ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTION OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

MECHANICAL ENGINEERING DEPARTMENT

THERMODYNAMIC MODELLING OF BIOMASS INTEGRATED GASIFICATION COMBINED CYCLE (BIGCC) POWER GENERATION SYSTEM

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A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfilment of the Degree of Masters of Science in Mechanical Engineering (Thermal Engineering stream)

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Thermodynamic Modelling of Biomass Integrated Gasification Combined Cycle (BIGCC) Power Generation System

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Abbreviations

IGCC	Integrated Gasification Combined Cycle
BIGCC	Biomass Integrated Gasification with Combined Cycle
HRSG	Heat Recovery Steam Generator
LPT	Low Pressure Turbine
IPT	Intermediate Pressure Turbine
HPT	High Pressure Turbine
SCC	Supplementary Combustion Chamber
HHT	Higher Heating Value
LHT	Lower Heating Value
HEx	Heat Exchanger
HPST	High Pressure Steam Turbine
LPST	Low Pressure Steam Turbine
CEP	Condensate Extraction Pump
BFP	Boiler Feed Pump
AC	Air Compressor
CC	Main Combustion Chamber
GT	Gas Turbine
ST	Steam Turbine
G	Generator
SC	Supplementary Firing Chamber
ER	Equivalence Ratio
G1	Generator one
G2	Generator two

Nomenclature

C_p	specific heat capacity, J/(kg·K)
E	power output, MW
ΔG^o	Gibbs free energy change, J/mole
$\Delta G^o_{f,T}$	Gibbs standard free energy change at temperature T, J/mole
$\Delta H^o_{f,298}$	heat of formation at 298 K, kJ/mole
B	flow exergy
R	universal gas constant
r_p	gas turbine pressure ratio
r_t	gas turbine temperature ratio
x	mass fraction
K_p	chemical equilibrium constant
m	mass flow, kg/s
H	enthalpy, J/kg
h	specific enthalpy
s	specific entropy
T	temperature
P	pressure
Q	heat transfer
W	work transfer
y	mole fraction

Greek symbols

ε	exergetic efficiency
η	thermal efficiency

Superscripts

ch	chemical exergy
th	thermomechanical exergy

ABSTRACT

An attractive and practicable possibility of biomass utilization for energy production is gasification integrated with a combined cycle. This technology seems to have the possibility to reach high efficiencies based on a fundamentally clean and renewable fuel.

Biomass Integrated Gasification Combined Cycle (BIGCC) systems replace the traditional combustor with a gasifier and gas turbine. Exhaust heat from the gas turbine is used to produce steam for a conventional steam turbine. The gas and steam turbines operate together as a combined cycle.

This paper investigates the ultimate potential for application of Biomass Integrated Gasification Combined Cycle (BIGCC) to biomass based power systems. It describes the elements of the gasification system and the methods to model the components of BIGCC system thermodynamically.

A computer program using MATLAB is used to estimate the syngas composition of the gasification system using a down draft gasifier and wood as input. It predicts the effects of moisture content, temperature, pressure, and air to fuel ratio on syngas composition.

This study also includes the economic importance of Biomass Integrated Gasification Combined Cycle (BIGCC) system over conventional bio-fuelled power plants.

CHAPTER ONE

INTRODUCTION

1.1 Background

Significant concern exists over relatively high cost of electricity for citizens and businesses worldwide, which imposes a financial burden and impairs countries ability to compete effectively. On the other hand, there is a significant cost to protect our environment. A component of that cost is electricity. New environmentally preferred technologies and strategies are needed to produce and deliver electricity at lower cost and decreased environmental impacts. The potential problem is further compounded by a fact that systems reliability and the cost of electricity are adversely affected by existing large inventory of outdated steam power plants. Moreover, it is further amplified by a need for new cost-effective pollution control technologies needed to reduce the health and environmental impacts from power plant emissions. Therefore, a pressing need exists to develop superior, but economical methods to produce electricity while reducing the wood and green waste landfills with the state-of-the-art control emissions of fine particles and vapor-phase aerosols/toxics [1].

Biomass gasifiers have the potential to be up to twice as efficient as using conventional boilers to generate electricity. For even greater efficiency, heat from the gas turbine exhaust can be used to generate additional electricity with a steam cycle. These improvements in efficiency can make environmentally clean biomass energy available at costs more competitive with fossil fuels.

The BIGCC Power Generation Concept offers qualities and characteristics that could not be found in other competing technologies for it:

- is environmentally superior to conventional green biomass fired power plants and can be designed to meet the most stringent regulations;
- surpasses thermal efficiencies of existing conventional technologies;
- could generate power at lower costs.

1.2 Statement of the Problem

A common practice in agricultural, forest, and paper industries is the direct firing of biomass upon a boiler to create processed steam or for power generation purposes via steam turbines. This conventional method is subject to low efficiency and high emissions of NO_X, CO and other pollutants. Typical small steam-boiler power systems have an electric energy conversion efficiency ranging from 20% to 30%. The low efficiency of such a system is caused by the inability of the steam system to effectively use the combustion energy at temperature levels higher than approximately 1700°C. The steam entering the steam turbine is restricted by metallurgical limitations (590°C) imposed by the material used to fabricate the heat exchangers [16]. The temperature difference between the combustion flame temperature and the acceptable steam temperature limits the steam cycle from obtaining higher efficiencies. Another limitation is the high manufacturing cost, which limits the thick and bulky pipes to contain high-pressure / high-temperature steam, which has the nature of achieving very high pressure at relatively low temperatures [15].

A method to resolve the aforementioned challenges is to install a gas turbine between the combustion flame and the steam turbine. The gas temperature entering a gas turbine is also restricted by metallurgical limitations, but without the corrosive nature of steam as in a steam turbine. A modern gas turbine can withstand inlet gas temperatures at approximately 1430 °C. Exhaust exiting from the gas turbine can be utilized to boil and superheat steam via a Heat Recovery Steam Generator (HRSG). Combining the gas turbine and steam turbine systems forms the combined cycle system, which is popularly used by many of the new natural gas fired power plants. Modern combined cycle efficiency ranges from 55 % to 58 %. A higher than 60% efficiency can be achieved by using an Advanced Turbine System [44].

1.3 Research Objectives

The intent of this study is to evaluate the ultimate potential for application of Integrated Gasification Combined Cycle technology to biomass based power systems, to model the components of BIGCC thermodynamically and compare the electrical efficiencies of a conventional bio-fuelled power plant with a BIGCC-plant and to estimate the economic importance of the integrated gasification process.

1.4 Research Methodology

In general, the following approaches were used during the progress of the research work:

- Literature review of key gasification concepts: Background and theory of BIGCC technology - The literature review introduces gasification and presents a rationale for the approach taken to gasification modelling.
- A review of BIGCC process equipment - The introduction to BIGCC process equipment introduces the major equipment items and some of the challenges in using them.

- An introduction and discussion of BIGCC thermodynamic modelling - Gasification modelling is a major part of this thesis and includes creating and testing a model capable of predicting the product gas composition from gasification
- The component material and energy Balance analysis results are used to size and cost major pieces of equipment from which the resulting cost of electricity and plant performance are calculated.
- A computer program by using MATLAB is used to determine the various parameter variations of the gasification system and to analyse and interpret the effects of gasification parameters on syngas composition.
- An introduction and discussion of economic importance of the gasification system.

1.5 Thesis Organization

The thesis is organized into six chapters. The literature review on previous researches on gasification is presented in Chapter 2. The theoretical study of BIGCC is elaborated in Chapter 3. Chapter 4 describes the detail thermodynamic analysis of the plant elements. Results and discussion of the gasifier model and some introduction to plant economics 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 TWO

ENERGY FROM BIOMASS

2.1 Introduction

Biomass is an attractive alternative fuel because it is renewable, sustainable and indigenous. Biomass power plants using the conventional method of power production are subject to high exhaust emissions and low efficiencies. New technologies that are being developed will significantly reduce emissions and increase the energy-conversion efficiency. The technical challenges in the new technologies will need to be overcome to reduce costs, enhance efficiency and improve system reliability, availability and maintainability (RAM) [4].

Biomass energy is based on the capture and the storage of chemical energy by green plants. This process is called photosynthesis and determines the reduction of atmospheric carbon dioxide. The leaves work as collectors and the plant stores the energy in complex compounds, which are rich in carbon. About 50% of the weight of dry wood is carbon [4].

The most interesting source of biomass for energy generation comes from waste correlated to other productions (mainly for human and animal alimentation). The use of this kind of resources assures cheap fuel and does not require dedicated fields for energy production or conversion from food to energy production. Another important resource is the forestry biomass, especially if such areas are actively managed [9].

An advantage of using biomass as energy source is its carbon neutrality. This expression means that if the amount of live biomass is regenerated, the amount of carbon dioxide released to the atmosphere during the combustion of biomass (or of its secondary products) is equal to the amount taken and stored by the plants. Consequently the managed usage of biomass as energy source does not increase the quantity of carbon dioxide in the atmosphere.

2.2. Conversion of Biomass into Energy

There are many approaches to convert biomass into energy; the most important in industry are [4]:

- Direct combustion
- Gasification
- Liquefaction
- Anaerobic digestion

- ✓ Direct Combustion

The direct combustion of biomass in order to get energy for cooking and for heating spaces is a very ancient technology. Nevertheless the combustion of biomass in an unvented and indoor environment is responsible for the production of toxic or hazardous gases as carbon monoxide, nitrogen oxides, hydrocarbons, organic compounds, aldehydes, aromatics and ketones. The emission of the unwanted gases increases with the moisture content. When complete combustion occurs, the efficiency is improved and the unwanted gas emissions are decreased. This is the case of direct combustion in a well vented area that takes place in the new domestic stoves and boilers where biomass substitutes fossil fuels.

- ✓ Gasification

The process of gasification is explained in details in section 2.3. Basically it is the conversion of biomass into producer gas and ash. The process is performed at high temperature in a reactor called gasifier. The gasification agent is usually oxygen, air, or steam. The producer gas consists mainly of components with a significant heating value (carbon monoxide, methane, hydrogen and tar), nitrogen, carbon dioxide and water. Nitrogen is present as a consequence of the use of air to supply oxygen. Generally the producer gas requires a specific treatment in order to be used for power and/or heat generation in conventional plants.

- ✓ Liquefaction

It is possible to convert biomass into liquid fuels that can be used for transportation applications, for example. The process is composed of three phases: grinding, hydrolysis and fermentation. Acids or enzymes (around one part over 100 by weight) and yeast addition are needed. Only the carbohydrates are converted. If other components of the biomass, such as protein, oil and fiber, may be valuable for other production, these substances have to be separated before hydrolyses and fermentation.

- ✓ Anaerobic Digestion

The anaerobic digestion process is the conversion of biomass into methane gas and humus materials, thanks to the use of microorganisms in absence of oxygen. Usually the process is executed in a reactor. The term digestion has to be differentiated by the term fermentation, which gives alcohol or lactic acid as product. The produced gas, mainly methane, may be used in different kinds of plants to generate heat and/or power.

2.3 Biomass Gasification

Gasification is a thermo-chemical conversion process for transforming solid & liquid carbonaceous fuels into a combustible gaseous fuel ‘producer gas. Producer gas is an energy carrier commonly comprised of hydrogen, carbon monoxide, methane, carbon dioxide, nitrogen and some higher hydrocarbons. Gasification occurs when sub-stoichiometric levels of oxygen are present with heat, during an oxidation process. A gasifier is the chemical reactor system used to carry out the gasification process within. The technologies of pyrolysis, partial oxidation and hydrogenation are included in gasification. Therefore the different techniques for gasification are varying and much dependent on the source of fuel and the desired product [44].

Gasification is performed because it allows wider utilisation of solid & low grade liquid fuels (such as black liquor), by converting these fuels into a mixture of combustible gases. Since biomass is converted into producer gas, its versatility is increased because a greater range of technologies exist which can operate with gaseous fuels. Hence gasification is an up-grading process for solid and liquid carbonaceous fuels into gaseous fuels. For example, wood and coal are largely restricted to being combusted in a boiler or fireplace to generate heat, but they cannot be directly used to fuel internal combustion engines (gas turbines, reciprocating engines), unless they are first converted into a gaseous or liquid state.

Having a combined cycle system provides higher efficiency, although care should be taken for fuel cleanliness to prolong the life of a gas turbine. Since direct firing of biomass fuel is unclean, gasification becomes necessary to provide gaseous fuel to be used for combustion in a gas turbine [8].

2.3.1 Biomass Gasification Processes

The main steps involved in the gasification process can be categorized as upstream processing, gasification and downstream processing (Figure 2.1) [9].

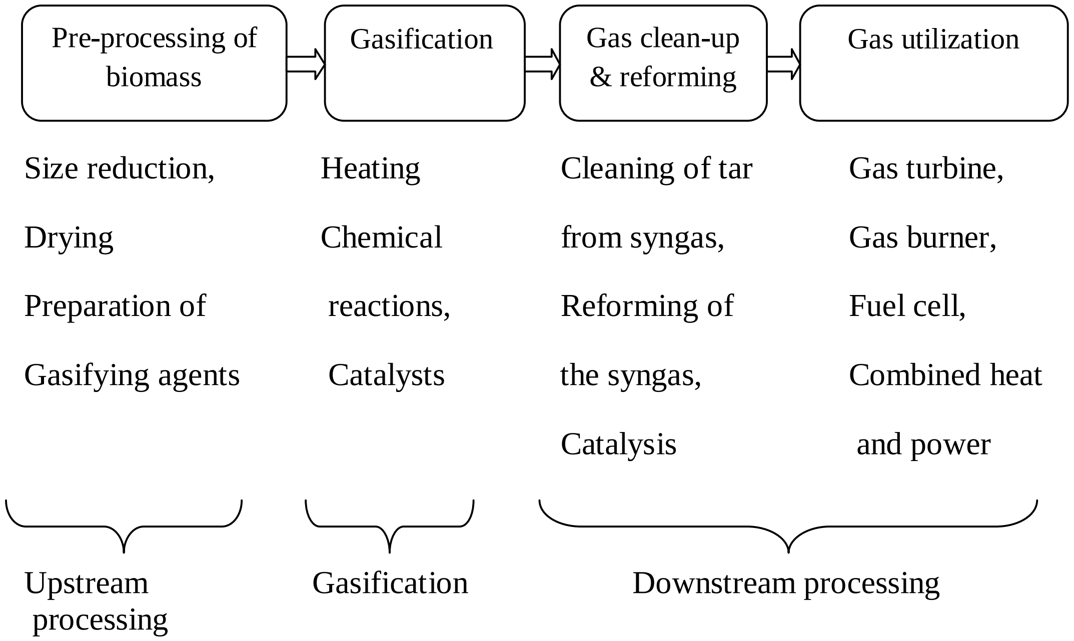

Figure 2.1 The principal steps of gasification.

Generally, the phases of gasification are [43]:

- Drying
- Pyrolysis
- Oxidation, and
- Reduction

A general scheme of the gasification phases, which is not intended to be exhaustive, is shown in below and is built following the wet wood in its transformation to ash and released products.

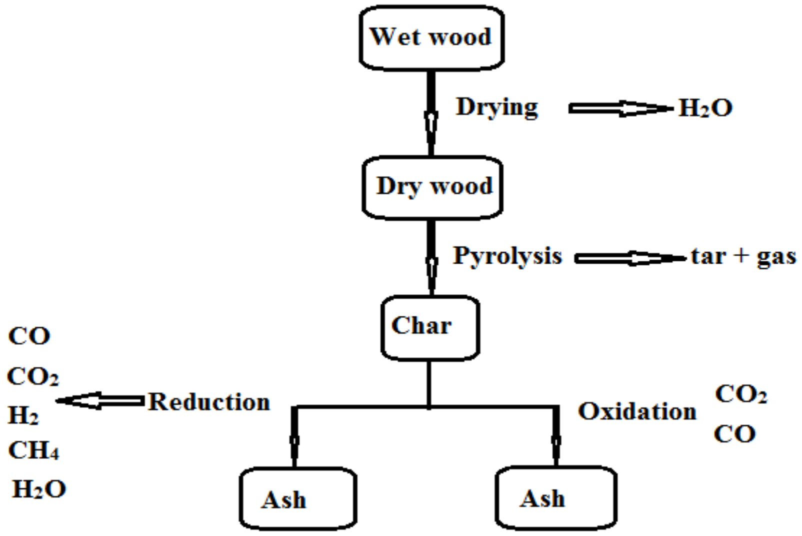

Figure 2.2 Gasification phases

According to the above figure, the wet wood is dried and releases water. The pyrolysis converts the dry wood into char (a solid substance rich in carbon), tar and other gases. The char faces reduction and oxidation. The actual sequence of these two processes is defined by the gasifier type. During reduction char is converted mainly into carbon monoxide, hydrogen, methane, carbon dioxide and water. Oxidation is the combustion of char and releases carbon monoxide, carbon dioxide and energy. The remaining solid that does not react is called ash. The gasification product is a gas mixture with a relevant heating value called producer gas.

2.3.2 Chemical Reactions in the Gasification Process

Gasification is a highly complex chemical process. Bridgewater described the gasification sequence as drying and evaporating processes of biomass followed by pyrolysis, and finally oxidation and reduction. However, the overall process can be reasonably described by the reactions described below [37].

$$\text{Biomass} \xrightarrow{\text{heat}(300\text{–}400^{\circ}\text{C})} \text{gases}(CO, CO_2, H_2, \text{light HC's}) + \text{pyrolyzed vapors} + \text{char} \tag{1}$$

$$\text{Pyrolized vapors} \xrightarrow{(\text{heat}+\text{high residence time})} \text{gases}(CO, CO_2, H_2, \text{light HC's}) \tag{2}$$

$$C + O_2 \leftrightarrow CO_2 \quad ,\Delta H = \text{-}395\,\text{KJ/mol} \tag{3}$$

$$C + \left(\frac{1}{2}\right)O_2 \leftrightarrow CO \quad , \Delta H = \text{-}110.5\ \text{KJ/mol} \tag{4}$$

$$C + CO_2 \leftrightarrow 2CO \quad , \Delta H = 172.4\ \text{KJ/mol} \tag{5}$$

$$C + H_2O \leftrightarrow H_2 + CO \,, \Delta H = 131.3\ \text{KJ/mol} \tag{6}$$

$$C + 2H_2 \leftrightarrow CH_4 \quad , \Delta H = \text{-}74.8\ \text{KJ/mol} \tag{7}$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \,, \Delta H = \text{-}41.1\ \text{KJ/mol} \tag{8}$$

$$CO + 2H_2 \leftrightarrow CH_4 + H_2O, \Delta H = 206.1\,\text{KJ / mol} \tag{9}$$

Among the reactions described above, the char-oxidation (Eq. 3) and partial-oxidation (Eq. 4) reactions are slowest, and consequently the rate controlling factor in the overall gasification process. Pyrolysis also results in liquid which is resistant to the cracking due to temperature increase though most of the pyrolyzed liquid does so at higher temperature. This requires subsequent cleaning set-up for the tar, which can be a substantial investment in many cases.

2.3.3 Effect of Various Parameters in the Gasification Process

Syngas composition varies widely and mostly depends upon the gasifier type, feedstock, feedstock pre-treatment, gasifying medium and operating parameters like temperature, pressure, and nature of interaction between reactants in the gasification process. The effects of major parameters affecting the quality of syngas are discussed in the sections below [37].

- Moisture Content

Biomass contains moisture in both ways: intrinsically by its nature, and extrinsically where in moisture is absorbed from the surrounding atmosphere. Moisture content in the biomass, during gasification, increases CO_2 concentration by the water-shift reaction which consumes CO and liberates H_2. While the equilibrium constant for water-shift reaction varies little over a wide range of temperatures, the direction tends to reverse at higher temperature. Since more heat is required for moisture evaporation than the small amount of heat gained due to the exothermic behaviour of the water-shift reaction, thermal energy inside the gasifier reduces when gasifying biomass with higher moisture content. Thus, the decrease in temperature further exacerbates the scenario and forms more CO_2 since the water-shift reaction is improved at lower temperature. The overall effect is the reduction in calorific value of syngas because, the small increase in H_2 is not sufficient to compensate the loss of significant amount of CO with increase in moisture content. However, the negative effect of moisture content on the calorific value of syngas is lower at lower equivalence ratio (ER).

The equivalence ratio (ER) is the ratio of actual air fuel ratio to the stoichiometric air fuel ratio which provides the basis for evaluating the amount of air supplied for the gasification with respect to the amount of air required for the complete combustion of the feedstock. Roy et al. have observed that, in a downdraft gasifier, when the moisture content is increased from 0 to 40%, heating value of syngas decreases by 8.72% at ER of 0.45 while the decrease was of 4.7% when the ER used was 0.29. This result was reported from their equilibrium model and thus is applicable to any gasification process.

