebanyakan sektor industri yang Menghadapi satu masalah untuk mendapatkan bekalan tenaga haba yang bersih dan murah. Cara yang biasa digunakan ialah pengering eletrikal dan stim. Untuk penjanaan kuasa elektrik, penggas alir bebas bawah atau lapisan terbendalir dengan enjin diesel atau enjin gas salingan telah menunjukkan keputusan yang menggalakkan, tetapi kos untuk sistem pembersihan adalah tinggi. Dengan pembakaran terus biojisim, tiada sistem tambahan diperlukan. Tenaga haba dari pembakaran juga boleh digunakan untuk penjanaan kuasa dengan menggunakan turbin gas pembakaran luar atau sebagai tenaga haba untuk proses pengeringan industri.

Pengkajian ini merupakan pembangunan dan pencirian sistem penjanaan udara panas skala kecil dengan biojisim, menggunakan turbin gas pembakaran luar berdasarkan sebuah “turbocharger” dan penghembus udara. Sebuah pembakar penggas telah digunakan untuk menukar sisa kayu perabot kepada tenaga haba. Tenaga haba ini kemudian dipindah kepada udara bersih sebagai produk sistem melalui penukar haba keluli.

Satu sistem turbin gas pembakaran luar telah direkabentuk, difabrikasi dan digunakan. Operasi turbin gas pembakaran luar tidak berjaya disebabkan oleh

kegagalan semasa proses permulaan. Tekanan udara maksimum di dalam penukar haba lebih kurang 0.65bar dan suhu salur masuk turbin maksimum adalah 693°C. Kecekapan penukar haba adalah lebih kurang 60.8%. Kemudian sistem pengeluaran udara panas telah dicirikan tanpa enjin turbocharger. Tenaga pengeluaran udara panas, suhu dan kadar aliran masing-masing berada dalam nilai 11.8 -13kWt, 400-500°C dan 0.02-0.03kg/s. Pengeluaran CO adalah kurang dengan nilai 0-164.22 mg/Nm^3. Pengeluaran NOx maksimum adalah lebih kurang 220.34 mg/Nm^3. Kecekapan penukar haba adalah 70% dan kecekapan keseluruhan sistem adalah 18%.

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ABSTRACT

Alternative fuels have been considered as a priority in the research field, especially for the renewable energy, due to the issue of fossil fuel depletion. Biomass is an important type of renewable energy fuel sources for thermal or electrical power production, especially in Malaysia since it has a large potential of the biomass fuel sources. As for the thermal power, one of the most important applications in the industry sector is the drying process. However, the big challenge is to get a cheap and clean heat source, knowing that the most used methods are electrical heaters or steam-based dryers. As for the electrical power generation, downdraft or fluidized bed gasifiers with diesel or gas reciprocating engines have shown a promising success but with high cost additional cleaning systems. However, by the direct combustion of the producer gas, no additional systems are required. Moreover, the combustion thermal power can be used for power generation using the externally fired gas turbine system (EFGT) or as a thermal power for any industrial drying process.

This research is to develop and characterize a small scale biomass hot air production system using biomass fuels, by employing a turbocharger-based EFGT method, and by using air blowers instead of the turbocharger engine. A gasifier-combustor has been used to convert off cut furniture wood into thermal power. Thereafter, the heat is transferred to a clean air as the system product, through a stainless steel heat exchanger.

An EFGT system with turbocharger was designed, fabricated and operated. However, the operation of the EFGT was not achieved due to the startup failure. The maximum air pressure inside the heat exchanger was about 0.65bar and the maximum

turbine inlet temperature was 693ºC. The heat exchanger effectiveness was about 60.8%. The hot air production system was then characterized without the turbocharger engine. The output hot air power, temperature and flow rate were in the range of 11.8 - 13 kWt, 400 - 560 ºC and 0.02 -0.03 kg/s respectively, with low CO emission of 0-164.22 mg/Nm^3. The maximum NOx emission was about 220.34 mg/Nm^3. The heat exchanger effectiveness was 70% and the overall efficiency of the system was 18%.

CHAPTER 1

INTRODUCTION

1.0 Background

In the last 20 years, the concern about the issue of fossil fuel depletion has led to more studies in alternative energy like renewable and nuclear energy. Biomass is an important type of renewable energy fuel sources for electrical or thermal power production. Biomass fuel refers to any organic substance from plant materials or animal wastes used as fuels. Biomass includes for example, agricultural residues, urban wastes even sewage sludge waste.

Biomass is a very promising source of renewable energy in Malaysia and at present, the oil palm waste is the most abundant waste in Malaysia. In general, the total technical potential of biomass is about 5% of the national energy requirement as reported in Economic Planning Unit, 1999 (Poh, Kong, 2002).

There are three methods to convert biomass material into a useful form of energy. The methods are the direct combustion, the biological conversion and the thermochemical conversion (Zainal, 1996). In this study, the main concern is on the thermochemical biomass converting method. In this method, two processes are used for the biomass conversion. The processes are:

I. Pyrolysis, which can be defined as the thermochemical reaction or decomposition of biomass material in the absence of air to produce combustible materials such as char, gas and oil. The product mix depends on the temperature and heating rate of the process. The temperature should be more than 200°C to start the process (Zainal, 1996).

II. Gasification, that is similar to pyrolysis except that the process occurs in limited presence of air with a higher temperature levels. The output product is a low heating value gas fuel known as producer gas or syngas (Zainal, 1996).

