

**INFLUENCE OF CO<sub>2</sub> INJECTION ON BIOMASS UPDRAFT GASIFICATION  
PROCESS**

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Sustainable process development

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## DECLARATION OF THE CANDIDATE & SUPERVISOR

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## **ABSTRACT**

The utilization of fossil fuels has enabled large-scale industrial development and largely supplanted water-driven mills, as well as the combustion of wood or peat for heat. The burning of fossil fuels by humans is the largest source of emissions of carbon dioxide, which is one of the greenhouse gases that allows radiative forcing and contributes to global warming.

This study focuses on to performance analysis of updraft gasifier with the injection of CO<sub>2</sub> as gasifying agent. During the study CO<sub>2</sub> was fed in to updraft gasifier in different feed ratios and producer gas composition was analyzed.

Rubber wood chips were used as the feed stock of gasifier and testings were carried out in input fractions of CO<sub>2</sub> to analyze its impact of CO yield.

**Keywords:** Updraft gasifier, biomass, equivalence ratio, Carbon dioxide to air ratio,

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# CONTENTS

DECLARATION OF THE CANDIDATE & SUPERVISOR .....	i
ABSTRACT.....	ii
ACKNOWLEDGMENTS .....	iii
FIGURES.....	viii
TABLES .....	ix
ACRONYMS.....	x
CHAPTER 1: INTRODUCTION.....	1
1.1    Global and Sri Lanka Energy Scenario.....	1
1.2    Importance of Biomass as a fuel .....	1
1.3    Biomass gasification .....	2
1.4    Research objectives .....	3
1.5    Scope of the study .....	3
1.6    Dissertation Outline.....	4
CHAPTER 2: LITRETURE REVIEW .....	5
2.1    Biomass as an energy source.....	5
2.2    Biomass Types .....	5
2.2.1    Cellulose .....	6
2.2.2    Lignin.....	7
2.3    Classification of fuel .....	7
2.3.1    Atomic Ratio.....	8
2.3.2    Relative Proportions of Ligno-Cellulosic Components.....	8
2.3.3    Ternary Diagram.....	9
2.4    Properties of Biomass.....	10

2.4.1	Physical properties .....	11
2.5	Thermodynamic Properties of Biomass .....	12
2.5.1	Thermal Conductivity .....	12
2.5.2	Heat of Formation .....	12
2.5.3	Heat of Combustion (Reaction) .....	13
2.6	Other Gasification-Related Properties of Biomass .....	13
2.7	Ultimate Analysis .....	13
2.8	Proximate Analysis .....	13
2.9	Biomass Gasification theory and Technology .....	14
2.9.1	Drying .....	14
2.9.2	Pyrolysis.....	14
2.10	Effect of Pyrolysis Temperature and Heating Rate.....	16
2.11	Gasification .....	16
2.11.1	Gasification System .....	16
2.12	Types of Gasifiers .....	17
2.12.1	Fixed/moving bed gasifier .....	18
2.12.2	Updraft gasifier .....	18
2.12.3	Cross draft gasifier .....	19
2.12.4	Downdraft gasifier .....	19
2.12.5	Stratified gasifier.....	21
2.12.6	Fluidized –bed gasifier.....	21
2.13	Gasification medium and kinetics .....	23
2.13.1	Overall kinetics of gasification .....	23
2.14	Description of each step of gasification process .....	23
2.14.1	Combustion zone reactions .....	24

2.14.2	Reduction zone.....	24
2.15	Gasification medium .....	24
2.15.1	Gasification in air.....	25
2.15.2	Gasification in steam: .....	25
2.15.3	Gasification in a steam–oxygen mixture.....	25
2.15.4	Gasification in carbon dioxide .....	26
<b>CHAPTER 3: EXPERIMENTAL SETUP OF UPDRAFT GASIFIRE UNIT .....</b>		<b>28</b>
3.1	Design parameters of the gasifier.....	28
3.1.1	Diameter of the reactor .....	28
3.1.2	Fuel Consumption Rate.....	29
3.1.3	Height of the reactor .....	29
3.1.4	Total working height of reactor .....	30
3.1.5	Time required to consume fuel: .....	30
3.2	Reactor Fabrication and Material selection.....	31
3.2.1	Air Supply to unit.....	32
3.3	Feed Stock Preparation, Analysis and Operation.....	32
3.3.1	Biomass feed stock .....	32
3.3.2	Fuel property Analysis .....	32
3.4	Overall equipment setup.....	34
3.5	Test procedure flow chart.....	35
3.5.1	Pre Testing .....	35
3.5.2	Feedstock preparation and feeding .....	35
3.5.3	Firing.....	36
3.5.4	Flue gas testing .....	36
3.5.5	Orsat Operation.....	36