- Equivalence Ratio

Equivalence ratio (ER) is the most influential parameter in any gasification process and often has significant impact on syngas composition. Increase in ER increases the temperature inside the gasifier while ER decrease increases char formation inside the gasifier. Zainal et al. compared the best optimal value for the downdraft gasifier with respect to equivalence ratio using furniture wood and wood chips as feedstock. The effect of equivalence ratio for each syngas component was analyzed with the conclusion of an optimal equivalence ratio of 0.38 for the gasifier performance for that particular feedstock. At this equivalence ratio, CO, CH_4 and calorific value each attain their maximum outputs while CO_2 reaches its minimum.

- Temperature

Increase in temperature reduces the tar content as well as decreases char inside the gasifier. Gas yield increases due to higher tar cracking. One of the means of increasing temperature is by internal recirculation of syngas. Tar cracking temperatures are often reported to be around 1000-1100 °C with some dependency on gasifier design. Other methods of tar cracking are also employed such as multi-stage gasifiers. CO content increases with increase in temperature because endothermic reactions are more favoured at higher temperature. Mass conversion efficiency decreases with decrease in temperature. An oxidation zone below a temperature of 725 °C gives significantly lower mass conversion efficiency.

- Biomass Type

Biomass elemental composition has a significant effect on syngas composition. The release of pyrolysis gas is highly dependent on hydrogen/carbon ratio as well as oxygen/carbon ratio and increases when these ratios increase, especially with an increase in Hydrogen/Carbon ratio. A higher oxygen concentration in biomass needs lower ER for gasification because of its inherent oxygen that will also be available for gasification.

Another important factor is the ash content of the feedstock. Although formation of clinkers can cause problems for the gasifier operation with biomass having ash-content above 5%, successful gasification with ash-content up to 25% is reported. Higher ash content causes slagging, and consequently ash agglomeration due to fusion, the rate of which is dependent upon the ash content in biomass and ash composition. Thus high ash content biomass should be gasified at the temperature below the oxidation or reducing temperature of the minerals constituents in the ash, often which is not possible if the constituents have relatively low ash-fusion temperature.

Common ash minerals in biomass are silica, potassium, calcium, aluminium, magnesium, iron, sodium and chlorine. These minerals present in biomass can exist as salts and vaporize during the gasification process contaminating the syngas. Also, it is highly possible for these minerals to react with silicon in presence of oxygen to create low-temperature melting silicates which can create a severe deposition problem. Alkali metals such as potassium and calcium silicates have melting temperatures even below 700°C. One other way to tackle the problem is to resort to some kind of removal process like leaching for alkali metal removal which has been reported to reduce these minerals by more than 80%. Removal of these alkali metals will increase the ash fusion temperature thus facilitating gasification. The presence of ash in biomass requires careful control over the operating temperature. Neither should it be high enough to fuse minerals in the ash forming a barrier to further gasification by formation of clinkers, nor too low leading to unburnt carbon resulting in lower carbon conversion efficiency.

- Particle Size

Fixed bed gasifiers have lower biomass feedstock size restrictions compared to fluidized bed gasifiers. Usually, feed size less than 51 mm and 6 mm is recommended for fixed bed and fluidized bed, respectively. Use of larger size feedstock has been tried and reported by several authors. The maximum particle size suggested for a conventional downdraft gasifier with throated design is one-eighth of the reactor throat diameter. The larger particles form bridges preventing the efficient flow of biomass inside a gasifier while smaller particles interferes with the air/gasifying agent passage creating high pressure drop and consequently can result in gasifier shut-down.

- Pressure

High-pressure gasification reduces the size of the reactor for the same amount of feedstock and can act to reduce the need for further compression when the gasification products are intended for subsequent use in Fischer-Tropsch process or other chemical synthesis which requires high pressure. Pressure drop across the gasifier increases with smaller particle size due to increased porosity.

Increase in pressure in a fluidized bed increases turbulence and thus increase in gas particle interaction is observed. Increase in pressure also results in bubble instability and bubble splitting in fluidized bed. Wiman and Almstedt have defined a parameter called bed expansion ratio (δ) as follows:

$$\delta = \left(\frac{H_{f1} - H_{mf}}{H_{f1}} \right)$$

Where, H_{f1} = fluidization height at given condition

H_{mf} = minimum fluidization height

Their finding shows a significant increase in δ with increase in pressure. Valin et al. have studied the effect of pressure upon syngas composition with pressure from 2 to 10 bar in fluidized bed with wood sawdust as a feedstock. With increase in pressure, an increase in CO_2, CH_4 and H_2 were observed, while CO decreased. In their lab-scale reactor using steam and N_2 as the gasification medium, with increase in pressure from 2 to 10 bars, an increase of 16%, 53% and 38% of H_2, CO_2 and CH_4, respectively and decrease of CO by 33% was reported. Overall, increase in dry gas yield increase is reported to be 20% with increase in pressure from 2 to 7 bars after which the gas yield remains constant. The increase in various gases and total gas yield is due to the increase in char hold-up rate which increases catalytic activity of char as well as improved reaction kinetics due to high pressure.

- Gasification Medium and Secondary Air

Biomass gasification can be done with any of the following medium:

- Air
- Oxygen
- Steam

Gasification with air results in syngas with low higher heating value (HHV) due to inherent dilution with N_2 present in the air. Conversely, gasification with oxygen yields syngas with a heating value of 10-12 MJ/Nm^3 and steam gasification results in syngas with heating value even higher, 15-20 MJ/Nm^3. Air gasification is widely used compared to oxygen and steam due to its economical and operational advantages.

Secondary air reduces the tar content in the syngas due to partial combustion of syngas. This in turn establishes local high temperature zone due to exothermic reactions. Thermal cracking of tar is thus due to these high temperature zones in the periphery of the secondary air. Since heat is obtained from the combustion, HHV decreases with increase in secondary air.

- Gasification of Wastes and Biomass Co-Gasification

Bacaicoa et al. have studied the co-gasification of a biomass and high density polyethylene (HDPE) mixture in a downdraft gasifier. As expected, biomass consumption rate decreased with increase in HDPE fraction in the mixture. Since HDPE vaporizes instantly at high gasification temperature, the biomass consumption rate is determined by the amount of lignocelluloses present in the mixture. A higher fraction of HDPE in the mixture consumes more oxygen from the air supplied and thus leaves less air for lignocelluloses to gasify consequently reducing the biomass flow rate. They also report increase in CH_4 and CO concentration with increase in HDPE fraction, while H_2 varies only slightly and CO_2 decreases. This is attributed in other study to the strong affinity of HDPE towards a Boudouard reaction (Eq. 5) compared to a water-shift reaction (Eq. 8).

- Bed Material

Proper consideration of bed material in a fluidized bed is important for achieving proper homogenization of feed particles and efficient heat transfer so that minimum temperature gradient is realized within the riser. In many cases, bed material can itself act as a catalyst facilitating efficient tar cracking. Skoulou et al. compared the effect of olivine over silica sand, latter of which is reported to have adverse effect upon effective fluidization due to agglomeration and tar formation when operating at the temperature below 800 ° C. Pfeifer et al. have studied in-bed catalysts in a dual bed fluidized bed reactor with Ni/olivine as the catalyst and observed significant tar reduction. Use of catalyst for tar cracking is itself a vast subject and further discussion is avoided here to remain within the scope of the review [37].

CHAPTER THREE

BIOMASS INTEGRATED GASIFIER COMBINED CYCLE (BIGCC)

3.1 Introduction

Biomass integrated gasification combined cycle (BIGCC) plants are currently at an early stage of commercialization. The first plant was established at Värnamo in Sweden in 1995. At present, several BIGCC plants, of capacities up to 75 MW, are in different stages of implementation in the USA and Europe. Two BIGCC projects have been initiated in Brazil; one of these is based on eucalyptus wood, while the other is based on sugarcane bagasse and trash. In India, a BIGCC project is being initiated currently [1].

The combined cycle, flue-gas cleaning and gasification are currently existing technologies. The main challenge is integrating these three technologies together to produce an affordable, highly efficient, environmentally friendly and reliable system. New technology for using biomass in an integrated gasification combined cycle (BIGCC) is in development and is subject to continuous improvement. Some of the technical challenges require in-depth understanding of the fundamental mechanisms involved in the process in order to overcome them. Other challenges require development efforts in pulling together existing technologies to make it work. The ultimate challenge is to build a demonstration plant, accumulate operating experience, and continuously improve the performance [8].

3.2 BIGCC Technologies and Projects

BIGCC is a relatively new technology and is still in its development stage. There is no commercial BIGCC project currently running anywhere in the world. The reasons for the lack of success are complex and vary with the projects, however, there are some common reasons such as financial shortages in project execution and unrealistic profit expectations from the demonstration operation. However, there have been a few projects that have come close to commercialization. Some of the projects were set up as demonstration and experimental projects, while others were set up as commercial ventures but had to shut down for various reasons. In this section, I describe the four major technology approaches and the projects associated with them. This will provide a sense of the status of the overall BIGCC technology.

3.2.1 Skydkraft-Foster Wheeler Technology

Sydkraft AB of Sweden and Foster Wheeler Energy International Inc., under the joint venture company of Bio flow Ltd. developed and built the first BIGCC plant in the world. The Värnamo demonstration plant (Figure 3.1) was commissioned in 1993 and generated 6 MWe of electricity and 9 MWth of heat. Wood, which is the primary fuel, is delivered to the gasifier via a lock hopper system, using pressurized nitrogen. This technology utilizes a refractory-lined, pressurized, circulating fluidized bed gasifier operating at 950-1000 ° C and approximately 20 bar.

The product gas, after exiting the gasifier, is cooled in two stages using radiant and convection coolers. It is then cleaned in a hot gas ceramic filter, before being fed to the combustor of the gas turbine. The gas turbine has an electricity generation potential of 4 MWe. The flue gas from the exhaust of the gas turbine passes through a single-pressure type HRSG that operates at a pressure of 40 bar on the steam side. The superheated steam at 40 bar generates 1.8 MWe of electricity in the bottoming SRC and 9 MWth energy for district heating.

Figure 3.1: The Värnamo biomass integrated gasifier combined cycle plant.
Image source: Chrisgas

The Värnamo plant was in operation from 1993-2000. The system was not designed for optimal performance but to demonstrate the feasibility of the pressurized BIGCC technology (Turn, 1999b). The plant accumulated 3600 hours with the gas turbines operating entirely on the gasifier product gas. Since 2004, the plant is working with the Chris gas project to demonstrate the production of hydrogen rich gas from biomass feed stocks. The Sydkraft-Foster Wheeler technology is one of the nearest to developing a commercial large scale BIGCC plant.

3.2.2 TPS Termiska Technology

TPS Termiska Processor AB is a Swedish research and development company. The TPS technology uses an air-blown, circulating fluidized bed (CFB) gasifier that operates at atmospheric pressure. The gasifier is followed by a catalytic tar cracker that uses dolomite as the bed media. The product gas then passes through a gas filter and a wet scrubber [44].

The first large scale TPS plant was set up in Greve-in-Chianti, Italy. Two CFB gasifier units, each with a capacity of 15 MWth produce product gas from refuse derived fuels. This product gas is not used in a combined cycle, but burned in a boiler to generate steam that runs a 6.7 MWe condensing steam turbine. The first large scale BIGCC plant using TPS technology was the 8 MWe Arable biomass renewable energy (ARBRE) project.

3.2.3 Institute of Gas Technology – Renugas Technology

The Renugas process, developed by the Institute of Gas Technology (IGT) is a pressurized, bubbling fluidized bed gasifier, which utilizes both air and steam as fluidizing agents. Two entities hold the license for the Renugas technology: Carbona Inc. and Pacific International Centre for High Technology Research (PICHTR) [44].

The development of the Renugas technology was pursued at the Biomass Gasifier Facility on the site of the HC&S sugar factory in Paia, Hawaii. The system was designed to consume approximately 90 dry tons of bagasse per day. The bagasse would be dried to 20 percent moisture content before being fed to the gasifier. Both plug screw as well as lock hopper feeders were tried at the facility. Limited testing of the system determined that the desired fuel feed could not be attained with the lock hopper feed system, while the plug screw feeder was not designed to maintain the required 20 bar pressure of the gasifier [44].

3.2.4 Batelle-Ferco Technology

Batelle Columbus Laboratories has been developing an indirectly-heated gasification technology to produce a medium heating value gas from biomass. The technology features two atmospheric pressure CFBs with solids exchange between the two reactors. The biomass is fed to the first CFB, which is operated as a steam blown gasifier. The bed material and un-reacted char exiting the gasifier are directed to the second CFB. This second CFB uses air as the fluidizing agent and operates as a combustor to heat the bed material. The hot bed material is recirculated back to the gasifier, where the fuel undergoes pyrolysis and gasification.

The gasification system with a 45 MW thermal input capacity was installed next to the existing 50 MW wood-fired direct combustion SRC system. The product gas was co-fired in the existing plant with wood chips to generate steam. Plans were being made to operate an 8 MW turbine on the product gas. However, due to financial reasons, the project is presently at a standstill [44].

The review of these four major gasification technologies and the status of their projects indicate that BIGCC technology is still in the development stage. However, BIGCC systems may have a much higher electricity generation potential than direct combustion SRC systems. With that in mind, it is important to evaluate the potential of BIGCC cogeneration systems.

3.3 Elements of BIGCC Power Generation

The basic elements of a BIGCC system include:

- A biomass dryer to reduce the moisture content of the biomass;
- A feeding system to feed the biomass into the gasifier;
- A gasifier for converting the biomass into a combustible gas;
- A gas cleanup system to remove the tars and particulates from the gas;
- A gas turbine-generator where the gas combusts and expands to run a generator;
- A heat recovery steam generator (HRSG) to produce steam from the hot exhaust of the gas turbine; and,
- A steam turbine-generator to produce additional electricity.

Figure 3.2 shows the block diagram for a BIGCC system. The exhaust low pressure steam from the steam turbine-generator is used to satisfy the process steam demand of the system. The exhaust flue gases from the HRSG can be used in the biomass dryer to extract waste heat.

In the next section, the different components of the BIGCC system and the challenges associated with their design and operation in the context of a biomass based cogeneration system are discussed.

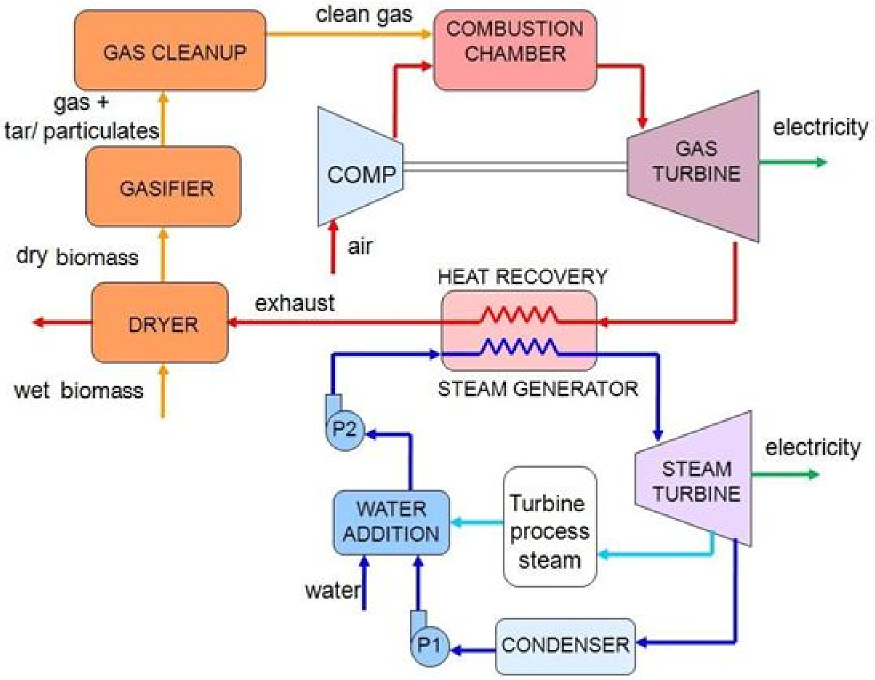

Figure 3.2: Block diagram of a biomass integrated gasification combined cycle cogeneration system

3.3.1 Fuel Pre-treatment

The main pre-treatment of the biomass fuel for a BIGCC system is the reduction of its moisture content. Fresh biomass has moisture content (wet basis) of approximately 50 percent [44]. The moisture content of the fuel entering the gasifier strongly affects the heating value of the produced gas, as energy is required for the vaporization of the moisture. Since the lower heating value of the gas is quite low, especially from a gasifier using air as an oxidant, reducing the moisture content of the fuel is critical for the successful operation of the turbine downstream. Drying the biomass in a dryer prior to feeding it into the gasifier requires less energy than that required inside the gasifier to evaporate the fuel moisture and heat it to the gasifiers operating temperature.

Additionally, drying biomass provides better gasifier control by producing a more uniform fuel. A dryer also offers the opportunity to recover heat from the flue gas exiting the HRSG and increase the overall system efficiency. However, some studies show that the HRSG flue gas may not have enough energy to dry the biomass to the required moisture content levels. A supplementary heat source may be needed to provide the additional thermal energy. Although biomass drying is advantageous from a system efficiency viewpoint, drying to levels below 20 percent moisture content can introduce feeding problems, especially in extrusion type feeders. This is mainly due to increased frictional characteristics and abrasiveness of the fuel. A drying system also increases capital costs and parasitic loads [44].

Fuel pre-treatment, other than drying, may include steps to increase the bulk density of the biomass, since feeding systems are limited by fuel volume. The bulk density might be increased by chopping to reduce particle size, pelletizing, cubing and baling. However, the associated processes introduce additional capital expenditures as well as operation and maintenance costs, especially for large commercial operations such as a sugar factory.

3.3.2 Fuel Feeding Systems for Biomass

After drying, the biomass is fed into the gasifier using a feeding system. The type of feeding system for a gasifier depends on whether the gasification system is pressurized or nominally atmospheric. Feeding is more challenging in pressurized than atmospheric pressure gasification systems.

For a pressurized gasification system, there are two main requirements of a feeding system. First, it should provide the fuel consistently at a controlled feed rate. Second, it should maintain a seal between the pressurized parts of the gasification system and the parts of the feed system operating at atmospheric pressure. We can use the following feeding systems [44]:

- The lock hopper feed system, where the lock hopper isolates the feed system from the reactor pressure. It is alternately pressurized and depressurized using an inert gas, typically nitrogen, as it introduces fuel into the reactor in a batch process. Due to the fibrous nature of biomass and its tendency to bridge, lock hopper feed systems have experienced issues with the biomass not flowing easily.
- A plug screw feeder where a tapered screw compresses the biomass in a dense plug, which provides the seal for the operating pressure of the reactor. However, biomass can cause severe abrasive wear on the inside surfaces of the feeder.
- A piston feeder where a piston is deployed to push the biomass into the reactor in a batch process. In this system, the fibrous nature of biomass can cause difficulties in loading the piston cylinders and can also cause abrasion on the feed system.

Atmospheric pressure gasifiers are easier to feed since no pressure seal needs to be maintained between the gasifier reactor and the feed system. Simple screw type feeders can be used. Even then, the low bulk density and cohesive characteristics of biomass may cause an accumulation of the fuel in the feeding system, making it difficult to flow into the gasifier.

3.3.3 Gasifier

There are numerous types of gasifiers. Basically, the gasifiers can be classified by its fuel flow direction as [5]:

- ✓ Up draft
- ✓ Down draft
- ✓ Cross draft

or by flow speeds as:

- ✓ Fluidized bed
- ✓ Moving bed
- ✓ Entrained bed

- Updraft Gasifier

The updraft gasifier (Fig. 3.3) is the simplest and oldest gasifier normally used for coal gasification [5]. In an updraft gasifier, the fuel is fed from the top via feedstock (dried biomass with 20 % moisture content or less), and this is fed from the bottom. The feedstock from the top is met by hot gasses produced further down, which helps dry the biomass fuel source further while cooling down the synthetic gasses produced (H_2 & CO). This demonstrates a good use of heat recovery. Next, the very dry biomass being pyrolyzed by the up-flow of hot gasses gives up the volatile combustible gas/vapours and becomes charcoal. These hot charcoals are a good reducing agent as it comes into contact with the rising hot CO_2 and H_2O to yield CO and H_2. In the last stage, the charcoal is combusted with the air/ O_2 at very high temperatures. The resulting ashes are collected and disposed off.

The advantages of this gasifier is the ability of slagging gasification where metals and minerals are melted due to the high temperature at the bottom of the gasifier and the ability of handling very wet fuels. On the other hand, the produced gas has high tars, which is detrimental to gas turbines or boilers. The tar must be removed before being fed into the gas turbine. The updraft gasifier requires a good temperature control and monitoring to avoid melting of grate at the bottom of the gasifier.