1.1 Thermal and Power Output

Biomass gasification is the thermochemical conversion of biomass fuels into combustible gaseous products. These products are used for thermal applications, Electrical generation or combined thermal and electrical power outputs (cogeneration). For thermal applications, the drying process is one of the biggest challenges for many industries to get a cheap and clean heat source, for example, timber drying and food processing. There are more than 9000 food processing factories in Malaysia as reported in the Ministry of International Trade and Industry 1993 (GSFTRS, 1995), and most of these industries are using the drying process as an important part of their process.

Mostly, the drying processes are using electrical heaters or steam based drying, the latter is more popular for drying because it is cheaper than the electrical heaters especially if the boilers are using biomass fuels. However, the steam based drying systems are complicated and require more maintenance.

For small scale electrical power applications in the range of 20-400kWe, downdraft and fluidized bed gasifiers with diesel or gas reciprocating engines have shown a promising success, especially for rural areas where fossil fuels are not available. However, the main problem with these systems is the cost of maintenance. Since the reciprocating engines are sensitive to the amount of tar, temperature and humidity in the producer gas, additional cleaning, cooling and drying systems are required after the gasifiers. Further more, the engines working life becomes shorter, and for the rural places with the difficulties of giving the villagers a significant training to perform all the operation and maintenance duties in a correct way, so the system could fail due to poor maintenance.

Another option for power generation is to use gas turbine engines. However, for the direct firing of the turbine, an intensive cleaning of the producer gas is required before compressing and injecting the gas into the combustion chamber to reduce the turbine fouling problem. The main concerns in the recent studies are to reduce the cost of the producer gas cleaning process and to develop the technology of the low quality gas combustion.

1.2 Externally Fired Gas Turbine System (EFGT)

The externally or indirectly firing of the gas turbine means that the combustion chamber is not directly connected to the gas turbine. Therefore, the combustion exhausted gases are not in direct contact with the turbine's impeller. The combustion process is heating up a compressed fluid (commonly air) using a high temperature heat exchanger, then the fluid is expanded in the turbine producing a high speed shaft power.

The indirectly and directly fired gas turbine, both are similar in concept and explained thermodynamically by the Brayton cycle. The indirectly fired open Brayton cycle is shown in the temperature-entropy (T-S) diagram (figure 1.1). The working fluid is drawn by the compressor (point 1), compressed (point 2), passed through a heat exchanger for heating up (point 3), expands through the turbine (point 4), and either discharged directly to the environment or returned back to the compressor after cooling process. The combustion process (a) to (b) is assumed to be under a constant pressure.

Thermal power (Q) is transferred to the working fluid by the heat exchanger in process (2) to (3). The isentropic processes (1 to 2 and 3 to 4) are presenting the ideal compressor-turbine operation.

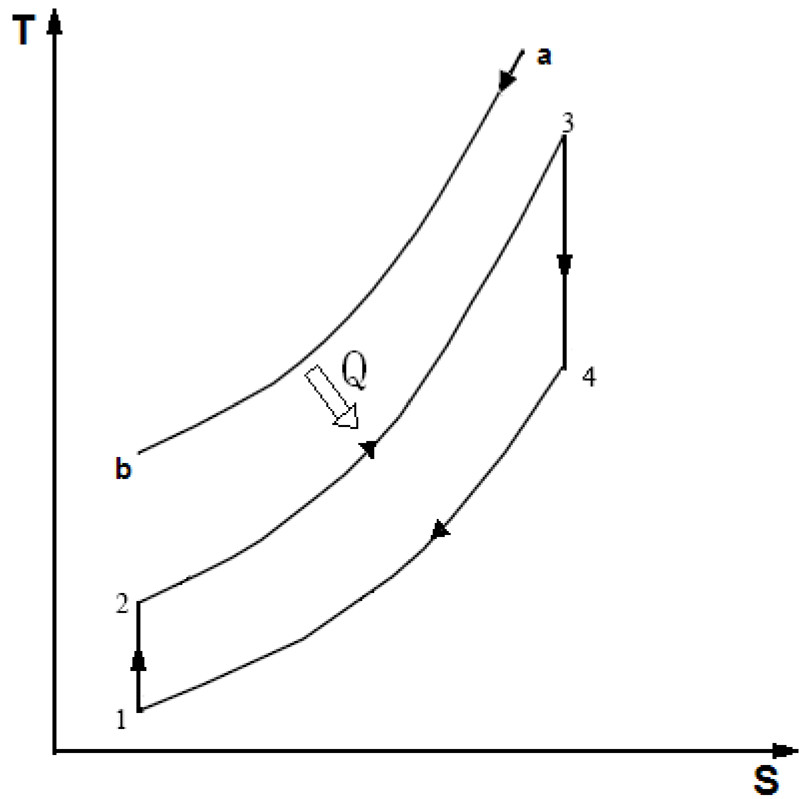

Figure 1.1: Temperature-Entropy Chart for the Externally Fired Open Brayton Cycle

The idea of the externally firing of the gas turbine is not a new idea. During the 1930’s to 1960’s, clean fuels like natural gas and oil were not available with low prices for the electrical power generation. Therefore, the dirty fuels like coal were directly burned in furnaces to produce a high temperature thermal power for super heated steam power plants or indirectly fired gas turbine. Lately, as the prices of the clean fossil fuels are rising continuously with continuous decreasing in the fossil fuels reserve, the world started to study the alternative fuels other than the conventional power sources. Most of the energy researches are focused on developing renewable energy technologies including the biomass fuel sources. In the United States in the mid-1979's, the development of the externally fired gas turbines was initiated. Also in different places like Brasilia and Western Europe, the interest in the externally fired gas turbine technology increased lately (Anheden, 2000).