3.6	Supportive Calculations .....	39
3.6.1	Specific gas production: Gas to Fuel Ratio.....	39
3.6.2	Air to Gas ratio (Specific air consumption).....	40
3.6.3	Biomass formula determination based on elemental analysis .....	41
3.6.4	Equivalence ratio .....	42
3.6.5	Stoichiometric air and gasification air flow rate calculation .....	42
CHAPTER 4: RESULTS FOR UPDRAFT GASSIFIRE PERFORMANCE .....		43
4.1	Biomass Analysis Results .....	43
4.1.1	Proximate analysis .....	43
4.1.2	Ultimate analysis.....	43
4.2	Temperature profile variation.....	44
4.3	Yield variation.....	45
4.4	Flame observation .....	46
4.5	Effect of CO <sub>2</sub> /C variation.....	46
4.6	Process influence of Moisture percentage for gasification .....	47
4.7	Effect of equipment sensitivity for overall results .....	48
CHAPTER 5: CONCLUSION AND FUTURE DIRECTIONS .....		49
5.1	Conclusion.....	49
5.2	Modern Development in gasification.....	49
5.2.1	Post-combustion.....	49
5.2.2	Oxyfuel .....	50
5.2.3	Pre-combustion .....	50
5.3	Future Work .....	50
APPENDECIS .....		51
References.....		54



## FIGURES

Figure 1 Molecular structure of cellulose .....	6
Figure 2 Molecular structure of a typical hemicellulose .....	7
Figure 3 Van Krevelen diagram.....	8
Figure 4 Classification of biomass by constituent ratios .....	9
Figure 5 C-H-O ternary diagram of biomass showing the gasification process .....	10
Figure 6 Gasification Technologies .....	17
Figure 7 Different Constructions of Fixed Bed / Moving Bed Gasifier (Left to right: Downdraft, Updraft, and Cross Draft) .....	18
Figure 8 Schematic of Downdraft Gasifier and Temperature Gradient with Height(Prabir Basu, 2012) .....	20
Figure 9 a) Imbert Downdraft Gasifier, (b) Stratified Downdraft Gasifier (Mendiburu et al., 2014) .....	20
Figure 10 Overall kinetics of gasification.....	23
Figure 11 Overall Arrangement A- Combustor, B - Temperature Display, C - CO <sub>2</sub> Cylinder, D - Air blower .....	34
Figure 12 Orsat equipment set up .....	34
Figure 13 Test procedure .....	35
Figure 14 Orsat setup .....	38
Figure 15 Temperature profile variation.....	44
Figure 16 CO yield variation with variable input fraction of CO <sub>2</sub> .....	45
Figure 17 Flame observations.....	46
Figure 18 Effect of CO <sub>2</sub> /C Ratio for CO yield.....	46

## **TABLES**

Table 1 Types of Biomass.....	5
Table 2 Gasification Mediums and Characteristic Parameters .....	25
Table 3 Comparison of tar production in three gasification mediums (Gil et al., 1999) .....	26
Table 4 Experimental results with varying CO <sub>2</sub> input fractions .....	27
Table 5 Fuel test standard .....	33
Table 6 Equivalence ratio and flow rate .....	42
Table 7 Proximate analysis results.....	43
Table 8 Ultimate Analysis Results.....	43
Table 9 Effect of equipment sensitivity for overall results.....	48