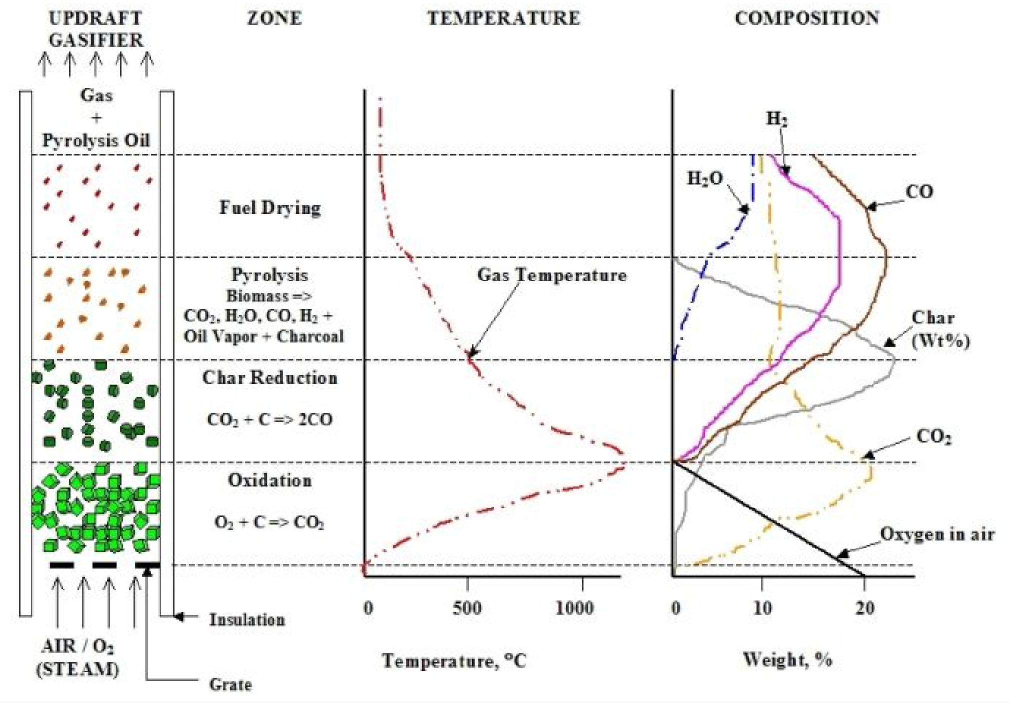

Figure3.3: Updraft Gasifier (Reed, 2001)

- Downdraft Gasifier

Downdraft gasifiers have both the air/ steam flowing with the fuel source from top to bottom, helping to burn 99.9 % of tars. The downdraft gasifier is good for biomass with high volatiles [5]. Flaming pyrolysis occurs intensely at the top to produce 5-15% charcoal, and also produces CO_2 and H_2O. The next stage, the hot charcoal reacts with the combustion gasses with the absence of oxygen to produce CO and H_2. The char ash at the end of the process is disposed. There is minimal tar cleanup necessity as roughly 99 % or more tar is combusted. The temperature of the produced gas is roughly at 700°C (973.15 K), which can be used to dry the raw biomass or preheat water or air before entering the cold clean-up process. Caution must be exercised with this type of gasifier as the fuel intake must have less than 20 % moisture content.

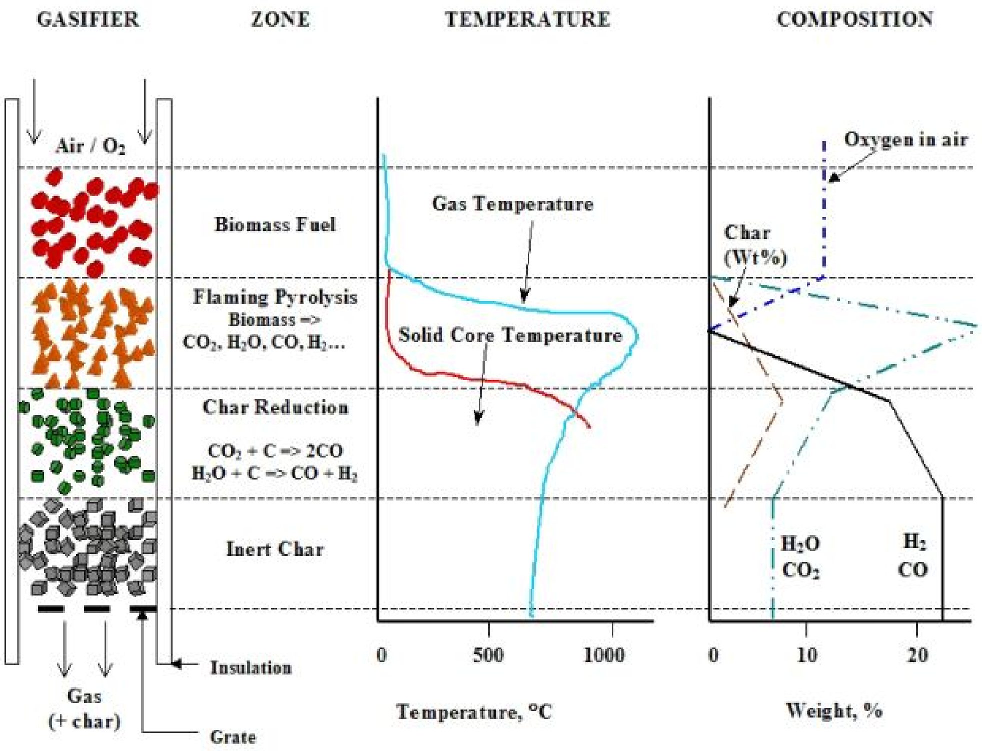

Figure 3.4: Downdraft Gasifier (Reed, 2001)

- Cross draft Gasifier

The cross draft gasifier is the lightest and simplest gasifier design. The container houses the fuel for storage and gasification. Figure 3.5 illustrates the basic design of the cross draft gasifier. The air blasts at high velocities enter the bottom of the cylinder to create a significant circulation across the bed of fuel and char. The syngas exits at the opposite end from the air blast entrance. A possible advantage of a cross draft gasifier is the fact that the ash and fuel insulates the inner wall of the gasifier, and hence permitting the gasifier to be fabricated from mild steel; however, caution should be taken for the grate and nozzles materials, which should be resistant to the high temperatures.

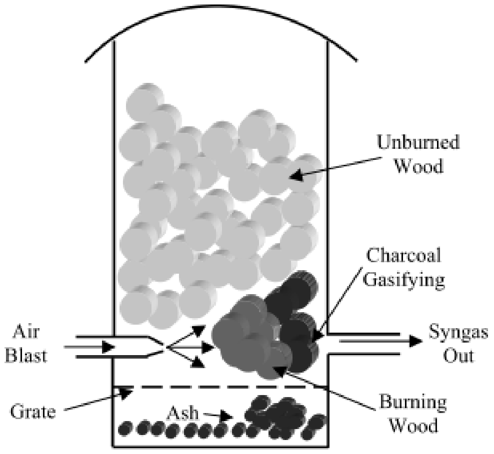

Figure 3.5: Cross draft Gasifier (Reed, 2001)

- Fluidized Bed Gasifier

Fluidized bed gasifiers are called because the bed material (biomass in this case) moves like a fluid) due to the levitation of biomass by the airflow. The fluidization occurs when the pressure drop across the gasification bed multiplied with the area of the bed is equal to or larger than the weight of the bed. The origins of this gasifier was to gasify coal, and currently the petrochemical industry utilizes this type of gasifier for cracking heavy hydrocarbons, catalysis etc.

- Entrained Flow and Moving Bed Gasifier

The entrained flow gasifiers on the other hand are fed with high-speed air flow such that all raw biomass is levitated and entrained in the airflow. A moving bed gasifier’s behaviour is somewhere between a fluidized and entrained flow gasifier with a flow moving over the bed, but the bed materials stay in the bed.

- Atmospheric Pressure vs. Pressurized Gasifier Systems

In a BIGCC system, the product gas from the gasifier is fired in a combustion gas turbine to generate electricity. The gas turbine requires the fuel gas and combustion air stream to be pressurized, based on the operating pressure of the turbine. Two approaches have been developed to meet this requirement. The first approach involves pressurizing the gasifier, maintaining the pressure through the gas cleanup/conditioning system, and feeding the product gas to the combustor of the turbine at that elevated pressure. The gas is filtered through the gas cleanup/conditioning system at a sufficiently high temperature to maintain the tars in vapor phase. The second approach is to operate the gasifier and gas cleanup/conditioning system at nominally atmospheric pressure, then compress the product gas to the required pressure before feeding it to the combustor of the turbine. Compressing the product gas is most efficiently done at a low temperature and after the condensation of the water vapour contained in the gas [16].

Both approaches have their advantages and disadvantages. In the pressurized gasifier system, the fluidizing agent is compressed to the operating pressure of the gasification system before introducing it in the gasifier. The product gas that exits is already at the elevated pressure and does not need compression prior to the gas turbine. On the other hand, the product gas from an atmospheric pressure gasifier needs to be compressed before injecting into the gas turbine. Since the mass and volume of the product gas is much more than the fluidizing agent (air or steam), the atmospheric pressure gasification system has higher parasitic loads than the pressurized gasifiers system. Additionally, the reactor size is smaller and the reaction rates between solids and gas are higher for a pressurized gasifiers system. However, the gasifier and the gas cleanup/conditioning system need to be built to withstand high pressure and temperature, thus increasing costs. Also feeding systems for a pressurized gasifier are difficult to design and operate, and may need a supply of pressurized inert gas, further increasing capital and operation costs. The atmospheric pressure gasifier system has a simpler feeding system but needs a more rigorous gas cleanup/conditioning system to remove the tars that would otherwise condense at the low operating temperature.

- Direct vs. Indirect Heated Gasifier Systems

Biomass gasifiers operate in one of two ways; with heat supplied directly by partial oxidation of the fuel or indirectly through a heat exchange mechanism. In directly heated gasifiers, air or oxygen (the latter is rarely used due to its high costs) is used as the gasifying agent. The air-blown pressurized or atmospheric pressure fluidized bed gasifiers are the most promising directly heated gasifier designs for BIGCC systems. The indirectly heated gasifier design operates at a much lower temperature (700-850 ° C). In an indirectly heated fluidized bed design, steam or an inert gas like nitrogen is used as the gasifying/fluidizing agent. Heat is provided indirectly by combusting char and heating the inert bed material in another reactor and circulating it back to the gasifier reactor. In-bed heat exchangers have also been used. This design produces a gas with higher energy content since it is not diluted by the nitrogen in the air. It is mainly suited for applications that synthesize the product gas into other chemical compounds and liquid fuels.

- Types of Oxygen Sources

A gasifier can be operated with air or oxygen as the source of oxidizing agent. An oxygen-blown gasifier requires expensive and energy-intensive air separator unit (ASU). The heating value of an oxygen-blown gasifier is about 50 % of the natural gas' value. An air-blown gasifier is relatively easier to operate than the oxygen-blown gasifier; however the heating value of the producer gas is about 20 ~ 30 % of the heating value of the natural gas' heating value [16].

- Selection of the Gasifier

Based on the literature survey conducted upon the different types of gasifiers, the preferred gasifier in this study for the proposed power plant is the air-blown downdraft gasifier, operating at atmospheric pressure condition. The following are the factors for choice of the downdraft gasifier:

- Ease of construction and operation
    - A cylindrical steel design, not designed as a pressure vessel
- Types of primary fuel being used for simulation
    - High cellulose and wet bagasse and bark with possible high tar content.
- Oxygen supply method: air-blown

The gas produced from the gasifier is then passed into a gas cyclone to remove the initial fly ash. An attemperator connected after the gas cyclone is used to cool the gas down slightly. A good utilization of waste heat from the attemperator would be to preheat water for the steam cycle or for fuel drying. After attemperation, the syngas is cleaned using the gas clean-up unit (GCU), pressurized and fed into the combustion chamber of the gas turbine to be combusted.

Table 3.1 Advantages and Disadvantages of different Gasifiers

Name	Advantages	Disadvantages
Updraft	Moisture for heat Small Scale Applications Can Handle High Moisture No Carbon in Ash	Feed size limits High Tar Yields Scale limitations Slagging Potentials
Downdraft	Small scale applications Large applications Low tars	Moisture sensitive Scale limitations Feed size limits Producer gas
Fluidized Bed	Large scale applications Direct and indirect heating Feed characteristics Can produce syngas	Medium tar yields High particle loading
Circulating Bed	Large scale applications Feed characteristics Can produce syngas	Medium tar yield High particle loading
Entrained flow	Can be scaled Can produce syngas Potential for low tar	Large amount of carrier gas Particle size limits Higher particle loading Potentially high S/C

3.3.4 The Gas Clean-Up Unit (GCU)

The gas clean-up unit (GCU) is important to ensure that clean syngas is passed into the combustion chamber of the GT. The combustion chamber and turbine of the GT is sensitive to the cleanliness of syngas due to the possibility of fouling and corrosion of component surfaces from burning unclean syngas. The GCU can be operated with hot gas or cool gas. The hot gas clean-up unit (HGCU) uses ceramic as the filtering material, is less reliable due to the cracking of the ceramic, leading to interrupted plant operation and reduced reliability. To achieve reliable operation, a low-temperature GCU (LGCU) is selected. The LGCU replaces the ceramic filter with a metallic filter material. LGCU requires the gas to be cooled down to below 800 K before being fed into the unit. This will reduce the plant thermal efficiency [43].

Gas cleanup/conditioning is one of the biggest challenges of a BIGCC system. In the sugar industry cogeneration case, the end use application for the product gas is a gas turbine. Hence, the gas turbine hardware imposes constraints on the level of condensable tars, particulates and alkali metals in the product gas. Sulphur and chlorine are also potential contaminants, but their concentration in biomass feed stocks such as bagasse is low.

- Particulates

Particulates consist principally of ash and char. Particulates, even in relatively small quantities, can cause turbine blade erosion. Hence, gas turbines have stringent particulate limits. Fluidized bed gasifiers produce a product gas with a particulate concentration of approximately 5000-10,000 ppmw. Hence, a BIGCC system requires a high efficiency filtration system that captures the particulates in filter media like ceramic candles or bag house filters. Wet scrubbers, where the particulates are captured in a spray of water can also be effective. However, they create the additional burden of waste water treatment. Filtration systems may consist of cyclones that provide the primary particulate removal. These can be followed by secondary methods that include hot gas filtering using media like ceramic candles that operate at high temperatures (> 500 ° C), or bag house filters that operate at low temperatures (< 300 ° C)

- Alkali metals

During biomass gasification, alkali metals such as sodium and potassium present in the biomass fuel are vaporized and leave the gasifier as part of the product gas. Alkali metals corrode turbine blades. The estimated tolerable concentration of alkali vapours in fuel gas for gas-turbine applications is very low at the gasifiers exit with corresponding several fold lower concentration allowable at the turbine inlet. The actual concentration of the alkali metals in the product gas far exceeds this limit. The removal of these metals can be carried out by cooling the gas to 350-400 ° C before particulate filtering. The alkali metals condense on the solids and are removed along with them in the filter. Alternately, wet scrubbing can be used, which ensures complete removal, but needs an additional step of waste water treatment.

- Tars

Tars are a complex mixture of condensable hydrocarbons, which includes single ring to five-ring aromatic compounds along with other oxygen containing hydrocarbons and complex polycyclic aromatic hydrocarbons (Devi et al., 2003). Typically, tars are defined as including all organic contaminants with a molecular weight larger than benzene. The amount and composition of the tars is dependent on the fuel, the pyrolysis conditions and the secondary gas phase reactions. In a typical fluidized bed gasifier, tars account for 2 to 4 percent by mass of the fuel or 0.5 to 1.5 percent by mass of the product gas. Tars can condense when the product gas is allowed to cool (< 400-500 ° C) and can cause operating difficulties by fouling heat exchanger surfaces in gas coolers, plugging particulate filters, and constricting pipes and valves.

Tar removal/mitigation methods have been widely reported in literature. These methods are fairly complex and detailed. Figure 3.6 shows the tar removal methods as classified by Han and Kim (2008). Devi et al. (2003)[42] classify these methods depending on the location where the tar is removed; either in the gasifier itself (primary) or downstream of the gasifier (secondary). In most cases, depending on the application, more than one method is applied to ensure that the tar content in the product gas is within acceptable limits.

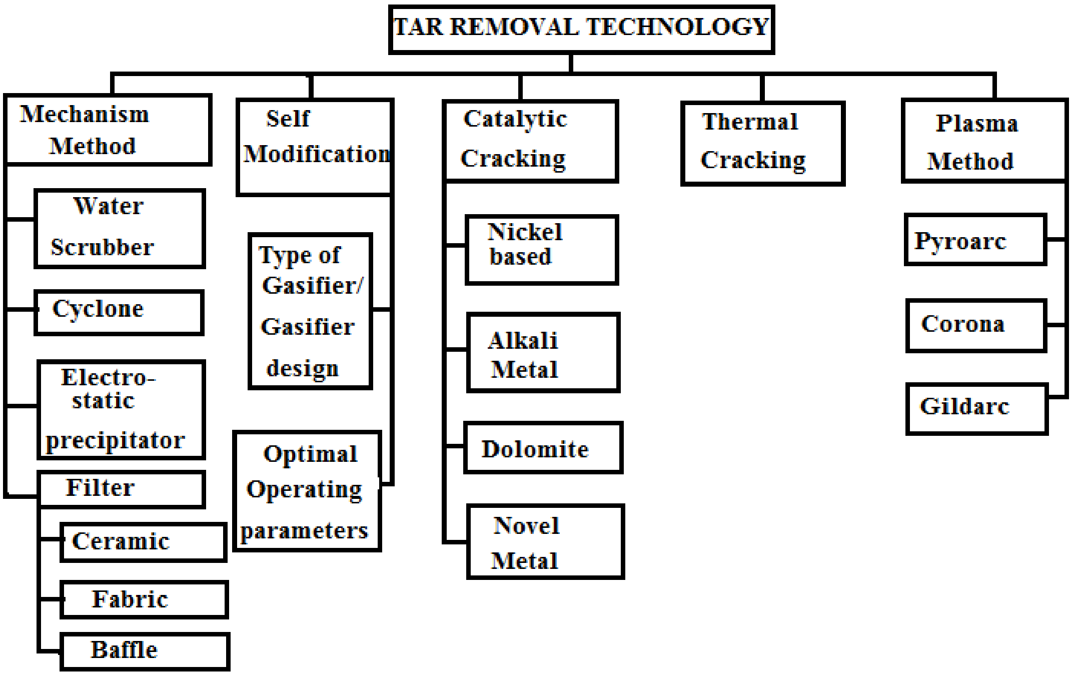

Figure 3.6: Tar removal methods for gasification systems (Han & Kim, 2008).

Primary methods for tar removal include [42]:

- Adjusting gasifier operating parameters
- Choosing the appropriate gasifier design and,
- Implementing catalytic and/or thermal cracking within the gasifier reactor.

The most important operating parameters include temperature, pressure, gasifying medium (air, steam, and oxygen), equivalence ratio (ER) and residence time. The selection of these parameters also depends on the type of gasifier. For a fluidized bed gasifier, a homogenous bed temperature profile and a well-functioning bed are important. A high operating temperature (above 800 ° C) is preferred to achieve a high carbon conversion of biomass and low tar content in the resultant product gas. Pressure, temperature and gasifying medium affect the tar composition. Increase in ER decreases the tar content, but also reduces the heating value of the gas. The actual gasifier design influences the tar content in the product gas. But the design also depends on the application. In the case of a CFB gasifier, experiments with two stage gasifiers with separate pyrolysis and gasification zones have reduced the tar content in the product gas. However, this design has the challenge of maintaining a stable pyrolysis zone in addition to the successful transfer of solids between the two reactors.

In thermal cracking, the raw product gas is heated to a high temperature, which makes the tar molecules crack into lighter gases. The increase in reactor temperature can be achieved by partially combusting the product gas by adding more oxidant. However, this comes at the expense of overall efficiency. The mechanism methods, which are secondary methods downstream of the gasifier, are the same as that for particulate removal [42].

In general, there are many options for gas cleanup/conditioning. However, there are no established norms or proven treatment trains, since there have been no continuously running commercial BIGCC systems.