The externally fired gas turbine (EFGT) has the advantage of freedom in choosing the fuel source either liquid, gas or even solid type. This advantage is also available in the Rankine steam cycle, but it has a lower thermodynamic efficiency comparing with the Brayton cycle which has a higher turbine inlet temperature with a lower pressure, comparing with steam temperature and pressure in the Rankine cycle.

The direct fired gas turbine (DFGT) has a higher thermodynamic efficiency comparing with the (EFGT) because of the higher turbine inlet temperature. However, it can only deal with the clean liquid or gas fuels along with the fuel compression and injection equipments that are not required in the (EFGT). The (DFGT) can use solid fuels after gasification process only after an intensive cleaning process for the producer gas.

The externally fired gas turbine cycle can be divided in to two types:

I. The open cycle externally fired gas turbine.
II. The close cycle externally fired gas turbine.

In the open cycle, the working fluid is discharged to the environment after a cooling process, or in case of air, it can be supplied to the combustion chamber as a heat and oxygen source. In the closed cycle, the working fluid is returned back to the compressor after a cooling process. A few important advantages of using externally fired gas turbine cycle can be summarized as following:

- This cycle has an ability to deal with a very wide range of the fuel options, it can use clean fossil fuels or even the dirty type of fuels like coal and different types of biomass including the combustible waste or treating the municipal solid waste. "Nuclear heat source like fission reactors and radioisotopes have also been investigated (Anheden, 2000)."

- Since the combustion process in this cycle is to heat up the working fluid of the turbine, the combustion is taking place in atmospheric pressure, and it is more like a furnace which eliminates the fuel compression and injection equipments. This simplifies the system and reduce the manufacturing and operating costs.

- For the open cycle, the working fluid of the turbine is mostly pure air, so the fouling or the eroding of compressor or turbine blades are minimized. Also, the heat exchanger is less sensitive than the blades of compressor or turbine and for good design of the combustion chamber and heat exchanger the problems of blocking, fouling or eroding could be minimized. Therefore, long life can be expected for the system.

- The changing between the fuel types is much easier comparing with the direct fired gas turbine which needs a major modification in order to change the fuel type. It is also less sensitive to the changes in the fuel quality.

There are some additional advantages for the closed cycle of the externally fired gas turbine cycle, it has been discussed amply in many references (Anheden, 2000), and here are some of the advantages:

- The working fluid is circulated in a close cycle. Therefore, it is possible to use a different type of fluids (other than air) which have a good heat transfer characteristics. “Gases such as nitrogen, carbon dioxide, helium, argon, krypton, xenon and various gas mixtures were suggested as suitable working fluids (Anheden, 2000)”.

- In some application where the environment has a little amount of air or no air at all like the submarine or in space applications, the closed cycle with different type of fluids (other than air) can be used with a different type of heat sources.

- In some application where the working fluid might be polluted or contaminated and should not be discharged to the environment, for example when the working fluid is used as a primary coolant for a nuclear reactor and might be contaminated with radioactive materials, the closed cycle is suitable.

For the EFGT system with electrical generation unit, using biomass fuel, no additional systems are required after the gasifier, since the heat exchanger has less sensitivity to the effects of the producer gas comparing with the reciprocating engines, and most of the producer gas is burned totally before reaching the heat exchanger.

The concept of the externally fired gas turbine (EFGT) using biomass fuel has been presented. Most of the recent projects in this field are focusing on the development of these systems for thermal, power or combined thermal and power applications, and requires extensive research until these systems will have enough reliability to be commercialized.

1.3 Objectives of the Study

1. The objective of this study is to investigate the (EFGT) concept with biomass fuels using a gasifier-combustor system with a truck turbocharger as a micro gas turbine for power and hot air production.
2. The study also aims at producing hot air without the gas turbine system.

1.4 Scopes and limitations of the Study

1. Design of the high temperature heat exchanger for hot air production using biomass fuels.
2. Fabrication and modification of the available gasification unit to be compatible with the system.
3. The investigation on the EFGT concept is using a truck turbocharger with no electrical generation unit.
4. Characterizing the system is based on experimental work.
5. Biomass fuel is limited to off cut furniture rubber wood from local furniture industries.
6. Flow rate and moisture content of the flue gases were not available for mass balance calculations.

1.5 Overview of the Study

There are many studies on the (EFGT) concept, especially with biomass as a fuel, and also the biomass combustors or stoves for hot air production. Some of these studies are presented in chapter 2. In chapter 3, the different theories of the biomass gasification energy systems are discussed under the light of other researches, to get the wise choices in different issues and the right start for the research.

Chapter 4 includes the methodology of the research, the system layout, the design / fabrication of the different parts of the system and the experiment rig. In chapter 5, the results of all experiments including the turbocharger startup trials and the system characterization with and without the turbocharger are summarized. More results are discussed under the temperature profile analysis. The final part of the chapter includes the system performance discussion and the different factors affecting the performance.

Conclusion of the study is presented in chapter 6. This chapter also includes different recommendations for further development of the system.