## **ACRONYMS**

HHV: Higher heating value

HHV<sub>f</sub> : Higher Heating value of fuel

LHV: Lower heating value

FCR: Fuel Consumption rate

VM: Volatile Matters

FC: Fixed Carbon

ER: Equivalence ratio

SGR: Specific Gasification rate

A/G: Air to gas ratio

G/F: Gas to fuel ratio

GHG: Green House Gases

# **CHAPTER 1: INTRODUCTION**

## **1.1 Global and Sri Lanka Energy Scenario**

Energy supply through sustainable sourcing is one major challenge that mankind will face over the coming decades, particularly because of need to address climate change. The coal and petroleum derivatives are the most conventional sources of energy today. With the latest projections total energy demand is set to increase by 20% by the year 2040. Governments worldwide has drawn its attention to increase the portion of renewable energy into their energy uses over decades (IEA, 2017)

The ever-increasing prices of fossil fuels and removal of fossil fuel subsidy in 2012 in Sri Lanka have made the industries to use biomass to operate their boilers in the recent years.(industry of power and energy, 2015) industries' that use biomass include textile and apparel industry, major rubber industries, smoked rubber industry, tea industry, desiccated coconut and copra industry sugar & distillery industry, and (other) bulk manufacturing industries. (World Energy Council, 2013)

## **1.2 Importance of Biomass as a fuel**

Biomass can make a substantial contribution of suppling future energy demands in sustainable manner. It is presently the largest contributor of renewable energy, and has significant potential to expand in the production of heat, electricity and fuels for transport.(Sustainable Energy Authority-Sri Lanka, 2016)

Last few years it was shown that interest of use of biomass has been increased in developed countries but now in a trend of use of biomass in other countries too especially in industrial applications. (Mckendry, 2002)

The direct combustion of biomass has several drawbacks in producing of thermal energy due to low heating value of the biomass, not suitable for high temperature application as a fuel source. Also, it cannot be directly used in internal combustion engines and low versatility is one major disadvantage. Therefore, in many of industrial applications biomass is converted into more versatile

secondary fuel by thermo-chemical, bio-chemical or extraction processes.(Sustainable Energy Authority- Sri Lanka, 2016; McKendry, 2002)

### **1.3Biomass gasification**

Gasification is a chemical process which converts carbonaceous materials like biomass into useful convenient gaseous fuels or chemical feedstock. Pyrolysis, partial oxidation, and hydrogenation are related processes.

Combustion also converts carbonaceous materials into product gasses but the difference is which in combustion, product gas has no heating value but in gasification it has a good heating value. On the other hand, Gasification takes place in reducing (oxygen-deficient) environments requiring heat; combustion takes place in an oxidizing environment giving off heat.

Gasification consists of three major steps namely drying, pyrolysis and gasification. In drying process with the heat available at the zone, moisture of the biomass reduces. Pyrolysis is a thermal decomposition process that partially removes carbon from the feed but does not add hydrogen.

The producer gas of this gasification is called syngas. Syngas is a mixture of carbon monoxide, carbon dioxide, hydrogen, methane, small amount of light hydrocarbons and nitrogen. The producer gas can be used for various applications including electricity generation, heat generation and hydrogen production (K.Srirangan, L Akawi, M.Moo-yong, 2012)

Gasifier is used for biomass gasification while which is acted as the reactor for the thermochemical conversion process. Producer gas quality is mainly depending on gasifier design and fuel properties including gasifying medium, properties of biomass, moisture content, particle size, temperature of gasification zone, operational parameters and equivalence ratio.

Extensive researches have been done to understand the effect of steam, air, oxygen and their combination on the gasification process. Only limited studies have been focused on injection of CO<sub>2</sub> as an oxidizing agent while majority of them are for coal gasification. A study by Narendra S has done biomass gasification using carbon dioxide and study was focused to identify the effect of temperature, CO<sub>2</sub>/C ratio, and the study of reactions influencing process and results were compared with oxygen gasifier. Lower char yield and consequently higher carbon conversions based was observed during the study. Also, the study concluded that increasing temperature, CO<sub>2</sub> gasification produces highly microporous char that greatly enhances CO<sub>2</sub> diffusion during gasification step

leading to higher conversion. This overall study was conducted in a fluidized bed gasifier.(Sadhvani, 2017)

Considering advantages of updraft type of gasifier of its simplicity, high charcoal burn out and internal heat exchange leading to low temperature of exit gas and high equipment efficiency it was used this study was done with updraft gasifier though it is old in concept. Niranjan F studied comprehensive two-dimensional computational fluid dynamic model for an updraft gasifier and concluded that optimal air flow rate to be 7 m<sup>3</sup>/hr for maximum cumulative CO production for the studied gasifier. This study also conducted in same gasifier hence same air flow rate was used throughout the study.