Finally, I want to highlight two different approaches to gas cleanup/conditioning depending on whether the gasification system is pressurized or operated at atmospheric pressure. A pressurized gasification system generally uses hot gas filtering and cleaning, and the product gas can be fed to the gas turbine after just the particulate removal. This is possible if the particulate removal can take place at a sufficiently low temperature to remove the alkali metals from the gas and at a sufficiently high temperature to maintain the tars in vapor phase. In an atmospheric pressure gasification system, compression of the product gas needs to take place at lower temperatures (typically 200 ° C). Hence, a cold gas filtering system is implemented using filter media like conventional bag house filters. In this case, tar removal/mitigation before particulate filtering is more critical due to the low temperature [42].

The attemperated syngas with ash, alkali vapor, tar vapor and other miscellaneous contaminants enter the GCU from the bottom and pass through a ceramic mesh. The mesh collects and precipitates the contaminants to the base of the unit, which will be emptied periodically. The end result is a cleaned syngas ready to be piped and / or combusted in the Gas Turbine.

3.3.5 Gas Turbines (GT)

A gas turbine (GT) burns fuel and compressed air to produce mechanical/ shaft work. The major components of a gas turbine are the compressor, combustion chamber and the turbine. The compressor intakes and compresses the air from ambient conditions to high pressure, and then fed into the combustion chamber. In the combustion chamber, fuel is injected/ introduced and burnt with the hot compressed air, which is then fed into the turbine for expansion to generate shaft work. The shaft work is connected to a generator to produce electrical power, or connected directly to a machinery, to provide mechanical work. The advantages of using a gas turbine over an internal combustion engine (ICE) is that it is a once-through flow of mass and has a higher power per mass ratio especially for the power production range above 5 MWe [16].

The gas turbine in a BIGCC design dictates a great majority of the power production. Factors for choice of GT are availability cost, efficiency and suitability of application for a BIGCC environment and operating configuration.

3.3.6 Waste Heat Usage

One of the critical design considerations is the exergical efficiency of the overall plant where proper uses of energy grades are considered [16]. For example the syngas is combusted in the GT, a high efficiency energy producer, while the exhaust, lower grade energy is not wasted and used to superheat steam for the steam power cycle. The exhaust from the HRSG is used to dry the raw biomass before storage.

During attemperation, depending on the thermal energy available to be harvested, heat can also be recovered either through a heat exchanger to pre-heat water before entering the steam power cycle, or possibly used to pre-dry the wet biomass. District water heating may also be utilized to cool the water / steam from the steam cycle if a local body of water is not present as a heat sink [7].

3.4 Power Generation Concept of BIGCC

The power generation part of the BIGCC system includes the Brayton cycle and the bottoming Steam Rankine Cycle (SRC). The product gas, after leaving the gas cleanup/conditioning system, is combusted in the Brayton cycle and expanded through its gas turbine to run a generator. The heat in the gas turbine exhaust is recovered in the heat recovery steam generator (HRSG) where steam is generated to run the bottoming SRC and generate additional power.

The gas turbine or Brayton cycle can achieve a higher thermodynamic efficiency than the conventional SRC because the peak cycle temperature of gas turbines (about 1250 ° C on the high side) is far higher than that for steam turbines (about 540 ° C on the high side), providing an inherent thermodynamic advantage for the gas turbine. There are two main types of gas turbines; heavy duty industrial and aero-derivative. An important distinction between the two turbine types is that the combustors of aero-derivative turbines operate at much higher pressures (22 bar or higher) compared to those of heavy duty industrial turbines (12-16 bar). For a given turbine inlet temperature, the turbine exhaust of heavy duty industrial turbines is hotter and capable of producing more steam than is possible with aero-derivatives. Typically, the bottoming SRC provides about one third of the total output of combined cycles utilizing industrial turbines. For aero-derivatives, the bottoming SRC accounts for about one-fifth the total combined cycle output. Hence, in the context of a cogeneration system for a sugar factory, industrial turbines may be better suited, since their higher temperature exhaust would generate enough steam to satisfy the process steam demand. However, aero-derivative turbines offer the advantages of higher efficiency and lower capital costs, and should be considered if their use in a combined cycle can satisfy the process steam demand of a sugar factory.

Most gas turbines today are designed for natural gas. The product gas from the gasifier has much lower energy content (4-5 MJ/Nm^3 for directly heated gasifiers and ~10 MJ/Nm^3 for indirectly heated gasifiers) than natural gas (35-40 MJ/Nm^3). Hence, gas turbine combustors and control valves need modifications to accommodate larger volumetric flows of gas to achieve an equivalent energy input. There has been some history of industrial turbines running on low energy content gas, with heating value as low as 3 MJ/Nm^3. There has been no commercial operating experience with low energy content gas in aero derivative gas turbines [16].

The HRSG for a BIGCC system is similar to that of a conventional natural gas based combined cycle. Usually, in conventional medium to large combined cycles, steam is produced at two or three pressure levels due to higher thermal efficiency gains. However, for a BIGCC system, a higher temperature HRSG exhaust can be used to dry the fuel. In that case, a single pressure HRSG could be used. The size of SRC is much smaller than that in a direct combustion Rankine cycle system, since it solely operates on the gas turbine exhaust. Both back-pressure and condensing extraction steam turbines could be used [25].

CHAPTER FOUR

Thermodynamic Analysis of BIGCC Power Generation

4.1 Plant Layout and Process Description

The combined cycle which is under study operates in the dual steam pressure mode, with steam generation taking place in two different devices at high and low pressures, respectively. Figure 4.1 shows the layout of the BIGCC plant.

A high-pressure biomass gasifier operating with sub-stoichiometric air fed from an auxiliary compressor (AC) produces the producer gas from biomass (dry and moisture free wood). The producer gas is cooled in a heat exchanger (HEx), where the cooling water is converted to low-pressure steam for the bottoming cycle (steam cycle). The producer gas is then cleaned in a gas clean-up system and the clean gas is burnt in the gas turbine combustion chamber of the topping cycle. The air flow from the main compressor (MC) to the combustion chamber is controlled to achieve the desired temperature at gas turbine inlet. The high pressure and temperature gas is expanded in the gas turbine coupled with the electric generator (G1).

Combustion of additional biomass fuel is performed in a supplementary combustion chamber (SCC), located after the gas turbine (GT), with the residual oxygen in the gas. The combustion products from the SCC are passed through the Heat Recovery Steam Generator (HRSG), where steam is generated at high pressure for the bottoming cycle. The outlet gas stream from the HRSG can be used for biomass drying in order to remove the moisture content of biomass before feeding it to the plant.

The bottoming cycle of the plant has three turbines, high pressure turbine (HPT), intermediate pressure turbine (IPT) and low pressure turbine (LPT), mounted on the same shaft and coupled with a second electric generator (G2). The steam reheating is done between the HPT and IPT. Some steam is extracted from the IPT outlet for feed water heating along with de-aeration in an open feed heater (de-aerator). The balance steam from the IPT outlet and the low-pressure steam generated in the HEx are expanded together in the LPT.

After condensation of steam in the condenser, the water from the hot well is pumped by the condensate extraction pump (CEP). A part of the water from the CEP outlet is diverted to the HEx for the low-pressure steam generation. The remaining water is led to the de-aerator. A feed pump (FP) pumps the water from the de-aerator to the HRSG for high-pressure steam generation.

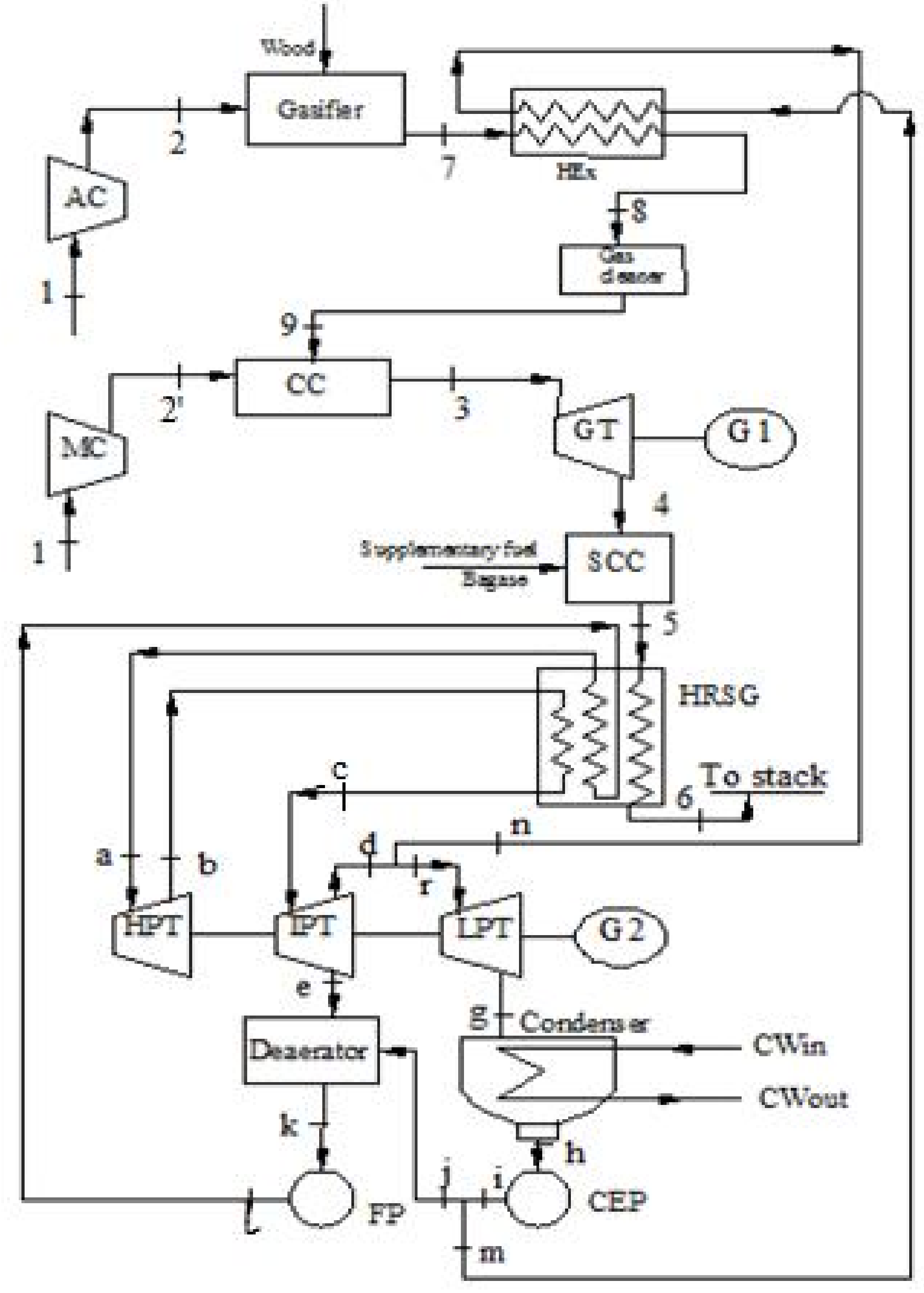

Fig.4.1 Schematic layout of a BIGCC plant with supplementary biomass firing

Where:

HRSG	Heat Recovery Steam Generator	LPT	Low Pressure Turbine
IPT	Intermediate Pressure Turbine	HPT	High Pressure Turbine

SCC	Supplementary Combustion Chamber	HEx	Heat Exchanger
CEP	Condensate Extraction Pump	BFP	Boiler Feed Pump
AC	Auxiliary Compressor	CC	Main Combustion Chamber
MC	Main Compressor	GT	Gas Turbine
G1	Generator one	G2	Generator two

4.2 Process Modelling Methodology

A thermodynamic model is developed for energy and exergy flows across the various plant equipments (refer Fig. 4.1) considering steady state steady flow operation with parameters listed in Table 4.3. Global chemical reactions of fuels are considered in the gasifier and Combustion Chambers. The first law of thermodynamics is used to perform the energy balance across the various equipments. The exergy balance across each individual device of the plant is performed based on the thermodynamic state points of the entry and exit streams as well as the energy exchange. A comprehensive energy and exergy balance for the entire plant is used to evaluate the overall plant performance.

4.2.1. Energy-Based Analysis

The energy balance equations across individual equipment are developed considering energy exchange in the form of heat and work transfers and along with mass flow at the entry and exit.

4.2.1.1. Compressors

The proposed model of the plant has employed two air compressors, the Main Compressor (MC) and the Auxiliary Compressor (AC). Both the compressors breathe air from the atmosphere (P_1=1 bar and T_1=300 K). The discharge pressure of the MC (P_2) is calculated from the Gas turbine pressure ratio ($r_p= P_2/P_1$). The discharge pressure of the AC ($P_{2'}$) is evaluated taking into account the pressure drops in the gasifier, gas side of the heat exchangers and the gas cleaning system, such that the producer gas enters the main combustion chamber at the same pressure as air from the main compressor ($P_9=P_2$). The outlet air temperature and the specific compression work are calculated for each compressor considering the variation in specific heat of air with temperature and the compressor polytrophic efficiency.

The temperature of air (T_{2S}) at pressure P_2 considering isentropic compression and a variable γ ($=C_p/C_v$), due to the variation in temperature, is calculated using a third-order polynomial variation in the specific heats with temperature.

The actual work done on the compressor per kmol of air is [44]

$$W_C = \left[\int_{T_1}^{T_{2S}} C_{P_{air}} \, dT \right] \Big/ \eta_{AC} \tag{1}$$

The work done can be expressed as

$$W_C = \int_{T_1}^{T_2} C_{P_{air}} dT = a_{air}(T_2 - T_1) + \left(\frac{b_{air}}{2}\right)(T_2^2 - T_1^2) + \left(\frac{c_{air}}{3}\right)(T_2^3 - T_1^3) + \left(\frac{d_{air}}{4}\right)(T_2^4 - T_1^4) \tag{2}$$

where the specific heat of air is represented by a polynomial as $C_{Pair} = a_{air} + b_{air}T + c_{air}T^2 + d_{air}T^3$. The constants used in the polynomial expression of C_P are taken from Turns. Equation (2) is solved using the Newton–Raphson method to get the actual temperature (T_2) of air at the compressor outlet.

4.2.1.2. Integrated Gasifier

The only difference between the integrated and stand-alone gasifier sections is the additional heat recovery from the char furnace gases. The gasifier is modelled considering chemical equilibrium of the species in the producer gas. The temperature and composition of the producer gas have been evaluated by the model. Wood is considered as the feedstock for the gasifier. The mass of air supplied by the AC (m_{aAC}) is calculated considering the composition of the feedstock and the gasifier equivalence ratio.

- **Description of the Modelling of the Gasification Process**

The following hypotheses were considered to draw the model:

As discussed in section 3.4, the assumed gasifier is an entrained flow down draft gasifier with the following assumptions.

- ✓ The process is in adiabatic conditions.
- ✓ This process was supposed to occur instantaneously at equilibrium with volatile products mainly made of H_2, CO, CO_2, CH_4 and H_2O.
- ✓ Tars are assumed to be negligible in the syngas and are not taken into account in this study.

The chemical composition of biomass is taken to be in the form $CH_xO_yN_z$ and the gasification reaction can be written in the following form:

$$CH_xO_yN_Z + m_wH_2O + x_g(O_2 + 3.76N_2) =$$
$$x_1CO + x_2H_2 + x_3CO_2 + x_4H_2O + x_5CH_4 + \left(\frac{Z}{2} + 3.76x_g\right)N_2 \tag{3}$$

where x, y, and z are the number of atoms of hydrogen, oxygen, and nitrogen per number of atom of carbon in the feedstock, respectively; m_w is the amount of moisture per kmol of feedstock; and m is the amount of oxygen per kmol of feedstock. All inputs on the left-hand side of Eq. (3) are defined at 25 ^oC. On the right-hand side, x_i are the numbers of mole of the species i that are also unknown. m_w in eq.3 can be calculated using the following relation.

where: M_con is taken to be the moisture content.

$$M\_con = \frac{\text{mass of water}}{\text{mass of dry biomass}}(100\%) \Rightarrow M\_con = \frac{18m_w}{M_{bio} + 18m_w}(100\%)$$

then,

$$m_w = \frac{Mbio * M\_con}{18(1 - M\_con)} \tag{4}$$

With M_{bio} being the molar mass of the biomass feedstock. Since the moisture content is known, the value of m_w becomes a constant.

To find the five unknown species of the producer gas, five equations were required. Those equations were generated using mass balance and equilibrium constant relationships.

- **Mass Balance**

Considering the global gasification reaction in Eq. (3), the first three equations were formulated by balancing each chemical element as shown in Eqs. (5) – (7).

Carbon balance:

$$x_1 + x_3 + x_5 = 1 \tag{5}$$

Hydrogen balance:

$$x + 2m_w = 2x_2 + 2x_4 + 4x_5 \tag{6}$$

Oxygen balance:

$$y + m_w + 2x_g = x_1 + 2x_3 + x_4 \tag{7}$$

- **Thermodynamic Equilibrium**

Chemical equilibrium is usually explained either by minimization of Gibbs free energy or by using an equilibrium constant. To minimize the Gibbs free energy, constrained optimization methods are generally used which requires an understanding of complex mathematical theories. For that reason, the present thermodynamic equilibrium model is developed based on the equilibrium constant and not on the Gibbs free energy. The remaining two equations were obtained from the equilibrium constant of the reactions occurring in the gasification zone as shown below:

Boudouard reaction:

$$C + CO_2 \rightarrow 2CO \tag{8}$$

Water - gas reaction :

$$C + H_2O \rightarrow CO + H_2 \tag{9}$$

Methane reaction:

$$C + 2H_2 \rightarrow CH_4 \tag{10}$$

Zainal et al. and Higman and van der Burgt presented that Eqs. (8) and (9) can be combined to give the water–gas shift reaction by subtracting Eq. (8) from Eq. (9)

Water - gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{11}$$

For the model in this study, the thermodynamic equilibrium was assumed for all chemical reactions in the gasification zone. All gases were assumed to be ideal and all reactions form at pressure 1 atm. Therefore, the equilibrium constants, which are functions of temperature for the water–gas shift reaction and the methane reaction, are:

The stoichiometric equilibrium constant for water–gas shift reaction

$$K_1 = \prod_i (x_i)^{vi} \left(\frac{P}{P^\circ}\right)^{\sum_i vi} = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}} = \frac{n_{CO_2} n_{H_2}}{n_{CO} n_{H_2O}} = \frac{x_3 x_2}{x_1 x_4} \tag{12}$$

The equilibrium constant for methane reaction

$$K_2 = \prod_i (x_i)^{vi} \left(\frac{P}{P_\circ} \right)^{\sum_i vi} = \frac{P_{CH_4}}{\left(P_{H_2}\right)^2} = \frac{n_{CH_4} n_{tot}}{n^2{}_{H_2}} = \frac{x_s}{x_2^2} n_{tot} \tag{13}$$

where x_i is mole fraction of species i in the ideal gas mixture, ν is stoichiometric number (positive value for products and negative value for reactants), P_o is standard pressure, 1 atm, and n_{tot} is total mole of producer gas. Eqs. (12) and (13) can be modified as:

$$K_1(x_1 x_4) = x_3 x_2 \tag{14}$$

$$K_2(x_2^2) = x_s n_{tot} \tag{15}$$

Gibbs free energy is used in determining the value of K_1 and K_2 as presented in eq 16. For the given ideal gas, the Gibbs free energy is a strong function of the reaction temperature and a weak function of pressure.

$$\ln K(T) = \frac{-\Delta G_T^\circ}{RT} \tag{16}$$

$$\Delta G_T = \sum_i \nu_i \Delta \bar{g}^\circ_{f,T,i} \tag{17}$$

where R is the universal gas constant, 8.314 kJ/(kmol.K), ΔG_T° is the standard Gibbs function of reaction, and $\Delta \bar{g}^\circ_{f,T,i}$ represents the standard Gibbs function of formation at given temperature T of the gas species i which can be expressed by the empirical equation below

$$\Delta \bar{g}^\circ_{f,T,i} = \bar{h}^\circ_{f,i} - aT\ln T - bT^2 - \frac{c}{2}T^3 - \frac{d}{3}T^4 + \frac{e}{2T} + f + gT \tag{18}$$

The values of coefficients a–g and the enthalpy of formation of the gases taken from Probstein and Hicks and are shown in Table 1 along with enthalpy of formation at standard reference state of 298 K and 1 atm pressure.

Table 4.1 Enthalpy of Formation and Coefficient for Equation 18

Species	$h^\circ_{f,298}$	a	B	c	d	e	f	g
CH_4	-74.8	$-4.62x10^{-2}$	1.13x10-5	$1.32x10^{-8}$	$-6.65\ x10^{-12}$	$-4.89\ x10^{2}$	14.1	-0.223
CO	-110.5	$5.62x10^{-3}$	-1.19x10-5	$6.38x10^{-9}$	$-1.85\ x10^{-12}$	$-4.89x\ 10^{2}$	0.868	-0.0613
CO_2	-393.5	$-1.95x10^{-2}$	3.12x10-5	$-2.45x10^{-8}$	$6.95\ x10^{-12}$	$-4.89x10^{2}$	5.27	-0.121
H_2O	-241.8	$-8.95x10^{-3}$	$-3.67x10^{-6}$	$5.21x10^{-9}$	$-1.48x10^{-12}$	0	2.87	-0.0172

For calculating K_1 and K_2 , the temperature in the gasification or reduction zone must be known. In this study, it was determined using energy balance method as explained below.