CHAPTER 2

LITERATURE SURVEY

2.0 Introduction

In this chapter, some of the studies on the EFGT using biomass as a fuel are presented, as well as the biomass combustors or stoves researches (without turbines) for hot air production.

2.1 Literatures Reviewed

1. A thermodynamic economic study using EFGT turbocharger based system with biomass fuels was published under the title: A concept for biomass fuelled gas turbine based on turbocharger technology (Tariq et al., 1995).Three cycles were studied:

I. One stage turbocharger open cycle. Part of the air after turbine was returned back to combustor, and the other part was released as output thermal power.
II. Two stage turbocharger with intercooler, and the rest is like the first cycle.
III. Two stage turbocharger closed cycle with intercooler and external air blower to supply air for the combustor with air preheater.

In the cycles, part of air after turbine was released out of the system in order to reduce the combustion below 1150ºC to avoid ash softening and that reduces the heat exchanger fouling and eroding. The turbine inlet temperature was low of about 750ºC. The electrical production net efficiency was about 18.3%, 20.1% and 18.1% for the three cycles respectively.

2. A project summary was published by The Forestry Research Program under the title: Indirectly fired gas turbine application to biomass fueled furnaces: a design comparison with traditional steam power (Hollingdale, 1995). The system is a combined heat and power generation for the rural places. The waste wood byproducts from the processing of forest products have been studied as fuel. The published paper showed that the system has been approved for funding to develop a low cost 200 kWe output system turbo charger based with an efficiency of 20-25%. It would be competitive with the systems based on gasifier/ internal combustion engines. Also at this scale it would be markedly superior to the systems based on steam, both technically and economically.

3. A renewable energy proposal to the joint solicitation offered by the USDA & DOE was presented (NRCS, 2003). The title of the study was: Biomass fueled micro turbine for combined heat and power. The system layout is shown in figure 2.1.

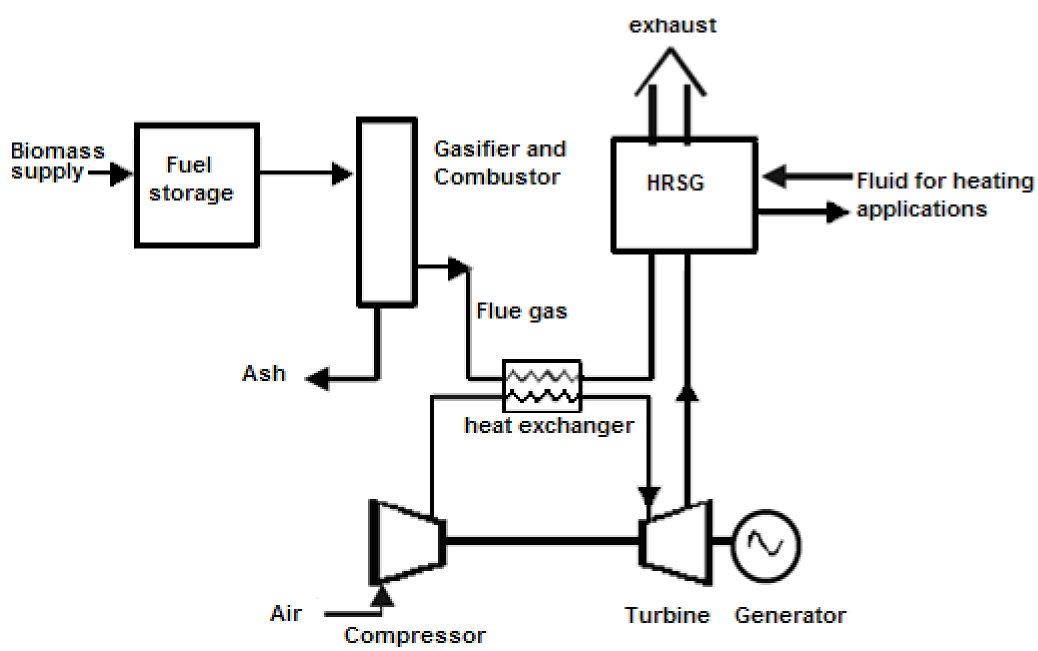

Figure 2.1: Diagram of Biomass Fueled Micro Turbine Cogeneration (NRCS, 2003)

The parts of the system were proposed to be manufactured by different manufacturers. A wood gasifier of 586 kWe was used. The gas out of the gas-producing chamber burns in a nozzle to a heat exchanger at a very high temperature. The gasifier used induced draft fan, primary and secondary fans with different control systems. The wood size was about 2½" with wide range of moisture content (8% - 55%). The heat exchanger was expected to achieve effectiveness of about 84%. A (C-30) micro gas turbine with high speed generator of 30 kWe output power was used in this project.