Rubber wood was selected as source of biomass since it is widely available in Sri Lanka and known as sustainable fuel source. (Weragama, 2011)

#### **1.4 Research objectives**

1. To gain a deeper understanding of biomass gasification process with CO<sub>2</sub> injection.
2. To optimize the volume of feed CO<sub>2</sub> with quality of producer gas

#### **1.5 Scope of the study**

The research scope has been outlined by considering the compatibility to the available resources. Therefore, the research goals have been sub divided, in order to easier identification of completed tasks.

The overall scope is limited for following

1. Conduct comprehensive literature review
2. Writing of thermo - chemical equations for biomass gasification
3. Measure actual scenario using standard updraft gasifier
4. Performance analysis with CO<sub>2</sub> injection and discuss the results

## 1.6 Dissertation Outline

**Chapter 1:** Explains on brief description on Sri Lankan and world energy scenario as well as the importance of research work on gasification as biomass rich country. Also described process of gasification and brief of overall study.

**Chapter 2:** This section it explains, Theory and literature review is presented about biomass, its properties gasification technologies, types of gasifiers and gasification reactions.

**Chapter 3:** This chapter focused on the research methodology which was used to conduct this present study

**Chapter 4:** describe the detail of results of the present study

**Chapter 5:** In this section conclusion and suggestions for future improvements and next step developments are discussed.

## CHAPTER 2: LITRETURE REVIEW

### 2.1Biomass as an energy source

Biomass refers to any organic materials that are derived from plants or animals. Since there is no generally accepted definition, the one used by the United Nations Framework Convention on Climate Change (UNFCCC, 2005) is used

Non-fossilized and biodegradable organic material originating from plants, animals and micro-organisms. This shall also include products, by-products, residues and waste from agriculture, forestry and related industries as well as the non-fossilized and biodegradable organic fractions of industrial and municipal wastes. (Prabir Basu, 2012)

Biomass to be considered as if biomass was grown at the same rate as it was consumed. In such case that net contribution to atmospheric would be zero. Compared to fossil fuels most of biomass sources as comparatively low sulfur contents and which gives additional benefit in considering environmental pollution. (Hallgren, 1996)

### 2.2Biomass Types

Biomass can be classified in a way based on the source of it generated as listed below in a table.

<b>Virgin</b>	Terrestrial biomass	Forest biomass Grasses Energy crops Cultivated crops
	Aquatic biomass	Algae/Water plant
<b>Waste</b>	Municipal waste	Municipal solid waste Biosolids, sewage/Landfill gas
	Agricultural solid waste	Livestock and manures Agricultural crop residue
	Forestry residues	Bark, leaves, floor residues
	Industrial wastes	Demolition wood, sawdust Waste oil or fat

Table 1 Types of Biomass



The main chemical constitutions of biomass cells can be classified into following.

1. Cellulose
2. Hemicellulose
3. Lignin

The two former comprise the cell walls in biomass fibers and are characterized chemically as high molecular weight glucose molecules. The third component, lignin, acts as a “glue”, keeping the fiber cells together. Lignin is a polymer that can form polyaromatic compounds in the conversion products. The proportion between lignin and cellulose content in biomass is 40/60. Biomass is also characterized by a high content of oxygen, what justifies its high thermal instability. (Prabir Basu, 2012)

### 2.2.1 Cellulose

Cellulose is an important structural component of the primary cell wall of green plants, many forms of algae and the oomycetes. Some species of bacteria secrete it to form biofilms. Represented by the generic formula  $(C_6H_{10}O_5)_n$ , It is a long chain polymer with a high degree of polymerization ( $\sim 10,000$ ) and a large molecular weight ( $\sim 500,000$ ).