- **Energy Balance**

The temperature of the gasification zone needs to be calculated in order to calculate the equilibrium constants (Eqs. (15) – (17)). For this reason, either energy or enthalpy balance was performed for the gasification process which was usually assumed to be an adiabatic process. When the temperature in gasification zone is T and the temperature at inlet state is assumed to be 298 K (25 ° C), the enthalpy balance for this process can be written as:

$$\sum_{j=reac} h^{\circ}_{f,j} = \sum_{i=prod} ni(h^{\circ}_{f,i} + \Delta h^{\circ}_{T,i}), \tag{19}$$

It can be rewritten as follows:

$$\sum \bar{h}_{f,i} = \sum_{i=prod} n_i h^{\circ}_{f,i} + \left[\left(\sum_i n_i a_i \right) T + \left(\sum_i n_i b_i \right) T^2 + \left(\sum_i n_i c_i \right) T^3 + \left(\sum_i n_i d_i \right) T^4 + \sum_i n_i k_i \right] \tag{20}$$

where h^o_f is the enthalpy of formation in kJ/kmol and its value is zero for all chemical elements at reference state (298 K, 1 atm), and Δh_T represents the enthalpy difference between any given state and at reference state. It can be approximated by:

$$\Delta \bar{h}_T = \int_{298}^{T} C_p(T) dT \tag{21}$$

where $C_p(T)$ is specific heat at constant pressure in kJ/kmol K and is a function of temperature. It can be defined by the empirical equation below (Eq.22)

The final equation was obtained by an enthalpy balance inside the gasifier. Total enthalpy content in any chemical species is the sum of its chemical enthalpy and sensible enthalpy and can be written as follows:

$$
\begin{aligned}
&H^{\circ}_{f-biomass} + m_w(H^{\circ}_{fH_2Ow} + H_{vap}) + x_g(H^{\circ}_{fO_2} + 3.76H^{\circ}_{fN_2}) \\
&= x_1(H^{\circ}_{fCO} + \int_{298}^{Tg} C_{P\,CO}dT) + x_2(H^{\circ}_{fH_2} + \int_{298}^{Tg} C_{PH_2}dT) \\
&+ x_3(H^{\circ}_{fCO_2} + \int_{298}^{Tg} C_{PCO_2}dT) + x_4(H^{\circ}_{fH_2O} + \int_{298}^{Tg} C_{PH_2O}dT) \\
&+ x_5(H^{\circ}_{fCH_4} + \int_{298}^{Tg} C_{PCH_4}dT) + \left(\frac{z}{2} + x_g 3.76\right)\int_{298}^{Tg} C_{PN_2}dT
\end{aligned}
\qquad (22)
$$

Zainal et al have used HHV for predicting syngas composition from biomass. However, the use of LHV for finding heat of formation is also common. In this study, LHV is used for evaluating heat of formation of biomass. Heat of formation of biomass is calculated by using the following equation:

$$H^{\circ}_{f,bio} = LHV + \sum_{i=1}^{n} n_i p_i \qquad (23)$$

LHV is calculated in dry basis of biomass and was calculated using the following equation:

$$LHV = 4.187(81C + 300H - 26(O - S) - 6(9H + m))(KJ/Kg) \qquad (24)$$

The above equation (eq. 15) can be reduced to following form since $H^{\circ}_f N_2, H^{\circ}_f H_2, \text{and } H^{\circ}_f O_2$ are zero at the reference temperature and pressure of 298 K and 1 atm.

$$
\begin{aligned}
&H^{\circ}_{f-biomass} + m_w(H^{\circ}_{fH_2Ow} + H_{vap}) = \\
&x_1(H^{\circ}_{fCO} + \int_{298}^{Tg} C_{P\,CO}dT) + x_2(H^{\circ}_{fH_2} + \int_{298}^{Tg} C_{PH_2}dT) \\
&+ x_3(H^{\circ}_{fCO_2} + \int_{298}^{Tg} C_{PCO_2}dT) + x_4(H^{\circ}_{fH_2O} + \int_{298}^{Tg} C_{PH_2O}dT) \\
&+ x_5(H^{\circ}_{fCH_4} + \int_{298}^{Tg} C_{PCH_4}dT) + \left(\frac{z}{2} + x_g 3.76\right)\int_{298}^{Tg} C_{PN_2}dT
\end{aligned}
\qquad (25)
$$

Equation 25 acts as the constraint for the gasification process and forms the basis for adjusting the amount of air to be supplied. The amount of air is adjusted in such a way that total enthalpy of the reactants is equal to that of products in gaseous form. C_p can be determined using empirical relation that holds for a wide range of temperature.

$$C_P(T) = C_1 + C_2T + C_3T^2 + C_4T^3(KJ/Kg) \qquad (26)$$

Table 4.2. Coefficients of Specific Heat Capacity for Various Gases

Species	C_1	C_2	C_3	C_4
N_2	31.2	$-1.36x10^{-2}$	$2.68x10^{-5}$	$-1.17x10^{-8}$
CO_2	19.8	$7.34x10^{-2}$	$-5.60x10^{-5}$	$1.72x10^{-8}$
H_2	29.1	$-1.92x10^{-3}$	$4.00x10^{-6}$	$-8.70x10^{-10}$
CO	30.9	$-1.29x10^{-2}$	$2.79x10^{-5}$	$-1.23x10^{-8}$
CH_4	19.3	$5.21x10^{-2}$	$1.20x10^{-5}$	$-1.13x10^{-8}$
$H_2O(g)$	32.2	$1.92x10^{-3}$	$1.06x10^{-5}$	$-3.60x10^{-9}$

Sensible heat of each gas species was found by integrating eq. 26 from the ambient temperature to gasification temperature. Values of C_1-C_4 were taken as reported by Reid et al.

An energy balance equation across the gasifier is formed considering the heat loss from the gasifier accounted through the gasifier efficiency term. Elemental balance equations of species, like carbon, hydrogen, oxygen and nitrogen, are formed between the reactant side and the product side of the gasification reaction.

Finally, the following relation is used for calculating the new value of temperature, T_2.

$$T_2 = T_1 + \frac{\left[\begin{array}{l} H^o_{fwood} + w(H^o_{fH_2O(l)} + H_{(vap)}) + H^o_{fO_2} + 3.76mH^o_{fN_2} + \Delta T^{'}(mC_{pO_2} + 3.76mC_{pN_2}) \\ x_1H^o_{fH_2} + x_2H^o_{fCO} + x_3H^o_{fCO_2} + x_4H^o_{fH_2O(vap)} + x_5H^o_{fCH_4} \end{array}\right]}{\left[(x_1C_{pH_2} + x_2C_{pCO} + x_3C_{pCO_2} + x_4C_{pH_2O(vap)} + x_5C_{pCH4} + 3.76mC_{pN_2})\right]} \quad (28)$$

- **Calculation Procedure**

To solve the values of nH_2 ; nCO ; nCO_2 ; nH_2O and nCH_4 an initial temperature was assumed and substituted into Eqs. (16) and (18) to initially calculate K1 and K2. Then, both equilibrium constants were substituted into Eqs. (14) and (15), respectively. Finally, the five simultaneous equations, Eqs. (5), (6), (7), (14), and (15), were used and solved by Newton–Raphson method. For calculating the new value of temperature, Eq. (28) was used. The outlined procedure was repeated until the temperature value was converged. The detail of the calculation procedure is illustrated in.

In this way, the model was run with an elemental composition of woody biomass feedstock. Syngas composition is determined by solving five equations in MATLAB. Complete MATLAB coding for these overall thermodynamic equilibrium model are attached in Appendix A and B.

The solution algorithm has the following some elementary parts:

1. The model requests the preliminary elemental composition and the work temperature.
2. The software computes the Gibbs potential variations in order to succeed in reaching the process temperature evolution.
3. In the stage, the program succeeds in building the equation system and obtains the find syngas composition in dry syngas basis.
4. Evaluate the process temperature and subtracts the evolution sense of the chemical reaction.
5. Using the energy balance could be found the next step temperature variation.

4.2.1.3. Combustion Chamber (CC)

The proposed BIGCC plant has two CCs - main CCs (MCC), firing the producer gas from the gasifier, and the Supplementary Combustion Chamber (SCC), firing additional biomass fuel. Heat loss through radiation and other unaccounted sources from the CC has been accounted through an efficiency term of the CC (refer Table 4.3). The chemical reaction of the fuel is considered to be complete in the CC. The energy balance across the CC is used to determine the mass flow of air (m_{aMC}) required for the combustion of producer gas, generated from the gasification of unit quantity of biomass feedstock, in order to achieve the desired turbine inlet temperature.

The analysis of the main CC evaluates the product gas composition, which contains excess oxygen in it. The maximum fuel that can be theoretically burned in the combustion chamber is that quantity which consumes all the oxygen present at the GT outlet. An energy balance equation is solved across the CC to determine the gas temperature following the combustion process.

We can take the following operating parameters for the plant.

Table 4.3. Assumed Operating parameters of the plant,

Polytropic efficiency of GT (%)	88
Polytropic efficiency of GT (%)	90
Efficiency of gasifier (%)	80
Efficiency of combustor (%)	97
Efficiency of supplementary fuel firing chamber (%)	97
Efficiency of HRSG (%)	98
Pressure drop in gasifier (bar)	0.02
Pressure drop across the cooler (bar)	0.03
Pressure drop in the gas cleaning system (bar)	0.06
Temperature of gas after gas cooler (K)	400
Temperature of gas after gas cleaning system (K)	300
Gasifier equivalence ratio	2.2
Main steam pressure (bar)	80
Main steam temperature (^{o}C)	500
Condenser pressure (bar)	0.1
Deaerator pressure (bar)	8
Steam turbine (HPT, IPT and LPT) isentropic efficiency (%)	85
Pump (CEP and FP) isentropic efficiency (%)	80
Pressure drop in main CC (bar)	0.02
Pressure drop in SCC (bar)	0.07
Pressure drop in HRSG (bar)	0.03
sHRSG minimum pinch point temperature difference (K)	10

Thermodynamic Modelling of the Combined Cycle Power Plant

In developing the model for the combined cycle plant, the energy and mass balance equations are used to analyse the irreversible Brayton and Rankine cycles, with air and water/steam as the working fluids respectively. The plants are combined by using the exhaust from the gas turbine to raise steam in the HRSG without additional fuel input.

The main relations of thermodynamic modelling developed for the various components of interest are developed using the following parameters: the compressor pressure ratio, compressor isentropic efficiency, gas turbine isentropic efficiency, turbine inlet temperature, pinch difference temperature, steam turbine inlet temperature, steam turbine isentropic efficiency, mass flow rates and pump isentropic efficiency. For every individual component, the balance equations are applied to find the power output and the heat required where necessary. The mass and energy balance equations (29) and (30) were used:

Mass Balance Equation:

$$\sum m_i = \sum m_e \tag{29}$$

where: m_i = mass of the working fluid entering the system

m_e= mass of working fluid leaving the system

Energy Balance Equation:

$$\sum E_i + Q_{cv} = \sum E_e + W_{cv} \tag{30}$$

where E_i= total energy of mass entering the system,

Q_{cv}=total energy crossing the boundary as heat

E_e=total energy of mass leaving the system

W_{cv} = total energy crossing the system boundary as work

The complete balance equations for each individual component of the combined cycle which consists the gas turbine, steam turbine and HRSG are summarised in the following sections.

4.2.1.4. Gas Turbine (GT)

The combustion products from the main CC expand in the GT, where no chemical change of the gas is considered. The inlet and outlet pressures across the GT are calculated taking into account the pressure drops across the various equipments in the plant (listed in Table 4.3). The polytrophic efficiency of the GT is used to find out the turbine exit gas temperature as well as the work output of the turbine, for a definite turbine inlet temperature.

By applying the steady flow energy equation to the gas turbine, the power output from a gas turbine according to ([6], [12], [37]) is given as:

$$W_{GT}= m_g C_{p,g}(T_3-T_4) \tag{31}$$

where W_{GT}= gas turbine power out put

m_g = mass of syngas,

$C_{p,g}$ = specific heat capacity of syngas entering the gas turbine,

T_3 = temperature of syngas at turbine inlet,

T_4 = temperature of syngas at turbine exit.

When the steady-state energy equation is applied to an adiabatic compressor, the power, Wcomp , required is given by ([6], [12], [37]):

$$W_{comp} = \dot{m}_a C_{p,air} T_1 \left[\left(1 + \frac{1}{\eta_{AC}} \left(p_r^{\frac{\gamma_a - 1}{\gamma_a}} - 1 \right) \right) - 1 \right] \tag{32}$$

where η_{AC} = compressor isentropic efficiency

p_r= pressure ratio

T_1= inlet air temperature

$\dot{m}_a$ = mass of air

γ_a = specific gas constant ratio

$C_{p,air}$= specific heat capacity of air

The exit temperature, T_2 of the compressor as given by [6] is given by equation (33):

$$T_2 = \left[1 + \frac{1}{\eta_{AC}}\left(pr^{\frac{\gamma_a - 1}{\gamma_a} - 1} - 1\right)\right] \tag{33}$$

Assuming dry air to consist of nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2), the mass of air can be calculated as [2]:

$$m_{air} = \frac{N_{O_2}}{n_{O_2}} \sum_j M_j n_j \tag{34}$$

where j= air component

M_j =molar mass of air compressor

n_{O_2} = mole fraction of oxygen in dry air

n_j= mole fraction of air component

In calculating the mass (m_g) of syngas and mass fractions (mf_i) of syngas components, all the contributions from the combustion air, fuel and oxidation process are summarised together with the mass of water/steam for NO_x control in the combustion chamber and are given by equations (34) to (38) ([2]),:

$$m_g = \sum M_i \left(N_{O_2} \frac{n_{i,air}}{n_{O_2,air}} + n_{i,fuel} + \left(\sum \alpha_i n_i \right)_{fuel} \right) + m_{steam} \tag{35}$$

$$mf_i = \frac{n_i \text{ x } M_i}{\sum_i n_i \text{ x } M_i} \tag{36}$$

where m_i= mass of a component

n_i= mole fraction of the combustible component in fuel

α_i= total number of carbon in a component

M_i = molar mass of a component

The specific heat capacity, Cp,g , of the syngas mixture at a given temperature is [2]:

$$C_{p,g} = \sum_i mf_i \, C_{p,i} \tag{37}$$

where: $C_{p,i}$ = specific heat capacity of a component

The fuel-air- ratio (F/A) for combustion is defined as (([2], ([6]):

$$F/A = \frac{m_{fuel}}{m_{air}} \quad \Rightarrow \quad F/A = \frac{mfuel}{\frac{N_{O_2}}{n_{O_2}} \sum_j M_j n_j} \tag{38}$$

where : m_{fuel}= mass of fuel

An energy balance over the combustion chamber assuming steady flow conditions and ideal gas behaviour is given as ([2], [6]):

$$m_{air} C_{p,air} T_2 + m_{fuel} \, x \, CV = m_g C_{p,g} T_3 + (1 - \eta_{CC}) m_{fuel} \, x \, CV \tag{39}$$

The temperature at the combustor exit is obtained from equation (40) as:

$$T_3 = \frac{C_{p,air} T_2 + F/A \, x \, CV - (1 - \eta_{CC}) F/A \, x \, CV}{(1 + F/A) C_{p,g}} \tag{40}$$

where: CV= calorific value of the fuel

η_{CC} = combustor efficiency

T_3= combustor exit temperature and inlet to the gas turbine

For a percentage pressure drop of ΔP_{CC} across the combustor, the pressure, P_3 in the combustor, when the pressure at the compressor exit is P_2 is determined from the initial compressor state as [10]:

$$P_3 = P_2(1 - \Delta P_{CC}) \tag{41}$$

The exit temperature of the gas turbine, T_4, with an isentropic efficiency, η_T, is modelled as [6]:

$$T_4 = T_3 \left(1 - \eta_T \left[1 - \left(\frac{P_4}{P_2 (1 - \Delta P_{CC})} \right)^{\frac{\gamma_a - 1}{\gamma_g}} \right] \right) \tag{42}$$

where P_4= pressure at the exit of the turbine

By substituting equations (35), (37), (40) and (42) into equation (31), the expected power output (W_{GT}) is given as:

$$W_{GT} = \left[\sum M_i \left(N_{O_2} \frac{n_{i,air}}{n_{O_2 air}} + n_{i,fuel} + \left(\sum_i \alpha_i n_i \right)_{fuel} \right) + m_{steam} \right] x \left(\sum_i mf_i C_{p,i} \right) T_3 \eta_T \left[\left(\frac{P_4}{P_3} \right)^{\frac{\gamma_g - 1}{\gamma}} - 1 \right] \tag{43}$$

4.2.1.5 The Steam Turbine (ST)

Steam turbines work on the principle of converting heat energy into useful work. This is done by nozzles and diaphragms directing the steam flow in such a way to expand from the inlet to the exhaust pressure through high-speed steam jets. The jets' aim is to strike rows of blades on a rotor. Thus, the collision of the steam with the movable blades causes the steam's kinetic energy to be converted to shaft rotation energy.

There are two types of steam turbines, namely, a reaction and an impulse steam turbine. A reaction steam turbine is run on the principle that the steam expands in both the stationary and moving blades. Thus, the moving blades utilise the kinetic energy from the blades on the stator, whilst also acting as nozzles themselves (this implies that there is also a pressure drop across the moving blades – which now act as nozzles). The pressure drop across the movable blades thus produces a reaction force and the force experienced by the high-speed steam jet cause the rotation force experienced by the moving blades.

An impulse steam turbines' concept states that little or no pressure drop is experience across the movable blades. The moving blades extract the shaft rotation energy entirely from the steam energy supplied by the high-speed steam jets. It should be noted that steam turbines are now designed with features from both reaction and impulse turbines in order to fulfil the thermal efficiency and power production demands.

A double pressure Rankine cycle with superheat and reheat is assumed as the bottoming cycle. The reheat pressure can be considered in the range of 0.2–0.25 of the main steam pressure. The main steam pressure and temperature, however, have been considered as input variables, with the pressure varying in the range of 100–150 bar and temperature in the range of 500–600^{o}C. An open type feed water heater is considered here for the deaeration purpose.

The expression for the steam turbine power output (W_{ST}) as given by ([6], [37] is:

$$W_{ST} = \dot{m}_w (h_a - h_g) \tag{44}$$

where: $\dot{m}_w =$ mass of steam flowing

h_a = enthalpy of steam at turbine inlet

h_g= enthalpy of steam at turbine out let

Applying the energy balance to the steam portion of Figure 4.1 and making the relevant substitutions gives the enthalpy at entry to the turbine as ([6], [37]:

$$h_a = \frac{\sum_i M_i \left(N_{O_2} \frac{n_{i,air}}{n_{O_2,air}} + n_{i,fuel} + \left(\sum_i \alpha_i n_i \right)_{fuel} \right) (h_5 - h_6)}{\dot{m}_w} + h_l \tag{45}$$

The pressure at the gas turbine exit is given as [45]:

$$P_4 = \frac{p_o}{(1 - \Delta P_{HRSG})} \tag{46}$$

where: ΔP_{HRSG} = percentage pressure drop in the HRSG

P_o= pressure corresponding to temperature of exhaust gas at HRSG exit

P_4= pressure at gas turbine exit

The enthalpy of steam at the exit of the steam turbine and entry to condenser is estimated as ([6], [37]):

$$h_g = h_h + \frac{\dot{m}_{cw}}{\dot{m}_w} (h_e - h_k) \tag{47}$$

where:

$\dot{m}_{CW}$ =mass of cooling water flowing through the condenser.

The enthalpy of steam at the exit of the pump is given by [6]:

$$h_l = h_h + \frac{W_p}{\dot{m}_w} \tag{48}$$

Applying the energy balance equation and steady flow assumptions and substituting equations (45), (47) and (48) in (44) gives the steam turbine power output as:

$$W_{ST} = \sum_i M_i \left(N_{O_2} \frac{n_{i,air}}{n_{O_2,air}} + n_{i,fuel} + \left(\sum_i \alpha_i n_i \right)_{fuel} \right) (h_5 - h_6) + \left(W_p - \dot{m}_{cw} (h_e - h_k) \right) \tag{49}$$

The pump work for the cycle is evaluated separately for the CEP and the BFP. Considering their respective isentropic efficiencies, the total work consumption in the two pumps is:

$$W_P = m_s(1 - m_e)(h_g - h_f) + m_s(h_i - h_h) \tag{50}$$

4.2.1.5. Heat Recovery Steam Generator (HRSG) and Heat Exchangers (HEx)

The HRSG system literally links the gas turbine with the steam turbine and is responsible for decreasing the temperature of a stream and maximising the energy recovery. Its advantages are that it has a high thermal efficiency, is easily constructed and environmentally friendly. Due to the gas and steam turbine producing useful work from one process stream of fuel, the process is more economical.