4. Another paper was published under the title: Open-cycle indirectly fired gas turbine for wet biomass fuels (Elmergaard et al., 2001). The main idea was to increase the efficiency of the externally fired gas turbine by pre drying the biomass before the gasifier. The results showed that the cycle can reach an efficiency of about 30.8% at a pressure ratio of 3.5, comparing with the efficiency of the simple cycle of about 24.6%. The system layout is shown in figure 2.2:

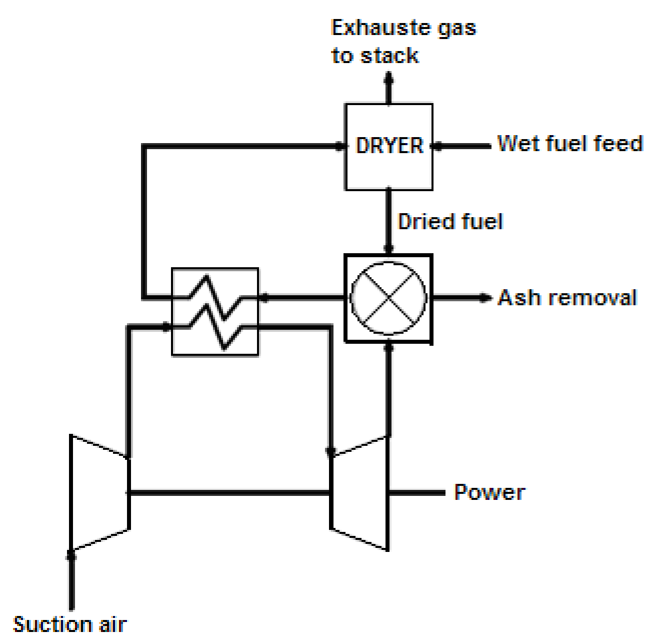

Figure 2.2: Open-Cycle Indirectly Fired Gas Turbine for Wet Biomass Fuels

The study also showed that the system can handle wet biomass feeding with water content up to 80%.

5. A similar research like the previous one was published under the title: Performance evaluation of small size externally fired gas turbine (EFGT) power plants integrated with direct biomass dryers (Daniele et al., 2005). The study was carried out using a parametric analysis of the EFGT system performance. Inlet temperatures of 800ºC, 1000ºC and 1200ºC have been studied. The study has used (T100) microturbine of 100 kWe, 0.75kg/s compressor air flow rate and 3-4 pressure ratios. A direct rotary dryer (RD) has been studied for continuous drying process for a 50% water content biomass fuels. The study showed that the efficiency of the system can rise up from about 22% to 33% using the drying process. Also, the rotary dryer was able to dry about 3.5 to 4 times more than the system uses. This allowed a flexible operation for any additional heat power demands and/or other external biomass uses. The system layout is shown in figure 2.3.

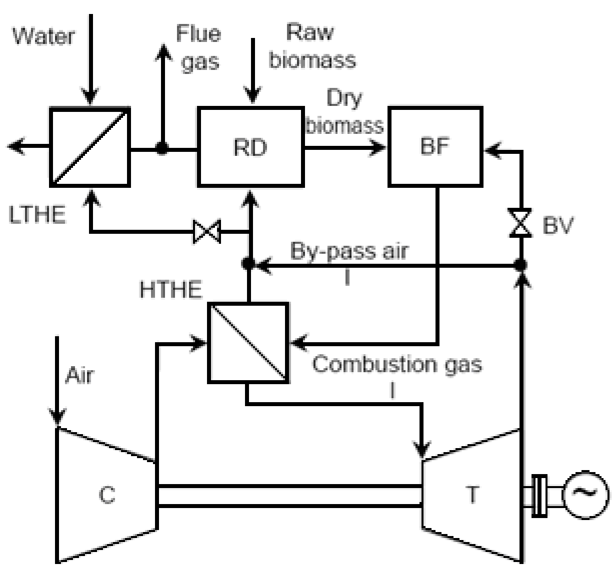

Figure 2.3: EFGT Power Plant Integrated with a Biomass Rotary Dryer

6. A paper was published under the title: Optimization of a wood-waste-fuelled, indirectly fired gas turbine cogeneration plant (Evans, Zaradic, 1996). The study used linear programming to examine the overall economic viability of the EFGT cogeneration system. The outputs of the system were electrical generation and heat production for lumber drying using wood-waste fuel from saw milling process. Three models have been used for the study:

a. Using a wood-waste combustor with metallic heat exchanger. The results showed that the turbine inlet temperature was 650ºC. Therefore, an auxiliary natural gas burner was used to bring the turbine inlet temperature up to the maximum level of 1130ºC.

b. Using a ceramic heat exchanger instead of the metallic one without the natural gas burner.

c. Using an atmospheric pressure fluidized bed type of wood-waste combustor with heat exchanger tubes immersed in the bed. The auxiliary natural gas burner was also used.

The results showed that the first model has represented the least degree of technical risk and shortest payback time for the cases with high levels of process heat demand. Second model represented the highest level of technical risk and appears to be not economical. The payback time was long because of the very high cost of the ceramic heat exchanger. Third model seemed to be economical for all considered cases with the shortest payback time for the cases with the lower levels of process heat demands. The payback time varied between 7 to 18 years.

7. A paper was published under the title: Cogeneration from poultry industry wastes: indirectly fired gas turbine application (Bianchi et al., 2005). The main goal of the study was to find out the best economical and environmental options to utilize the organic wastes from the poultry industry as fuel. Two power plant designs have been compared: the EFGT and the steam turbine plants, with a heat recovering systems for the poultry industrial processing.

The study used a thermodynamic simulation to evaluate the performance of the plants. The fuel contained a moisture content of 70-73%. The fuel has to be processed before the biomass combustor using the cooker (CK), hydrolyser (HY), Feather dryer (FD) where steam from the steam generators SG1&SG2 were used (see figure 2.4).