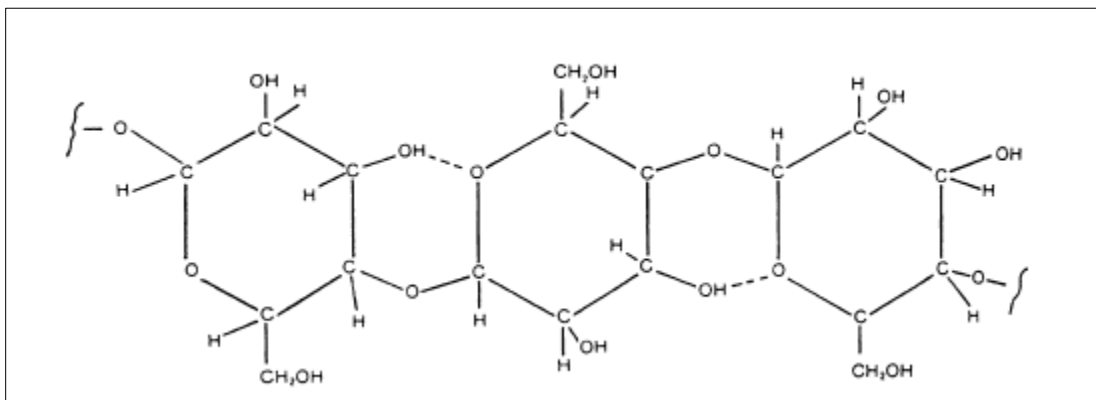


Figure 1 Molecular structure of cellulose

Hemicellulose is another constituent of the cell walls of a plant. While cellulose is of a crystalline, strong structure that is resistant to hydrolysis, hemicellulose has a random, amorphous structure with little strength. It is a group of carbohydrates with a branched chain structure and a lower degree of polymerization ( $\sim 100-200$ ), and may be represented by the generic formula  $(C_5H_8O_4)_n$ .

When the use of biomass increases, it is required to have dedicated energy crops. The short rotation woody crops will be preferred for dedicated energy crops in the future of biomass sources. These species are generally hardwood trees that would be harvested every 5-10 years and regrown from the tree stump reducing then annual costs for establishing and managing crops. The production of energy crops requires less intensive management than other agricultural crops because of the low need for fertilizers and pesticides. (Barrio, 2002)

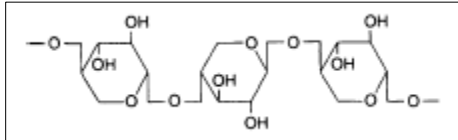


Figure 2 Molecular structure of a typical hemicellulose

### 2.2.2 Lignin

Lignin is a complex highly branched polymer and particularly important in formation of cell walls, especially in wood and bark. It is primarily a three-dimensional polymer of 4-propenyl phenol, 4-propenyl-2-methoxy phenol, and 4-propenyl-2,5-dimethoxyl phenol. It is one of the most abundant organic polymers on Earth (exceeded only by cellulose). It is the third important constituent of the cell walls of woody biomass. (Prabir Basu, 2012)

### 2.3 Classification of fuel

Chemical constituents, atomic ratios, the ratio of lingo – cellulose constituents and ternary diagram are the three methods of classifying and ranking fuels. All hydrocarbon fuels may be classified or ranked according to their atomic ratios, but the second classification is limited to ligno-cellulose biomass.

### 2.3.1 Atomic Ratio

Fuel heating value is described based on atomic ratio. For an example Coal contains between 75-90% carbon while biomass carbon content is about 50% which means that the heating value of biomass is lower. This type of differences is explained the O/C and H/C ratios of each fuel, shown in the Van Krevelen diagram figure 3.

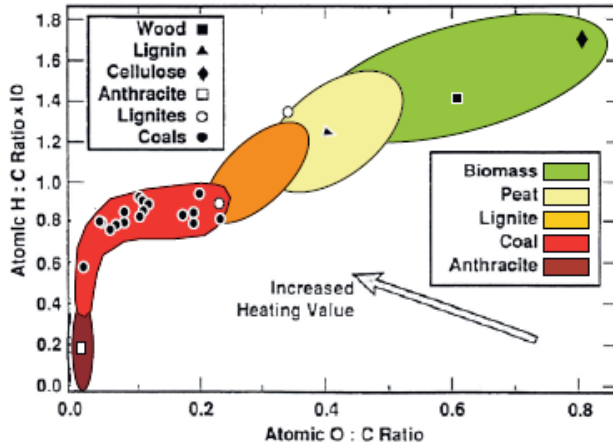


Figure 3 Van Krevelen diagram.