The HRSG is implemented directly after industrial processes or power generation systems that release high-temperature exhaust gases. In the case of power generation systems, the HRSG is located directly after the gas turbine in order to increase the overall thermal efficiency of the power generation plant. A gas turbine's exhaust stream generally has temperatures ranging from 450-600°C. Thus, a gas turbine is thermally, inefficient. However, by incorporating a HRSG, steam can be generated and utilised to produce further useful work by driving a second generator through a steam turbine.

A gas turbine HRSG system can be sub-divided into 3 main sections; a super heater, boiler or evaporator and economiser. The gas inlet stream is located at the super heater and the gas outlet stream at the economiser. The super heater is responsible for heating the steam. The evaporator has a steam drum and is responsible for the steam temperature decrease of the process stream. The economiser reduces the overall fuel requirements of the boiler by preheating the water boiler-feed to a higher temperature using the boiler's heated stack gas; hence the boiler requires less energy to boil the water.

The waste heat from the topping cycle as well as the energy added in the supplementary firing are recovered for the generation of high pressure bottoming cycle steam in the HRSG. Additionally heat is also recovered from the high temperature producer gas in a HEx, before supplying the gas to the gas cleaning system. The recovered heat in the HEx is utilized to generate low-pressure steam for the bottoming cycle. The analysis of the HRSG and the HEx are done, based on energy balance across the devices, to evaluate the steam flow rate through them. The steam parameters (pressure and temperature) are chosen as plant input data (given in Table 3). Suitable efficiency terms are considered in the energy balance equations accounting the heat losses from the devices.

The high temperature gas is considered to be cooled from T_5 at the inlet to the HRSG to T_6 at its outlet, whereas the condition of feed water at the entry to the HRSG is obtained from the steam cycle analysis as the condition after the feed pump. The steam parameters at the HRSG exit are fixed by the turbine inlet parameters, which are given as inputs.

In case of HEx, the temperature of the gas at the outlet of the device is set at 400 K based on the requirement of cleaning system. This condition results in a relatively higher pinch point temperature difference for the steam parameters associated with the device.

4.2.2. Exergy Analysis of the Cycle

The exergy analysis of the cycle involves both the thermo mechanical exergy and chemical exergy of the streams across each device. The specific thermo mechanical flow exergy (b_i^{th}) at any state is calculated as,

$$b_i^{th} = h_i - h_r - T_r(S_i - S_r) \tag{51}$$

Where ‘i’ represents the state point (as given in Fig 4.1) at which the exergy is evaluated and ‘r’ is the exergy reference environment. In Eq. 32, h and s represent the specific enthalpy and specific entropy, respectively where,

$$h_i - h_r = \int_{Tr}^{Ti} C_p dT \tag{52}$$

$$s_i - s_r = \int_{Tr}^{Ti} C_p \frac{dT}{T} - R \ln \frac{P_i}{P_r} \tag{53}$$

In the above two equations C_p and R represent the specific heat and gas constant, respectively, and P and T are the pressure and temperature.

The chemical exergy is defined with respect to the true dead state, which considers the chemical composition of the reference environment in addition to the reference pressure and temperature. In the combustion literature chemical availability is often associated when useful work can be extracted through chemical reaction at reference temperature and pressure conditions. We have followed this concept in evaluating chemical exergy.

The specific chemical exergy of the biomass (b_b^{ch}) is obtained from its lower heating value using a multiplication factor β given as:

$$\beta = \frac{1.044 + 0.0160\frac{H}{C} - 0.34493\frac{O}{C}\left(1 + 0.0531\frac{H}{C}\right)}{1 - 0.4124\frac{O}{C}} \tag{54}$$

where, C, H and O are the carbon, hydrogen and oxygen percentages in the biomass, respectively.

The producer gas from the gasifier possesses chemical exergy (b_g^{ch}) in addition to the thermo mechanical exergy (b_g^{th}), which is due to the elevated pressure and temperature of the gas and the mixing of the constituents. The specific chemical exergy of the producer gas is given as,

$$b_g^{ch} = \sum_j x_j b_j^{ch} \tag{55}$$

where, b_j^{ch} represents the specific chemical exergy of the j^th^ species in the producer gas and X_j denotes the mass fractions in the producer gas.

The exergy balance equation across any equipment of the plant for a steady state operation can be written as follows:

$$B_{in} - B_{out} - W + \left(1 - \frac{T_r}{T_s}\right)Q - B_d = 0 \tag{56}$$

where, B_{in} and B_{out} represent the exergy flowing in and out, respectively, along with the respective mass flows across the equipment and W is the work transfer across the control surface. The flow exergy terms consider both the thermo mechanical and chemical contributions associated with the mass flow. The term $\left(1 - \frac{T_r}{T_s}\right)Q$ represents the exergy loss associated with heat transfer Q and T_s represents the temperature of the system from which the heat transfer takes place. The exergy destruction due to process irreversibility is represented by B_d. Exergy analysis of equipment depicts the deviation of the performance of the equipment from ideality. This deviation is the result of various process irreversibility associated with the equipment and can be gauged by the exergetic efficiency. Exergy analysis is particularly useful in identifying the locations of major thermodynamic irreversibility in a process so that appropriate measures can be taken to improve the performance.

Exergetic efficiency expressions for different equipment are derived by applying the exergy balance equation which takes different forms depending upon the function of the equipment.

Table 4 lists the exergetic efficiency expressions of the major equipments in the proposed cycle.

Table 4.4. Expressions of exergetic efficiency of different plant components.

Main Compressor(MC)	$\frac{B_2^{th} - B_1^{th}}{W_{AC}}$
Gasifier	$\frac{B_7^{th} + B_g^{ch}}{B_2^{th} + B_{wood}^{ch}}$
Heat Exchanger(HEx)	$\frac{B_n^{th} - B_m^{th}}{B_7^{th} - B_8^{th}}$
Gas Cleaner	$\frac{B_8^{th}}{B_9^{th}}$
Combustion Chamber(CC)	$\frac{B_3^{th} + B_3^{ch}}{B_2^{th} + B_9^{th} + B_g^{ch}}$
Gas Turbine(GT)	$\frac{W_{GT}}{B_3^{th} - B_4^{th}}$
Supplementary Firing Chamber	$\frac{B_5^{th} + B_5^{ch}}{B_{bagasse}^{ch} + B_4^{th} + B_4^{ch}}$
Heat Recovery Steam Generator(HRSG)	$\frac{\left(B_a^{th} - B_1^{th}\right) + \left(B_c^{th} - B_b^{ch}\right)}{B_5^{th} - B_6^{th}}$
High Pressure Steam Turbine	$\frac{W_{HPT}}{\left(B_a^{th} - B_b^{th}\right)}$
Intermediate Pressure Steam Turbine	$\frac{W_{IPT}}{\left(B_c^{th} - B_d^{th}\right)}$
Low Pressure Steam Turbine	$\frac{W_{LPT}}{\left(B_f^{th} - B_g^{th}\right)}$
Deaerator	$\frac{B_k^{th}}{B_e^{th} + B_f^{th}}$

4.3. Performance Indicators of the Cycle

The thermal efficiency of the plant is computed using the net work output and the thermal energy input as follows,

$$\eta = \frac{W_p - W_n}{Q_{in}} \tag{57}$$

where, W_p and W_n are the total positive and negative work transfers across the plant and Q_{in} is the net heat input as fuel energy. Based on the performance of the individual equipment,

$$W_p = W_{GT} - W_{ST} \tag{58}$$

And,

$$W_n = W_{MC} + W_{AC} + W_{CEP} + W_{FP} \tag{59}$$

In the above equations, W_{GT} is the work done by the GT and W_{ST} is the total work done by the steam turbine (i.e. HPT, IPT and LPT taken together). While, W_{MC}, W_{AC}, W_{CEP}, and W_{FP} are the work required for the MC, AC, CEP and FP, respectively. The net heat input is given by,

$$Q_{in} = m_{b1} LHV_{b1} + m_{b2} LHV_{b2} \tag{60}$$

where, m_{b1} and m_{b2} are the mass of wood and bagasse, respectively, which are consumed for the energy conversions and LHV_{b1} and LHV_{b2} are the lower heating values of the two fuels, respectively.

The exergetic efficiency of the total plant is defined as the net work output of the plant as a fraction of the total exergy input (B_{in}), i.e,

$$\varepsilon = \frac{W_p - W_n}{B_{in}} \tag{61}$$

The exergy input is computed as,

$$B_{in} = m_{b1}\, b_{b1}^{ch} + m_{b2}\, b_{b2}^{ch} + (m_{aMC} + m_{aAC}) b_1 \tag{62}$$

where, b_{b1}^{ch} and b_{b2}^{ch} are the specific chemical exergy of wood and bagasse, respectively, and m_{aMC} and m_{aAC} are the mass of air inducted in the MC and AC, respectively. The thermo mechanical exergy of the inlet air stream to the compressors at the atmospheric pressure and temperature conditions is given by b_1.

4.3.1 Analysis of Heat and work transfer in a GT-ST combined cycle plant

In order to find out the reason behind the nature of variation in thermal efficiency of a BIGCC plant, I analyzed the plant performance using heat and work transfers as shown in Figure 4.2.

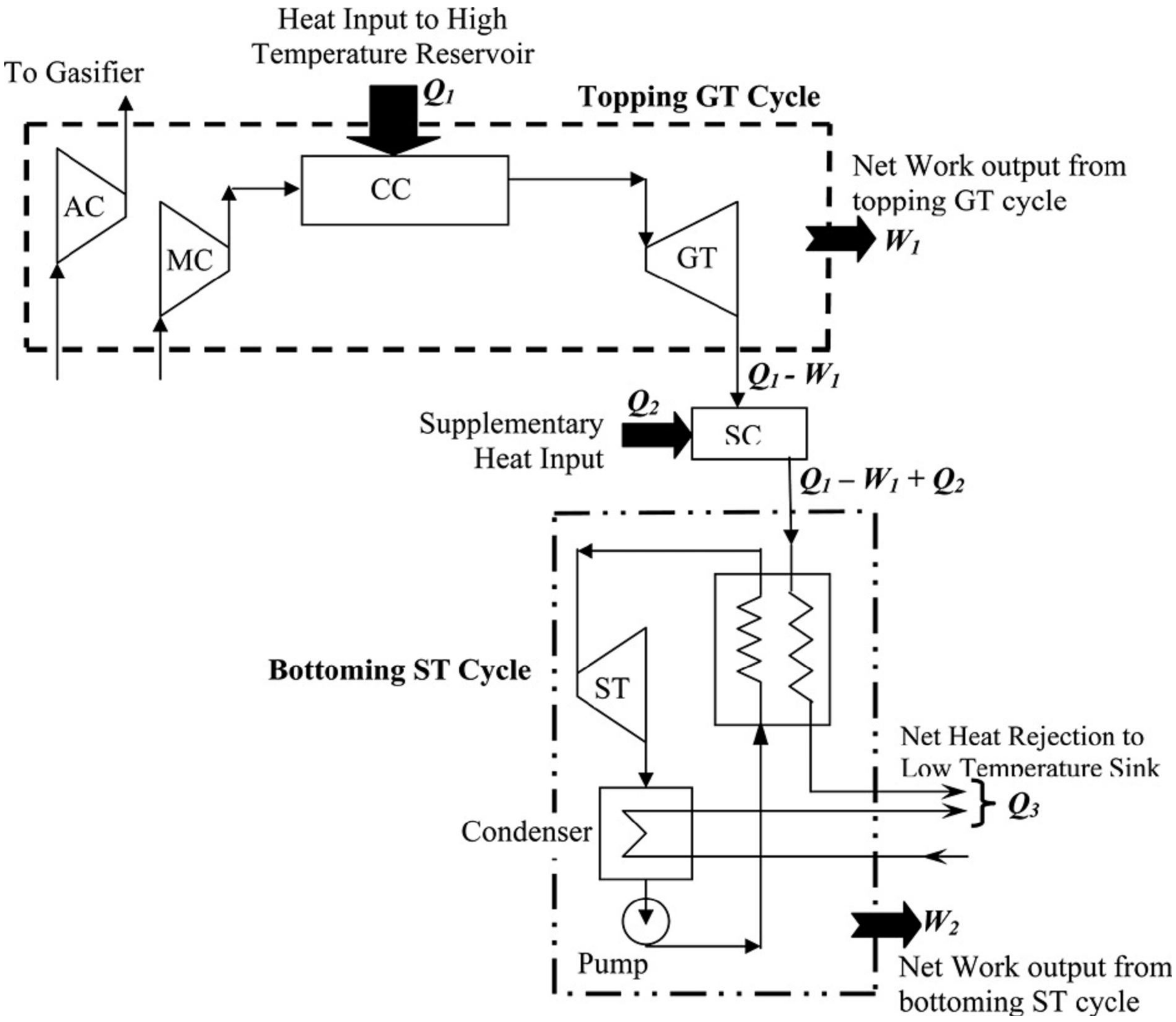

Fig.4.2 Heat and work transfer in a GT-ST combined cycle plant.

From the figure, the overall efficiency of the plant can be expressed as,

$$\eta = \frac{W_1 + W_2}{Q_1 + Q_2} \tag{63}$$

where, W_1 and W_2 are the work output from the topping and bottoming cycles, respectively, and Q_1 and Q_2 are the heat added in the main and SCCs, respectively.

The efficiency of the topping cycle can be expressed as,

$$\eta_1 = \frac{W_1}{Q_1} \tag{64}$$

while that for the bottoming cycle is,

$$\eta_2 = \frac{W_2}{(Q_1 - W_1) + Q_2} \tag{65}$$

The overall efficiency can be expressed in terms of the efficiencies of the component cycles as,

$$\eta = \eta_2 + \eta_1(1 - \eta_2)\left(\frac{Q_1}{Q_1 + Q_2}\right) \tag{66}$$

The combined cycle efficiency is much greater than either the gas turbine or the steam turbines efficiencies separately.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 Effects of Gasification Operating Conditions on the Product Properties

The composition of the gas obtained from a gasifier depends on a number of parameters such as:

- Fuel composition
- Gasifying medium,
- Operating pressure
- Operating Temperature
- Moisture content of the fuels
- Mode of bringing the reactants into contact inside the gasifier, etc.

It is very difficult to predict the exact composition of the gas from a gasifier. Introduction of the water–gas equilibrium concept provides the opportunity to calculate the gas composition theoretically from a gasifier, which has reached equilibrium at a given temperature.

To obtain the desired product gas composition, the least amount of impurities, and to increase the net energy conversion efficiency, gasification operating conditions need to be optimized. The following section describes the effects of the main operating conditions on the quantity and composition of the product gas and its impurities as obtained from the MATLAB model.

Parameters that Effect the Composition of Producer Gas

The composition of the producer gas is highly important, and determines what types of applications gasification can be used with. The specifications for producer gas are very different for fuel and chemical applications than they are for thermal and engine applications.

5.1.1. The Effect of Moisture Content on Syngas Composition

The effect of moisture content on the composition of producer gas from waste gasification is an interesting aspect. Fig. 5.1 shows the effect of moisture content on the composition of producer gas. It can be seen that the fraction of H_2, H_2O, and CO gradually increases when moisture content increases from 0% to 45%. In the case of CO, it showed an inverse tendency. CO decreases with an increase in moisture content. The useful gas CH_4, has a very low percentage in the producer gas, though it showed a slight increase from.

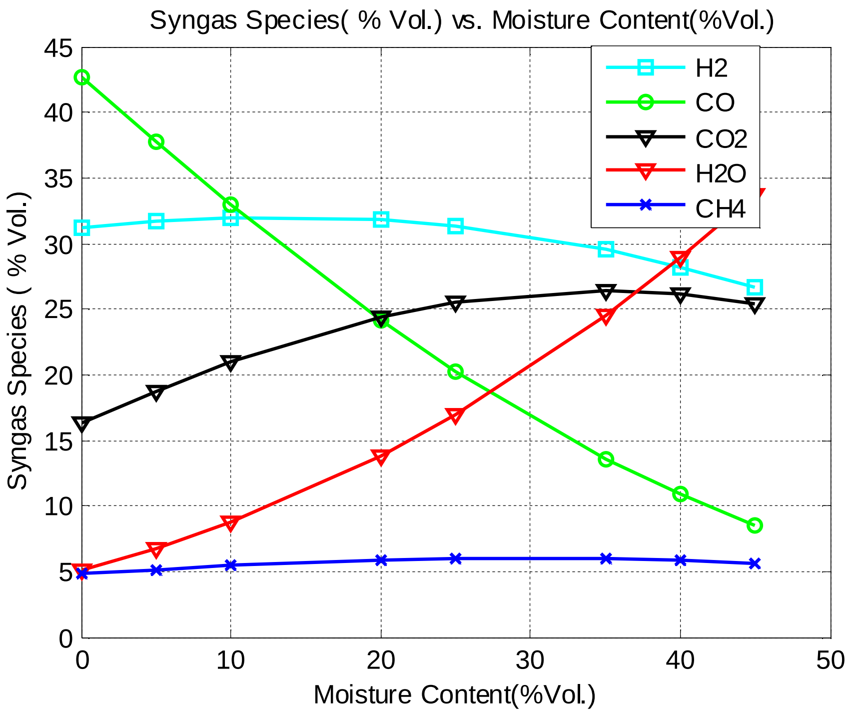

Fig.5.1 Effect of moisture content on syngas composition

5.1.2. The Effect of Temperature on Gasification Reactions

Gasification temperature is one of the most influential factors affecting the product gas composition and properties. Higher temperature results increased gas yield because of higher conversion efficiency. Since, the reactions (Equations 5–8, chapter 4) occur simultaneously, the contents and ratios of H_2, CO, CO_2 and CH_4 in the product gas are affected by temperature and partial pressures of reactants.

At higher temperatures, total gas yields are generally higher but the heating value of the producer gas decreases, because less methane and light hydrocarbons are formed with more hydrogen instead. Although the heating value of the gas is reduced, the quantity yielded increases with increasing temperatures. Correspondingly the quantities of char and liquids formed are reduced. This is believed to be due to the further cracking of liquids and enhanced char reaction with the oxidising agent. Other factors which may increase gas yields at higher temperatures include: a higher production of pyrolysis gases, greater gas production from char at higher endothermic reaction temperatures, and an increase in gas yield due to steam reforming and cracking of heavier hydrocarbons.

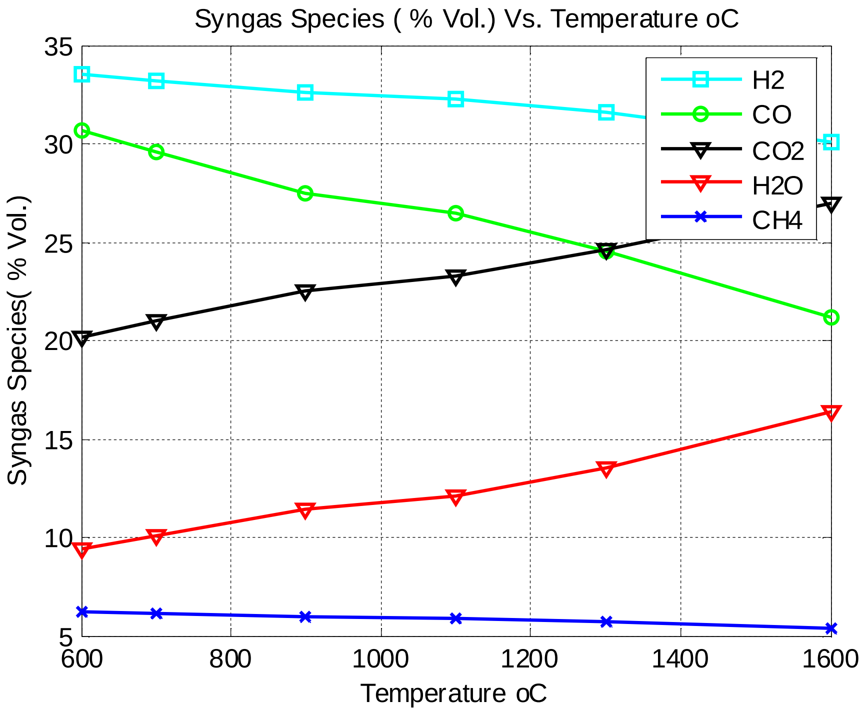

Fig. 5.2 Effect of temperature on syngas composition

From the thermodynamic model, we can conclude that raising gasification temperatures favours the formation of hydrogen and usually carbon monoxide (but CO trends can differ). The increase in the hydrogen content is more distinct with increasing temperatures. Hydrocarbon contents often decrease with increasing reactor temperatures. The formation of methane and to a lesser extent CO_2 is favoured by lower reaction temperatures.