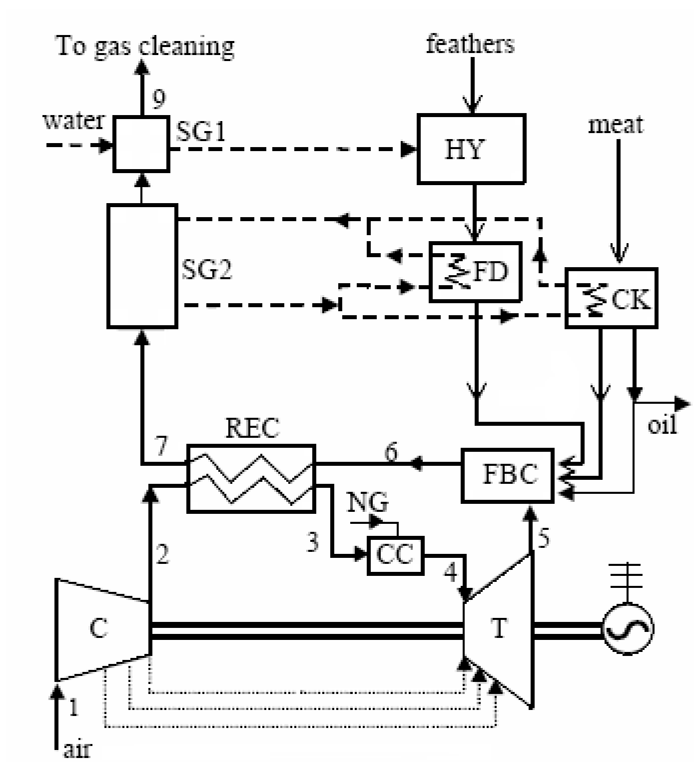

Figure 2.4: Schematic Lay-Out of EFGT for Poultry Industry Wastes

The combustor was a fluidized bed combustor (FBC) with maximum combustion temperature of 800-830ºC. The hot gases were supported with a natural gas combustor after the metallic heat exchanger to raise the turbine inlet temperature up to 1150ºC. Results showed that the EFGT plant presented the best performance even with the natural gas combustor.

8. A study was published under the title: The use of biomass fuels in gas turbine combined cycles: gasification vs. externally fired cycle (Ferreira et al., 2003). In this study, the following gas turbine cycles and their performance at design point were compared:

i. The biomass integrated gasification/ gas turbine cycle (BIGGT), with direct turbine firing.

ii. The externally fired gas turbine (EFGT), with ceramic heat exchanger.

iii. The intercooled externally fired cycle (ICEFGT), with two stage intercooled compression process.

iv. The intercooled/ recuperated integrated gasification/ gas turbine cycle (BIGICR), with two stage intercooled compression process.

The turbine inlet temperature for the directly fired cycles is around 1450K, and 1350K for the indirectly fired cycles. The results shows that the intercooling and recuperating processes increase the thermal efficiency but with high cost and large supply of cooling water for the first one. The ICEFGT cycle is the one with the highest thermal efficiency. In the simple cycle case, the EFGT presented the best performance.

9. A paper was published in EFPE winner theses of 2003 under the title: IFGT for drying and combustion of sewage sludge (Madsen, Sigvardsen, 2003). Many simulation studies have been successfully carried on the externally fired gas turbine with wet biomass fuel, with high theoretical efficiencies. This study continued on the same path but with a troublesome fuel which is the sewage sludge which has a very high water content (94-97%). There were two mathematical models for this investigation:

I. Integration of fluid bed steam-drying and the EFGT.

II. Integration of belt air-drying and the EFGT.

First, the raw sludge entered the digester for partial digesting. Biogases, CO_2 and CH_4 were collected. CH_4 was compressed and then directly combusted and passed to the turbine after the heat exchanger. The sludge should be mechanically dried by the decanter centrifuge, and then thermally dried by either a fluid bed steam-dryer or a belt air dryer, before the combustion. The air-belt dryer presented the higher efficiency. In general, this plant offers a preferably economical and environmental option comparing with the current sewage sludge treatment plants.

10. A paper under the title: Indirectly fired gas turbine (IFGT) for rural electricity production from biomass (Harie, 1995) used a marine turbocharger of about 3.5 pressure ratio as a micro turbine engine. The turbocharger was coupled to a high speed generator for electrical power generation. The required heat transfer area for the gas-to-air heat exchanger was large due to the low overall heat transfer coefficient. One-pass shell and tube heat exchanger with 385 tubes of 8.4 meters were required for a 242.5 kW electrical power output. The external tube diameter and the wall thickness were 31.8 mm and 2.5 mm respectively. In order to choose the suitable materials for the high temperature heat exchanger, a detailed review has been done on different materials to study the critical aspects of material fouling and corrosion when it is exposed to flue-gas from biomass based power plants. A quantitative relationship has been determined to describe the condensation of alkali salts on the tubes of heat exchanger. Five materials were exposed to biomass flue gases under maximum temperatures. SS-310 has been selected for further examination and based on the observed corrosion, the estimated metal loss after 15 years would be about one mm.

11. Another paper was published in 2002 under the title: Biomass combustion gas turbine chp (Pritchard, 2002). TG50 (50KWe) single shaft micro gas turbine was modified to be suitable for the system. The combustion chamber was totally removed and modifications were made to compressor and turbine housings along with extensive software changes. Waste heat from turbine exhaust was totally recuperated back to combustion air streams, and the fuel piping system was removed.