### 2.3.2 Relative Proportions of Ligno-Cellulosic Components

It can be predicted that the behavior of biomass during the pyrolysis by using the knowledge of relative proportion of cellulose, hemicellulose and lignin.

The figure below describes the ratio of hemicellulose to lignin against the ratio of cellulose to lignin. Despite some scatter, a certain proportionality can be detected between the two. Biomass falling within these clusters behaves similarly irrespective of its type. For a typical biomass, the cellulose–lignin ratio increases from ~0.5 to ~2.7, while the hemicellulose–lignin ratio increases from 0.5 to 2.0.

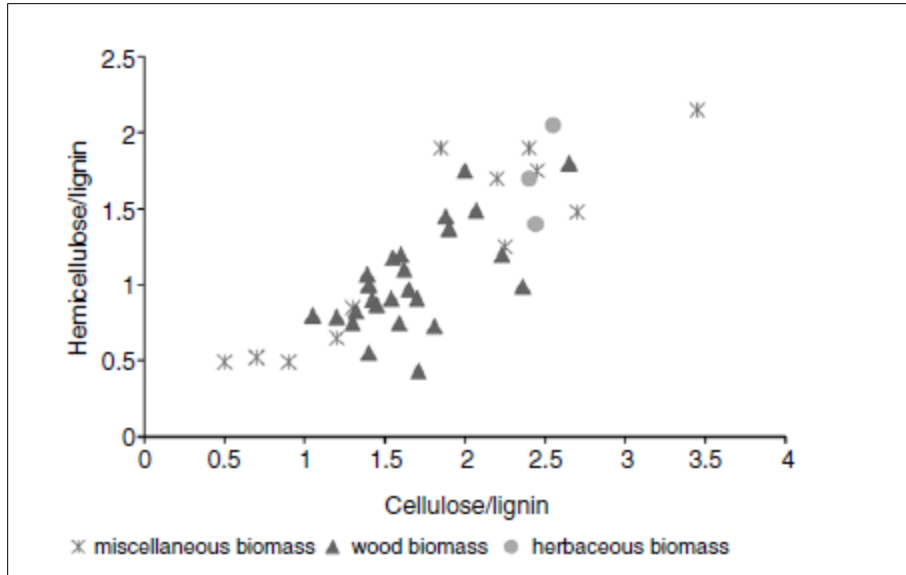


Figure 4 Classification of biomass by constituent ratios

### 2.3.3 Ternary Diagram

Though the ternary diagram (Figure 5) is not a tool for biomass classification, it is useful for representing biomass conversion processes. (Demirbas, 2007) in describing the diagram, three corners of the triangle represent pure carbon, oxygen, and hydrogen which is having concentration of 100%. Points within the triangle represent ternary mixtures of these three substances. The side opposite to a corner with a pure component (C, O, or H) represents zero concentration of that component base opposite to the hydrogen corner represents zero hydrogen— that is, binary mixtures of C and O. (Prabir Basu, 2012)