5.1.3. Effect of Pressure on Gasification Reactions

Elevated pressures increase the concentration of methane and carbon dioxide yielded, while the concentrations of hydrogen and carbon monoxide decrease many gasifiers operate at elevated pressures. The reason for operating at elevated pressures is the compression energy requirements are less and equipment can be smaller, improving economic viability. The pressure in a gasifier is generally selected in accordance with the requirements of the process or downstream equipment. When elevated pressures are required, compression of the reactants is energetically superior to compression of the producer gas.

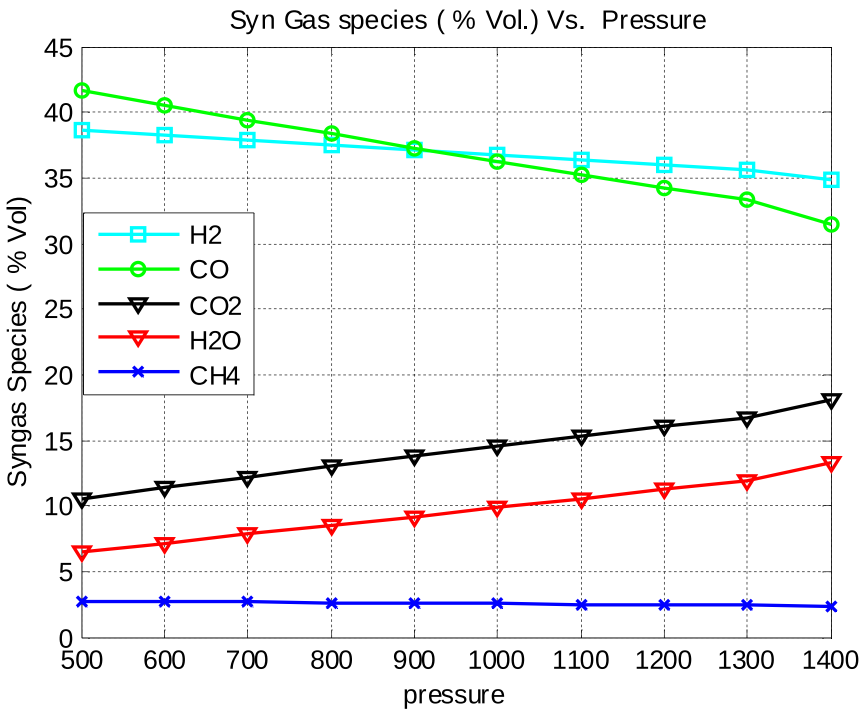

Fig.5.3 Effect of pressure on syngas composition

5.1.4. Steam to Air Ratio Variation and its Effect on the Composition

In some gasifiers, the injection of steam in the bed allows controlling reaction temperature and favors the hydrogen production by water gas shift reaction. At the same time carbon monoxide amount decreases.

With increasing steam to fuel ratio, hydrogen increases and methane levels decrease. A parameter which needs to be considered when investigating the steam to biomass ratio is the water consumption. The steam content in the producer gas increases with increasing steam to biomass ratio. This relationship does not appear to have a linear dependency and is shown in adding excessive amounts of steam can cause too much thermal energy to be consumed in raising the steam to the temperatures found in the gasification reactor. However, excess steam can be desirable to minimise the levels of tar.

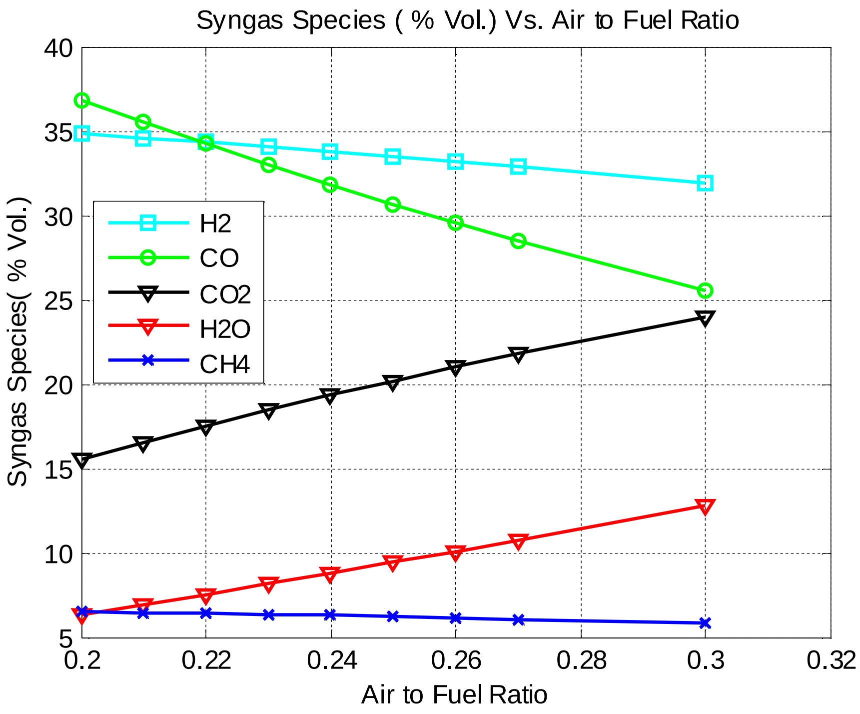

Fig.5.4 Effect of air to fuel ratio on syngas composition

5.2. Economical and Social Issues

5.2.1 Economical Issues

Plant economics is the primary important parameter in any engineering design. Unit size, treatment capacity, the nature of the material to be treated, and the mode of energy recovery chosen, all determine the purchase and installation costs for an integrated biomass gasification system. Thermal efficiency is considered to be important in the design of thermodynamic power cycle, as it has a direct bearing upon the fuel cost. An efficient power cycle produces more work output from the same heat input, i.e. more energy can be produced by burning the same quantity of fuel in a more efficient cycle.

The ideology of a biomass integrated combined cycle plant is appealing. Biomass gasification combined cycle offers the world a high technology, high-efficiency renewable generation option. It increases the resource efficiency of the nation by using a fuel which is often waste and reduces our fossil fuel dependence by offering a carbon neutral base-load generation technology. However, BIGCC does not utilise the advantages of gasification. Primarily gasification is an enabling technology for gas turbine and gas engine power generation fuelled by biomass, which is presumably in plentiful supply and cheap. In order for the additional step of gasifying a fuel to be economically viable, the additional capital costs of the gas turbine/engine process has to be justified by the gains from increased efficiency. Increased efficiency gains are fuel savings. When the cost of fuel is low, as is the case with biomass, fuel savings are less important.

For instance, installing a natural gas combined cycle process instead of the simpler natural gas turbine process is economically appealing when the price of natural gas is above ~$4/GJ based on assuming the two systems have similar installation costs. If the gasification and associated units increased the cost of each process equally, then there is a $4/GJ hurdle which fuel costs need to exceed for combined cycles to be favoured over gas turbine only cycles. This analysis takes no heed of the higher value heat provided by a gas turbine cycle and compares the relative merits of gas turbine cycles against combined cycles. It does not speak for the economics of each process individually. Unfortunately for biomass gasification, the economics of both are not favourable.

Fully commercialized, BIGCC is expected to be a major cost-competitive, large-scale bio power technology. Recent estimates from the U.S. Energy Information Administration (EIA) put the levelized cost of electricity from BIGCC in the U.S. at 10.7 cents per kilowatt-hour (kWh) (2007

USD) [8], which is nearly 20 percent more than the expected levelized cost of electricity from a traditional new coal or natural gas power plant. These estimates also put the levelized cost of bio power above that of wind power, but since bio power is not variable like wind power, bio power can still be a preferred choice in many situations.

BIGCC is now in early stage of deployment. The size of a BIGCC plant is determined by the gas turbine selected. The number of suitable gas turbines is rather limited today. The main issue is the development of the gas turbine combustion system to burn low calorific value gas obtained from biomass gasification. The cost/kWe of the plants is higher compared to fossil fuel based steam cycle plants, but is expected to fall in the future due to likely advances in gas turbine technology.

Considering the growing importance of the technology, various authors have attempted to estimate the cost of BIGCC systems (van den Broek et al., 1996; Craig and Mann, 1998 and DOE, 1997 [8]). In general the cost depends on technology type and capacity of the systems.

5.2.2 Social Issues

There are many social benefits of using green biomass for energy production, such as: the creation of a market for biomass fuels, local employment opportunities for entrepreneurs and development of skills, rural stability on an environmentally sound basis, local control of reserves, and promotion of an appropriate political and economic infrastructure. On the other hand, there are worries that a widespread use of gasifiers could greatly increase the pressure in existing wood and charcoal supplies. In areas of fuel scarcity, the impact on the poor, who depend mainly on biomass fuels, could be severe.

5.2.2.1 Environmental Consideration

In comparison to oil and coal fuels, producer gas from the gasification of biomass has much lower sulfur content. This reduces SO_2 emissions and lowers the risk of soil and water acidification. Producer gas has a number of adverse impacts on land-use, occupational and public health, as well as in the natural environment. However, with properly designed management systems and by following safety procedures, the impacts of using producer gas can be minimized. If these problems are taken care of, producer gas can be a good alternative to fossil fuels, and help many developing countries to improve their balance of payments by decreasing fossil fuel imports.

5.2.2.2 Advantages

One of the most attractive features of the BIGCC Power Generation technology is its potential applicability to a variety of fuels. The most pressing need for advanced gasification technology is for repowering of older coal-, oil-, and/or gas-fired boilers that typically have low efficiency and high emission levels. This technology solves the problems associated with conventional wood-burning technologies and holds great promise as a technology that can effectively dispose of biomass and wood waste while meeting strict fine particle regulations at a lower cost than current systems. BIGCC technology brings many advantages to an energy-hungry but cost-conscious world:

- A Clean Environment

BIGCC can meet all future environmental permitting constraints for the generation of electric power. In an BIGCC system, 99 percent of the coal's sulfur is removed before combustion, NO_x is reduced by over 90 percent, and CO_2 is cut by 35 percent. This environmental performance matches or exceeds that of alternate energy sources.

- High Efficiency

The efficiencies that will be achieved by BIGCC over the next two decades, ranging from 42 to 52 percent, contrast favourably with efficiencies of at best 34 percent offered by existing coal plants with installed flue gas desulfurization capabilities.

- Low-Cost Electricity

BIGCC offers low cost of electricity. The cost of BIGCC-generated electricity is now competitive with the cost of electricity produced by a conventional pulverized coal plant, and by 2010, it will drop to 75 percent of this cost.

- Low Capital Costs

The BIGCC plant is cost-competitive to build, at a plant construction cost of $1,200-1,500 per kilowatt right now, and $1,050 per kilowatt by 2010. Costs will drop further in subsequent years.

- Repowering Of Existing Plants

The components of the BIGCC system can be integrated into an existing system in modular form, allowing a user to take advantage of an existing site and its steam-generating equipment. Staged additions can be made in blocks to match one or more steam generators, and will give the resulting system two-and-a-half times the generating capacity.

- Modularity.

The modular nature of BIGCC plant systems allows for staged additions in blocks ranging in size from 100 to 450 megawatts. As advanced turbine systems evolve, the capacity of single units will increase, and the trend will be to add large-capacity modules.

- Fuel Flexibility

The combined-cycle portion of a BIGCC plant can be fuelled by natural gas, oil, or coal. This means not only that a plant can switch to coal from natural gas as gas becomes unavailable or unacceptably expensive, but also that an BIGCC plant can be fuelled by natural gas or oil in case of unplanned events such as disruption in fuel supply. In addition, most gasifier systems can be easily adapted to different coals.

- Phased Construction

BIGCC systems are unique in the economical way in which they meet the demands of utility growth patterns. A first-phase installation might include only a gas turbine, operating as a simple natural gas-fired cycle and providing about two-thirds of the plant’s ultimate capacity. Addition of a steam turbine would create a combined cycle with full capacity. A third phase of installation would integrate the gasifier and gas cleanup systems when justified by low coal prices, lack of gas availability, or need for conversion to base load capacity.

- Low Water Use

The water required to operate a BIGCC plant is only 50 to 70 percent of the quantity required to run a pulverized coal plant with a flue gas desulfurization system.

- Low CO_2 Emissions

BIGCC systems offer significant reductions in CO_2 emissions per unit of power produced, because their higher efficiency means that less coal must be burnt to produce each unit. When combined with the fuel cell systems of the future, BIGCC technology will be able to further reduce CO_2 emissions per unit of electricity.

- Continuous Product Improvement.

The BIGCC system is composed of several major elements that are the subject of ongoing advanced research and development. This development follows a planned progression toward ever more efficient performance by the technology.

- Reusable Sorbents.

Reusable process media remove sulphur from the coal-derived gas prior to combustion in the gas turbine. By contrast, Rue gas desulfurization of pulverized-coal and fluidized-bed power plants uses limestone, dolomite, or other sulphur sorbents that require disposal.

- Marketable By-Products.

Waste disposal is minimal at an BIGCC plant. The sulfuric acid or elemental sulfur that is produced is a marketable product. Ash and any trace elements are melted, and when cooled, become an environmentally safe, glass-like slag that can be used in the construction or cement industries.

- Co-Products.

In addition to producing electricity, the coal gasification process can be diverted to co-produce such products as fuels in the form of methanol or gasoline, urea for fertilizer, hot metal for steel making, and chemicals.

- Demonstrated Success

The BIGCC system is being demonstrated fully by multiple projects under way that not only foster competition and rapid product improvement, but also show conclusively how successfully the system operates and how it can be maintained. A full range of variations of the BIGCC process will be demonstrated: several different gasifiers, cleanup systems, repowering applications, and coals, and combinations of such elements.

- Public Acceptability

IBGCC sites offer an acceptable electric power generation option to a public concerned about environmental hazards and waste. Negligible plant emissions, little or no waste, safe jobs for workers, safe environments for their families, low-cost electricity for their homes, and job security based on a dependable demand for the plant’s product are factors that result in acceptance by the general public.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

A thermodynamic analysis has been performed on a BIGCC using a downdraft gasifier fuelled by wood derived gases. A BIGCC power plant is essentially an electrical power plant in which a gas turbine and a steam turbine are used in combination to achieve greater efficiency than would be possible independently.

The fuel is biomass in the form of wood chips and is converted into producer gas by a downdraft gasifier. The gas cleaning is performed to separate dry syngas and tar. The dry syngas provides the top cycle with energy, while tar and the flue gas from the engine are the source of energy for the bottom cycle. The top and the bottom cycle are respectively a gas engine and a Rankine cycle (steam cycle).

The paper concludes that it is possible to integrate a gas turbine and a steam turbine to get additional power in an efficient way as BIGCC plants use the hot exhaust gas from gas turbines to make steam, which drives a steam turbine which drives a generator to produce electricity. Power output of the steam turbine is typically $^{1}\!/_{3}$ of the total output of the total power output of the combine cycle power plant. It is this “extra” electricity produced from the same amount of turbine energy (without additional fuel consumption) that makes a combined cycle plant much more efficient than a simple cycle gas turbine peaking plant.

From the proposed model, it is shown that by changing various relevant parameters of the integrated gasifier, parametric studies can be carried out to determine thermodynamic and engineering parameters as well as suitable operational conditions.

BIGCC systems are efficient low cost systems that provide assurances of performance and operating objectives. BIGCC systems can be customized to the utility needs and preferences. They offer attractive economical reliable power generation. Operating flexibility of Combine Cycle power generating warrant their consideration for most power generation applications. Besides they are fun to work on and offer the utility engineer a unique and challenging design opportunity.

When efficiency, cost-of-electricity, and environmental benefits are compared, BIGCC technology scores higher than many other advanced technologies that will be available to meet the energy needs of the next several decades, and it is likely that BIGCC will be one of the most attractive power generation technologies for the 21st century.

6.2 RECOMMENDATIONS

The following areas of interest can be looked to extend the research work on BIGCC power generation system:

- It can be modelled using different softwares such as ASPEN plus and IPSE pro.
- Designing each individual components of the system
- Individual component cost estimation calculations
- Experimental investigation of the cycle