The micro gas turbine was not able to start with the normal speed of the startup motor/generator which was about 32,000 rpm. The turbine was able to start only after increasing the speed of the motor/generator up to 44,000 rpm.

The heat exchanger was a shell-tube type with stainless steel tubes. The air in the shell side passes across the vertically placed tubes and the hot flue gases were in the tube side with two passes. The primary air fans provided a vigorous combustion reaction, and the secondary air fans for the complete combustion. The hot gases from the combustion chamber were induced up and down through the tubes of the heat exchanger using a draft fan fixed in the exhaust of the chamber. The high temperature heat exchanger was designed to transfer 150 kW thermal power to the compressed air with about 800°C turbine inlet temperature. The air pressure and flow rate inside the heat exchanger were about 3 bar (pressure gauge) and 0.23 kg/s respectively. After many modifications on the system, a second paper was published under the title:

Biomass fuelled indirect fired micro turbine (Pritchard, 2005). The combustor was completely rebuilt and the heat exchanger was extended using the old one with additional piping with the same geometry. The system overall efficiency was 15%, therefore the commercial and marketing research proposed the 100 kWe as the minimum justifiable size. Figure 2.5 shows the Combustion Chamber and Heat Exchanger of The Talbott's Project.

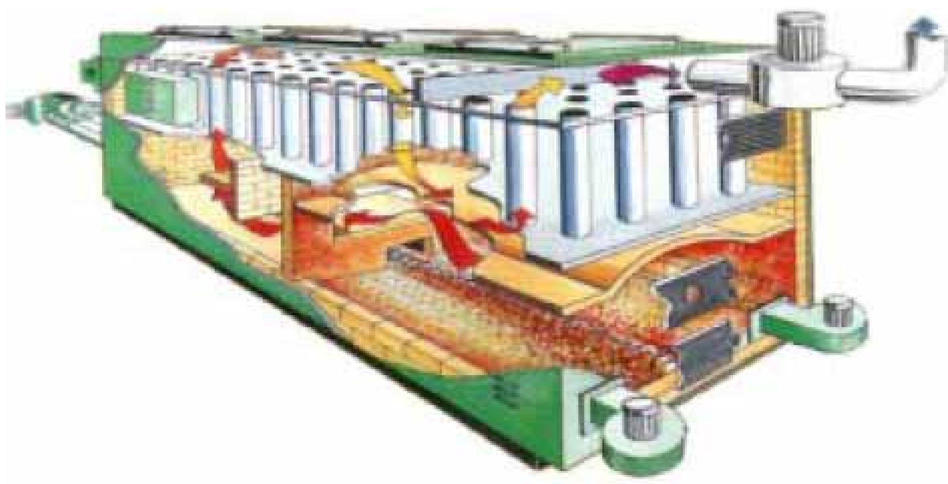

Figure 2.5: The Combustion Chamber and Heat Exchanger of the Talbott's Project

12. For hot air production using a biomass burner without gas turbine system, an experimental study was published (Cooper et al., 1986) under the title: Evaluation of a wood waste burner and heat recovery system – I. Operation, thermal efficiency and particulate emissions. And the second part of the study (Fels et all., 1986): Evaluation of a wood waste burner and heat recovery system – II Economics. And from environmental point of view in (Fels et all., 1989) under the title: An analysis of wood-burning installations from an environmental aspects. A metallic heat exchanger was used to transfer thermal power from the combustion gases to the air flow in the shell side. The hot air was used for kiln- drying lumber with a thermal output of about 300-450 kWt. The overall efficiency was about 53%.

13. With a same concept as the previous study, a PhD. thesis summary (Beedie, 1996) has described the technology of a multi chamber gasifier-combustor for hot air production using a metallic heat exchanger. The main concern was the gasifier control system, in order to maintain a low pollution operation mainly by controlling the primary and secondary air supplies.

2.2 Literature Summary

Most of the studies on the (EFGT) focused on the efficiency of system and how to increase it using combined heat and power systems or steam and gas turbines systems. Also, comparing between different systems either with metallic or ceramic heat exchangers with some minor systems like heat recuperating units, intercoolers or auxiliary natural gas burners. The advantage of the biomass pre drying process using the flue gases thermal power was also studied, and even the organic waste fuels like sewage sludge and poultry wastes with the (EFGT) system have been investigated. However, only few experimental studies were conducted to evaluate the (EFGT) system because of the high cost of manufacturing such a system.

For hot air production using biomass fuels, two methods were presented:

i Using the EFGT system with gas turbines or turbocharger engines as a micro gas turbine.

ii Using furnaces or combustors along with the gasification systems without turbine or turbocharger engines.

For both methods, gas-to-air heat exchanger was used to heat up clean air as a thermal power output for drying process, space heating or any other thermal process. Shell-tube heat exchanger type was the preferred type in all the previewed studies. Theoretically, the air temperature inside the heat exchanger can reach as high as the combustion gases temperature, unlike the steam that has a limited temperature because of the pressure limitations. Most of the studies have discussed the heat exchanger design limitations that involved mainly:

- The materials of the heat exchanger that can withstand the high operation temperature.
- The heat transfer surface area, since the gas-to-air heat exchanger requires a big surface area due to the low heat transfer coefficient.