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APPENDICES

APPENDIX A

The following MATLAB code is used for syngas equilibrium modelling for adiabatic conditions.

```
%Syngas Species (% Vol.) Vs. Moisture content (% Vol.)
clear all
clc
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% M_Con   Moisture content (% Vol.)
% mwb     Moles of water per moles of biomass
% mob     Moles of oxygen per mole of biomass
% x_i     Composition of syngas
% K_i     Equilibrium constant
% T1      Temperature at first assumed value in K

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
format short
for M_Con=0.0:0.05:0.45;
    T1 = 650;
    error =1;
    error_max =0.5;
    iter =0;
    a =[0.1 0.1 0.1 0.1 0.1];
    for i =1:5
        x1 =a(i);x2 =a(i);x3 =a(i);
        x4 =a(i);x5 =a(i);
    end
    R =8.314;
    w=(24*M_Con)/(18*(1-M_Con));
    m =0.30;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % MAIN LOOP FOR SOLVING THE EQUATIONS OF INTERESTS %%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    while (error >= error_max)
        iter =iter+1;
        result(iter,1) =iter;
        T =T1;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % Function for finding sensible heat for various gases constants 
(KJ/Kmol)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        Cp_CO2 =22.26+5.981*10^-2*T-3.501*10^-5*T.^2-7.469*10^-9*T^3;
        Cp_CO =28.16+0.1675*10^-2*T+0.5372*10^-5*T.^2-2.222*10^-9*T^3;
        Cp_CH4 =19.89+5.204*10^-2*T+1.269*10^-5*T.^2-11.01*10^-9*T^3;
        Cp_H2O =32.24+0.1923*10^-2*T+1.055*10^-5*T.^2-3.595*10^-9*T^3;
        Cp_N2 =28.90-0.1571*10^-2*T+0.8081*10^-5*T.^2-2.873*10^-9*T^3;
        Cp_H2 =29.11-0.1916*10^-2+0.4003*10^-5*T.^2+-0.8704*10^-9*T^3;
        Cp_O2 =29.11-0.1916*10^-2+0.4003*10^-5*T.^2+-0.8704*10^-
9*T^3;%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % finding general equations for calculating K1 and K2

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
        delta_gfT_CH4 =-74.8+4.62*10^-2*T*log(T)-1.13*10^-5*T^2-(1.32*10^-
8/2)...
            *T^3+(6.65*10^-12/3)*T^4-4.89*10^2/(2*T)+14.1-0.223*T;
        delta_gfT_CO =-110.5-5.62*10^-3*T*log(T)+1.19*10^-5*T^2-(6.38*10^-
9/2)...
            *T^3+(1.85*10^-12/3)*T^4-4.89*10^2/(2*T)+0.868-0.0613*T;
        delta_gfT_CO2 =-393.5+1.95*10^-2*T*log(T)-3.12*10^-5*T^2+(2.45*10^-
8/2)...
            *T^3-(6.95*10^-12/3)*T^4-4.89*10^2/(2*T)+5.27-0.121*T;
        delta_gfT_H2O =-241.8+8.95*10^-2*T*log(T)+3.67*10^-5*T^2-(5.21*10^-
9/2)...
            *T^3+(1.48*10^-12/3)*T^4-0+2.87-.0172*T;
        delta_gfT_H2 =0;
        delta_GT_1 =x3*delta_gfT_CO2+x1*delta_gfT_H2-x2*delta_gfT_CO-
x4*delta_gfT_H2O;
        delta_GT_2 =x5*delta_gfT_CH4-x1*delta_gfT_H2;
        k1 =exp(-delta_GT_1/(R*T));k1=0.3165;
        k2 =exp(-delta_GT_2/(R*T));k2=2.3379;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %Heat of formation of different compounds at 298K, kJ/kmol %%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        H_f_H2 =29.11*T-0.1916*10^-2*T^2+0.4003*10^-5*T^3-0.8704*10^-9*T^4;
        H_f_CO =28.16*T+0.1675*10^-2*T^2+0.5372*10^-5*T^3-2.222*10^-9*T^4;
        H_f_CO2 =22.26*T+5.981*10^-2*T^2-3.501*10^-5*T^3-7.469*10^-9*T^4;
        Hf_H2O_g =32.24*T+0.1923*10^-2*T^2+1.055*10^-5*T^3-3.595*10^-9*T^4;
        H_f_CH4 =19.89*T+5.204*10^-2*T^2+1.269*10^-5*T^3-11.01*10^-9*T^4;
        H_f_N2 =28.90*T-0.1571*10^-2*T^2+0.8081*10^-5*T^3-2.873*10^-9*T^4;
        H_f_H2O_l =32.24*T+0.1923*10^-2*T^2+1.055*10^-5*T^3-3.595*10^-9*T^4;
        H_f_O2 =28.90*T-0.1571*10^-2*T^2+0.8081*10^-5*T^3-2.873*10^-9*T^4;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %p_i Products of complete combustion of biomass(kmol)for species
        %i(p_H2O_g,p_CO2)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        p_CO2 =-393.51;
        p_H2O_g =-241.83;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %compositions in feed stock per carbonate atom
        %C,H,O,N,S  :Carbon, Hydrogen, Oxygen, Nitrogen and Sulfur
respectively

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        C =1;H =1.44;O =0.66;N =0.0;S =0.0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % H_f_biomass               Heat of formation of biomass(kJ/kmol)
        % LHV                      Lower Heating Value(kJ/kmol)
        % H_f_biomass=LHV+x_i*p_i
        % G=x_i*p_i

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        LHV =4.187*(81*C+300*H-26*(O-S)-6*(9*H+m));
        G =x1*p_H2O_g+x3*p_CO2;
```

```
        Hf_biomass =LHV+G;

  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %%%%%%%%% m_biomass     Molecular weight of the biomass
        %%%%%%%%% m_water       Number of moles of water vapor(%dry basis)
        %%%%%%%%% m           Moisture content in biomass(% dry basis)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        M_biomass =C*12+H*1.008+O*16;
        m_water =(M_biomass*m)/(18*(1-m));
        M =m_water;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %Function to solve the compositions of syngas

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        syms x1 x2 x3 x4 x5 a b c d e
        a =x1^2*k1-x5;
        b =x1-3*x2-4*x3+2*m+1.94;
        c =k2*x2*x4-x1*x3;
        d =x2+x3+x5-1;
        e =-x1+2*x2+2*x3+w-1.28-x4;
        [x1,x2,x3,x4,x5] = solve(a,b,c,d,e);
        q =[x1';x2';x3';x4';x5'];
        q =single(q);
        x1 =q(1,:);x2 =q(2,:);x3 =q(3,:);x4 =q(4,:);x5 =q(5,:);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %T4         inlet temperature
        %T5         air inlet temperature
        %dT=T5-T4   temperature difference

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        T4 =298;
        T5 =298;
        dT =T5-T4;
        for i =1:4
            if (x1(i)>=0 && x2(i)>=0 && x3(i)>=0 && x4(i)>=0 && x5(i)>=0)
                H2 =x1(i);CO=x2(i);CO2=x3(i);H2O=x4(i);CH4=x5(i);
                p =[H2';CO';CO2';H2O';CH4'];
                H2 =p(1,:);CO =p(2,:);CO2 =p(3,:);H2O =p(4,:);CH4 =p(5,:);
                T1
=T+(Hf_biomass+w*(H_f_H2O_l+Hf_H2O_g)+m*H_f_O2+3.76*m*H_f_N2+...
                    dT*(m*Cp_O2+3.76*m*Cp_N2)-
(x1*H_f_H2+x2*H_f_CO+x3*H_f_CO2+...
                    x4*Hf_H2O_g+x5*H_f_CH4))/(x1*Cp_H2+x2*Cp_CO+x3*Cp_CO2+...
                    x4*Cp_H2O+x5*Cp_CH4+3.76*m*Cp_N2);
                result(iter,2) =T1;
                result(iter,3) =M_Con;
                result(iter,4) =H2;
                result(iter,5) =CO;
                result(iter,6) =CO2;
                result(iter,7) =H2O;
                result(iter,8) =CH4;
            end
        end
      error =(T1-T);
    end %%%%%%%%%%%  WHILE LOOP END  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    sum_gas=(H2+CO+CO2+H2O+CH4)/100;
```

```
H2=H2/sum_gas;CO=CO/sum_gas;CO2=CO2/sum_gas;H2O=H2O/sum_gas;CH4=CH4/sum_gas;
    M_Con=M_Con*100;
    if (M_Con==0)
        w_0=M_Con; T_1=T1; H2_0=H2;CO_0=CO;CO2_0=CO2;H2O_0=H2O;CH4_0=CH4;
    elseif (M_Con==5)
        w_5=M_Con; T_2=T1; H2_5=H2;CO_5=CO;CO2_5=CO2;H2O_5=H2O;CH4_5=CH4;
    elseif (M_Con==10)
        w_10=M_Con; T_3=T1;
H2_10=H2;CO_10=CO;CO2_10=CO2;H2O_10=H2O;CH4_10=CH4;
    elseif (M_Con==0.15)
        w_15=M_Con; T_4=T1;
H2_15=H2;CO_15=CO;CO2_15=CO2;H2O_15=H2O;CH4_15=CH4;
    elseif (M_Con==20)
        w_20=M_Con; T_5=T1;
H2_20=H2;CO_20=CO;CO2_20=CO2;H2O_20=H2O;CH4_20=CH4;
    elseif (M_Con==25)
        w_25=M_Con; T_6=T1;
H2_25=H2;CO_25=CO;CO2_25=CO2;H2O_25=H2O;CH4_25=CH4;
    elseif (M_Con==30)
        w_30=M_Con; T_7=T1;
H2_30=H2;CO_30=CO;CO2_30=CO2;H2O_30=H2O;CH4_30=CH4;
    elseif (M_Con==35)
        w_35=M_Con; T_8=T1;
H2_35=H2;CO_35=CO;CO2_35=CO2;H2O_35=H2O;CH4_35=CH4;
    elseif (M_Con==40)
        w_40=M_Con; T_9=T1;
H2_40=H2;CO_40=CO;CO2_40=CO2;H2O_40=H2O;CH4_40=CH4;
    elseif (M_Con==45)
        w_45=M_Con; T_10=T1;
H2_45=H2;CO_45=CO;CO2_45=CO2;H2O_45=H2O;CH4_45=CH4;
    end
end
W=[w_0 w_5 w_10 w_15 w_20 w_25 w_30 w_35 w_40 w_45];
T=[T_1 T_2 T_3  T_4 T_5 T_6 T_7 T_8 T_9 T_10];
H2_M=[H2_0 H2_5 H2_10 H2_15 H2_20 H2_25 H2_30 H2_35 H2_40 H2_45];
CO_M=[CO_0 CO_5 CO_10 CO_15 CO_20 CO_25 CO_30 CO_35 CO_40 CO_45];
CO2_M=[CO2_0 CO2_5 CO2_10 CO2_15 CO2_20 CO2_25 CO2_30 CO2_35 CO2_40 CO2_45];
H2O_M=[H2O_0 H2O_5 H2O_10 H2O_15 H2O_20 H2O_25 H2O_30 H2O_35 H2O_40 H2O_45];
CH4_M=[CH4_0 CH4_5 CH4_10 CH4_15 CH4_20 CH4_25 CH4_30 CH4_35 CH4_40 CH4_45];
plot(T,H2_M,'-cs',T,CO_M,'-go',T,CO2_M,'-kv',T,H2O_M,'-rv',T,CH4_M,'-
bx','linewidth',1.5)
xlabel('Moisture Content(%Vol.)')
ylabel('Syngas Species ( % Vol.)')
title('Syngas Species( % Vol.) vs. Moisture Content(%Vol.)')
legend('H2','CO','CO2','H2O','CH4')
grid on
```

APPENDIX B

The following MATLAB code is used to estimate the effects of air to fuel ratio on syngas composition at adiabatic conditions.

```
%Syngas Species (% Vol.) Vs. Air to Fuel Ratio
clear all
clc
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% M_Con   Moisture content( % Vol.)
% mwb     Moles of water per moles of biomass
% mob     Moles of oxygen per mole of biomass
% x_i     Composition of syngas
% K_i     Equilibrium constant
% T1      Temperature at first assumed value in K
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
format short
for m=0.20:0.01:0.30;
    T1 = 650;
    error =1;
    error_max =0.5;
    iter =0;
    a=[0.1 0.1 0.1 0.1 0.1];
    for i=1:5
        x1 =a(i);x2 =a(i);x3 =a(i);
        x4 =a(i);x5 =a(i);
    end
    R =8.314;
    w =0.30;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    while (error >= error_max)
        iter =iter+1;
        result(iter,1) =iter;
        T =T1;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
       % Function for finding sensible heat for various gases constants
(KJ/Kmol)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        Cp_CO2 =22.26+5.981*10^-2*T-3.501*10^-5*T.^2-7.469*10^-9*T^3;
        Cp_CO =28.16+0.1675*10^-2*T+0.5372*10^-5*T.^2-2.222*10^-9*T^3;
        Cp_CH4 =19.89+5.204*10^-2*T+1.269*10^-5*T.^2-11.01*10^-9*T^3;
        Cp_H2O =32.24+0.1923*10^-2*T+1.055*10^-5*T.^2-3.595*10^-9*T^3;
        Cp_N2 =28.90-0.1571*10^-2*T+0.8081*10^-5*T.^2-2.873*10^-9*T^3;
        Cp_H2 =29.11-0.1916*10^-2+0.4003*10^-5*T.^2+-0.8704*10^-9*T^3;
        Cp_O2 =29.11-0.1916*10^-2+0.4003*10^-5*T.^2+-0.8704*10^-9*T^3;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % finding general equations for calculating K1 and K2

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        delta_gfT_CH4 =-74.8+4.62*10^-2*T*log(T)-1.13*10^-5*T^2-(1.32*10^-
8/2)...
            *T^3+(6.65*10^-12/3)*T^4-4.89*10^2/(2*T)+14.1-0.223*T;
        delta_gfT_CO =-110.5-5.62*10^-3*T*log(T)+1.19*10^-5*T^2-(6.38*10^-
9/2)...
            *T^3+(1.85*10^-12/3)*T^4-4.89*10^2/(2*T)+0.868-0.0613*T;
        delta_gfT_CO2 =-393.5+1.95*10^-2*T*log(T)-3.12*10^-5*T^2+(2.45*10^-
8/2)...
            *T^3-(6.95*10^-12/3)*T^4-4.89*10^2/(2*T)+5.27-0.121*T;
```

```
        delta_gfT_H2O =-241.8+8.95*10^-2*T*log(T)+3.67*10^-5*T^2-(5.21*10^-
9/2)...
            *T^3+(1.48*10^-12/3)*T^4-0+2.87-.0172*T;
        delta_gfT_H2 =0;
        delta_GT_1 =x3*delta_gfT_CO2+x1*delta_gfT_H2-x2*delta_gfT_CO-
x4*delta_gfT_H2O;
        delta_GT_2 =x5*delta_gfT_CH4-x1*delta_gfT_H2;
        k1 =exp(-delta_GT_1/(R*T));k1=0.3165;
        k2 =exp(-delta_GT_2/(R*T));k2=2.3379;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %   %Heat of formation of different compounds at 298K, kJ/kmol

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        H_f_H2 =29.11*T-0.1916*10^-2*T^2+0.4003*10^-5*T^3-0.8704*10^-9*T^4;
        H_f_CO =28.16*T+0.1675*10^-2*T^2+0.5372*10^-5*T^3-2.222*10^-9*T^4;
        H_f_CO2 =22.26*T+5.981*10^-2*T^2-3.501*10^-5*T^3-7.469*10^-9*T^4;
        Hf_H2O_g =32.24*T+0.1923*10^-2*T^2+1.055*10^-5*T^3-3.595*10^-9*T^4;
        H_f_CH4 =19.89*T+5.204*10^-2*T^2+1.269*10^-5*T^3-11.01*10^-9*T^4;
        H_f_N2 =28.90*T-0.1571*10^-2*T^2+0.8081*10^-5*T^3-2.873*10^-9*T^4;
        H_f_H2O_l =32.24*T+0.1923*10^-2*T^2+1.055*10^-5*T^3-3.595*10^-9*T^4;
        H_f_O2 =28.90*T-0.1571*10^-2*T^2+0.8081*10^-5*T^3-2.873*10^-9*T^4;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % p_i   Products of complete combustion of biomass (kmol) for
        %               species i(p_H2O_g , p_CO2)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        p_CO2 =-393.51;
        p_H2O_g =-241.83;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %       %compositions in feed stock per carbonate atom
        %C,H,O,N,S  :Carbon, Hydrogen, Oxygen, Nitrogen and Sulfur
respectively


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        C =1;H =1.44;O =0.66;N =0.0;S =0.0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % H_f_biomass               Heat of formation of biomass(kJ/kmol)
        % LHV                      Lower Heating Value(kJ/kmol)
        % H_f_biomass=LHV+x_i*p_i
        % G=x_i*p_i


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        LHV =4.187*(81*C+300*H-26*(O-S)-6*(9*H+m));
        G =x1*p_H2O_g+x3*p_CO2;
        Hf_biomass =LHV+G;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % M_biomass     Molecular weight of the biomass
        % m_water     Number of moles of water vapor (%dry basis)
        % m             Moisture content in biomass (% dry basis)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
        M_biomass =C*12+H*1.008+O*16;
        m_water =(M_biomass*m)/(18*(1-m));
        M =m_water;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % Function to solve the compositions of syngas

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        syms x1 x2 x3 x4 x5 a b c d e
        a =x1^2*k1-x5;
        b =x1-3*x2-4*x3+2*m+1.94;
        c =k2*x2*x4-x1*x3;
        d =x2+x3+x5-1;
        e =-x1+2*x2+2*x3+m-1.28-x4;
        [x1,x2,x3,x4,x5] = solve(a,b,c,d,e);
        q =[x1';x2';x3';x4';x5'];
        q =single(q);
        x1 =q(1,:);x2 =q(2,:);x3 =q(3,:);x4 =q(4,:);x5 =q(5,:);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        % T4         Temprature of the inlet
        % T5         Air inlet Temprature
        % dT=T5-T4   Temprature difference b/n T4 and T5

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        T4 =298;
        T5 =298;
        dT =T5-T4;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        for i =1:4
            if (x1(i)>=0 && x2(i)>=0 && x3(i)>=0 && x4(i)>=0 && x5(i)>=0)
                H2 =x1(i);CO=x2(i);CO2=x3(i);H2O=x4(i);CH4=x5(i);
                q =single(q);
                T1;m;w;
                p =[H2';CO';CO2';H2O';CH4'];
                H2 =p(1,:);CO =p(2,:);CO2 =p(3,:);H2O =p(4,:);CH4 =p(5,:);
            end
        end
        for i =1:4
            if (x1(i)>=0 && x2(i)>=0 && x3(i)>=0 && x4(i)>=0 && x5(i)>=0)
                T1
=T+(Hf_biomass+w*(H_f_H2O_l+Hf_H2O_g)+m*H_f_O2+3.76*m*H_f_N2+...
                    dT*(m*Cp_O2+3.76*m*Cp_N2)-
(x1*H_f_H2+x2*H_f_CO+x3*H_f_CO2+...
                    x4*Hf_H2O_g+x5*H_f_CH4))/(x1*Cp_H2+x2*Cp_CO+x3*Cp_CO2+...
                    x4*Cp_H2O+x5*Cp_CH4+3.76*m*Cp_N2);
                result(iter,2) =T1;
                result(iter,3) =m;
                result(iter,4) =H2;
                result(iter,5) =CO;
                result(iter,6) =CO2;
                result(iter,7) =H2O;
                result(iter,8) =CH4;

            end
        end
        error =(T1-T);
    end %%%%%%%%%%  While loop end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
    m;H2;CO;CO2;H2O;CH4;
    sum_gas=(H2+CO+CO2+H2O+CH4)/100;

H2=H2/sum_gas;CO=CO/sum_gas;CO2=CO2/sum_gas;H2O=H2O/sum_gas;CH4=CH4/sum_gas;
    if (m==0.20)
        m_0=0.20;H2_0=H2;CO_0=CO;CO2_0=CO2;H2O_0=H2O;CH4_0=CH4;
    elseif (m==0.21)
        m_1=0.21;H2_1=H2;CO_1=CO;CO2_1=CO2;H2O_1=H2O;CH4_1=CH4;
    elseif (m==0.22)
        m_2=0.22;H2_2=H2;CO_2=CO;CO2_2=CO2;H2O_2=H2O;CH4_2=CH4;
    elseif (m==0.23)
        m_3=0.23;H2_3=H2;CO_3=CO;CO2_3=CO2;H2O_3=H2O;CH4_3=CH4;
    elseif (m==0.24)
        m_4=0.24;H2_4=H2;CO_4=CO;CO2_4=CO2;H2O_4=H2O;CH4_4=CH4;
    elseif (m==0.25)
        m_5=0.25;H2_5=H2;CO_5=CO;CO2_5=CO2;H2O_5=H2O;CH4_5=CH4;
    elseif (m==0.26)
        m_6=0.26;H2_6=H2;CO_6=CO;CO2_6=CO2;H2O_6=H2O;CH4_6=CH4;
    elseif (m==0.27)
        m_7=0.27;H2_7=H2;CO_7=CO;CO2_7=CO2;H2O_7=H2O;CH4_7=CH4;
    elseif (m==0.28)
        m_8=0.28;H2_8=H2;CO_8=CO;CO2_8=CO2;H2O_8=H2O;CH4_8=CH4;
    elseif (m==0.29)
        m_9=0.29;H2_9=H2;CO_9=CO;CO2_9=CO2;H2O_9=H2O;CH4_9=CH4;
    elseif (m==0.30)
        m_10=0.30;H2_10=H2;CO_10=CO;CO2_10=CO2;H2O_10=H2O;CH4_10=CH4;
    end
end
M=[m_0 m_1 m_2 m_3 m_4 m_5 m_6 m_7 m_8 m_10];
H2_M=[H2_0 H2_1 H2_2 H2_3 H2_4 H2_5 H2_6 H2_7 H2_8 H2_10];
CO_M=[CO_0 CO_1 CO_2 CO_3 CO_4 CO_5 CO_6 CO_7 CO_8 CO_10];
CO2_M=[CO2_0 CO2_1 CO2_2 CO2_3 CO2_4 CO2_5 CO2_6 CO2_7 CO2_8 CO2_10];
H2O_M=[H2O_0 H2O_1 H2O_2 H2O_3 H2O_4 H2O_5 H2O_6 H2O_7 H2O_8 H2O_10];
CH4_M=[CH4_0 CH4_1 CH4_2 CH4_3 CH4_4 CH4_5 CH4_6 CH4_7 CH4_8 CH4_10];
plot(M,H2_M,'-cs',M,CO_M,'-go',M,CO2_M,'-kv',M,H2O_M,'-rv',M,CH4_M,'-
bx','linewidth',1.5)
xlabel('Air to Fuel Ratio')
ylabel('Syngas Species( % Vol.)')
title(' Syngas Species ( % Vol.) Vs. Air to Fuel Ratio')
legend('H2','CO','CO2','H2O','CH4')
grid on
```

APPENDIX C

SUPPLEMENTAL DATA FOR SELECTED FIGURES

The data used for figures in chapter 5 is reported in this appendix. Data in each table corresponds to the figure mentioned alongside.

Table C.1 Data for Fig. 5.1

Moisture Content (%wet basis)	H_2 (%vol.)	CO (% vol.)	CO_2 (% vol.)	H_2O (%vol.)	CH_4 (%vol.)
0.0	31.5	43.0	16.2	5.0	5.0
5.0	32.0	37.5	18.5	7.1	5.1
10.0	32.5	33.6	21.8	8.2	5.6
15.0	32.6	27.2	23.2	12.3	5.9
20.0	32.7	24.3	24.6	13.9	6.0
25.0	32.5	20.3	25.8	17.2	6.0
30.0	31.0	17.2	26.1	20.9	6.0
35.0	29.5	14.0	26.8	24.8	5.9
40.0	28.0	11.2	26.4	28.0	5.8
45.0	27.2	8.2	25.7	34.1	5.6

Table C.2 Data for Fig. 5.2

Temperature	H_2 (%vol.)	CO (% vol.)	CO_2 (% vol.)	H_2O (%vol.)	CH_4 (%vol.)
600	33.8	30.6	20.4	9.3	6.4
700	33.1	29.5	21.6	10.1	6.4
800	32.8	28.0	22.0	10.8	6.2
900	32.7	27.5	22.8	11.2	6.1
1000	32.5	27.0	23.4	12.0	6.0
1100	32.3	26.8	23.9	12.8	5.9
1200	32.0	25.8	24.2	13.5	5.8
1300	31.7	24.7	24.8	14.1	5.8
1400	31.0	23.9	25.4	14.7	5.7
1500	30.6	22.7	26.0	15.9	5.5