For the EFGT system, a high turbine inlet temperature after the heat exchanger is required. Therefore, Stainless Steel was the preferred material for the heat exchanger, unlike the system without turbine where an ordinary steel can be used.

CHAPTER 3

BIOMASS GASIFICATION ENERGY SYSTEMS

3.0 Introduction

Biomass gasifiers have been used lately in a wide range for thermal and power applications. This chapter includes a discussion on the gasification system theories. These theories involve:

- Gasifiers.
- Micro gas turbines.
- Heat exchangers.
- Power generation systems.

3.1 Gasifiers

The gasifiers can be classified into:

1. Fixed bed gasifiers.
2. Fluidized bed gasifiers.
3. Suspension gasifiers

In this project, the main concern is on the fixed bed gasifier type. The fixed bed gasifiers can be divided according to the air flow direction into three types: up-draft gasifier, down-draft gasifier, and cross-draft gasifier (see figure 3.1).

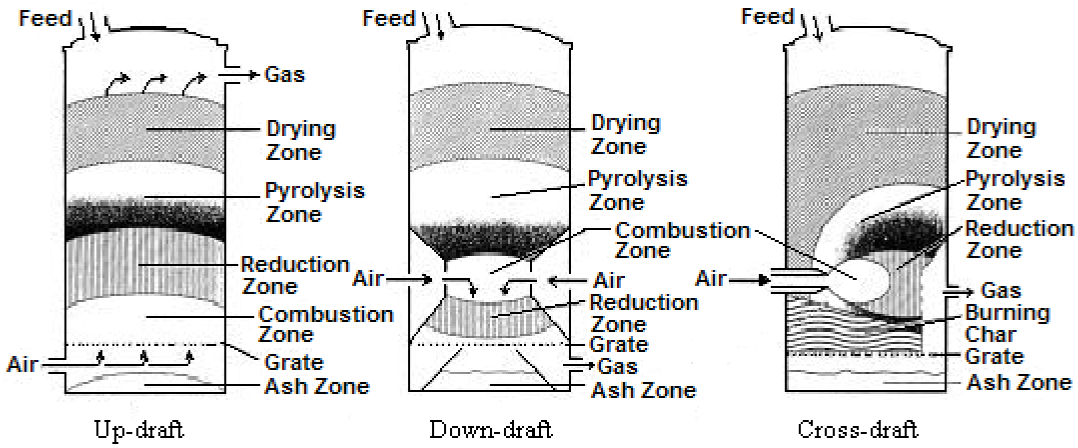

Figure 3.1: Types of Gasifier (DMU, 2001)

Up-draft gasifier is the oldest type in this group. It is very simple in construction and it is not very sensitive to the biomass fuel size. Because of the high working temperatures of this gasifier, it can handle high moisture content up to 50% without any pre-drying process. This makes this type the most popular type in the big thermal applications (<10MWt). However, on the other hand, no gasifier is producing as much tar as this type. This disadvantage makes this type of gasifiers not desirable for electrical power applications using an internal combustion engines. The up-draft gasifier is highly efficient for direct burning of the producer gas after the gasifier for heating or thermal application (Zainal, 1996; Beenackers, Maniatis, 1996).

Down-draft gasifier is the preferred type of gasifiers for the small electrical power plants (up to about1MWe), because it produces the least amount of tar in the fixed bed gasifiers “typically of the order 0.1 % of the biomass material (Zainal, 1996)”.

In the downdraft gasifiers there is a throat in the down side of the conical shape. The fresh air enters the gasifier just above the throat creating a hot combustion zone more than 1000ºC. Since the upside of the down-draft gasifier is sealed, the gases are forced downward through the combustion zone and the throat. Because of the small dimensions of the throat, the hot combustion zone creates a uniform temperature. This gives a good chance of cracking all the tar passing through the throat (Zainal, 1996; Beenackers, Maniatis, 1996).

For bigger size of the down-draft gasifier, the dimensions of the throat will be big to handle the high gas flow rates, therefore cold zones in the sides of the throat start to appear which increases the amount of tar passing through the throat. To cope with this problem an annular throat was invented at Twente University as early as 1979. This was realized by putting a rotating cone in the center of the throat thus allowing for a relatively large throat area which is still narrow enough to guarantee the high temperature required for proper tar cracking everywhere in the throat (see fig.3.2). This concept was applied again in the so-called HTV- juch gasifier (Beenackers, Maniatis, 1996).

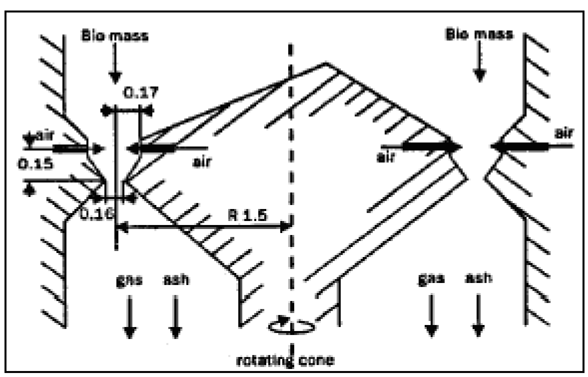

Figure 3.2: Sketch of a 100 t/d Downdraft Gasifier (Groeneveld, Swaaij, 1979)

The down-draft gasifier is the most popular type for the small power plants as mentioned earlier, but it has some disadvantages from the view of flexibility with the biomass fuel. The acceptable biomass feed is the lump or blocks type with a uniform