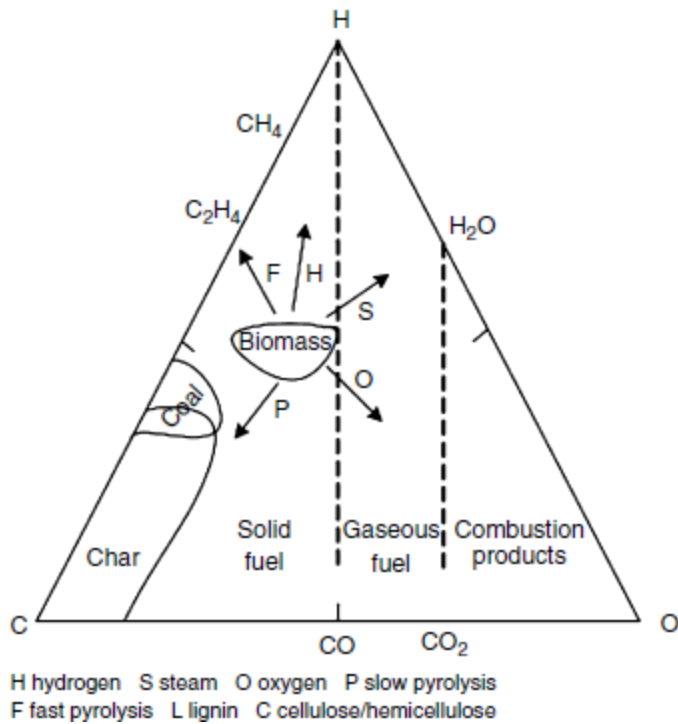


Figure 5 C-H-O ternary diagram of biomass showing the gasification process

In interpretation of diagram biomass is closer to Hydrogen and Carbon corners of the diagram, which signs that biomass has more carbon and hydrogen than coal.

Coal resides further toward the carbon corner and lies close to the oxygen base in the ternary diagram, suggesting that it is very low in oxygen and much richer in carbon. Anthracite lies furthest toward the carbon corner because it has the highest carbon content. The diagram can also show the geological evolution of fossil fuels. With age the fuel moves further away from the hydrogen and oxygen corners and closer to the carbon corner.

## 2.4 Properties of Biomass

Properties of biomass is to be considered when selecting conversion process, mainly physical and thermodynamic properties are considered when selecting biomass as a fuel for any of the conversion process.

## 2.4.1 Physical properties

Some of the physical properties are critically impacted for biomass gasification and pyrolysis including permeability and density.

### 2.4.1.1 Density

Four characteristics are defined for granular biomass, true, apparent, bulk, and biomass (growth) density.

#### 2.4.1.2 True Density

True density is the weight per unit volume occupied by the solid constituent of biomass. (Prabir Basu, 2012)

Equation 1

$$\rho_{true} = \frac{\text{Total mass of biomass}}{\text{Solid volume in biomass}}$$

#### 2.4.1.3 Apparent Density

Apparent density is based on the apparent or external volume of the biomass. This includes its pore volume (or that of its cell cavities). For a regularly shaped biomass, mechanical means such as micrometers can be used to measure different sides of a particle to obtain its apparent volume

Equation 2

$$\rho_{apparent} = \frac{\text{Total mass of biomass}}{\text{Apparent volume of biomass including solids and internal pores}}$$

### 2.4.1.3 Bulk Density

Bulk density is based on the overall space occupied by an amount or a group of biomass particles. (Prabir Basu, 2012)

Equation 3

$$\rho_{bulk} = \frac{\text{Total mass of biomass particles or stack}}{\text{Bulk volume occupied by biomass particles or stack}}$$

## 2.5 Thermodynamic Properties of Biomass

Thermo dynamic properties of biomass is important in consideration in gasification, since it is a thermochemical conversion process, generally thermal conductivity, specific heat, and heat of formation of biomass are having influences in gasification process.

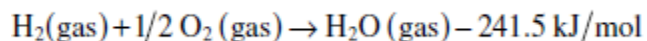
### 2.5.1 Thermal Conductivity

Pyrolysis behavior of biomass is influenced since due to small of particles, are subject to heat conduction along and across their fiber. Thus, the thermal conductivity of the biomass is an important parameter. It changes with density and moisture.(Yaman, 2004)

### 2.5.2 Heat of Formation

Heat of formation, also known as enthalpy of formation, is the enthalpy change when 1 mole of compound is formed at standard state (25 °C, 1 atm) from its constituting elements in their standard state. For example, hydrogen and oxygen are stable in their elemental form, so their enthalpy of formation is zero. However, an amount of energy (241.5 kJ) is released per mole when they combine to form steam. (Prabir Basu, 2012)

Equation 4



### **2.5.3 Heat of Combustion (Reaction)**

The heat of reaction (HR) is the amount of heat released or absorbed in a chemical reaction with no change in temperature.

### **2.6 Other Gasification-Related Properties of Biomass**

Apart from above properties in designing of any combustor depend on composition of the fuel and its energy content. Therefore, ultimate analysis, proximate analysis and heating values are experimentally determined under ASTM E 870-6.

### **2.7 Ultimate Analysis**

In ultimate analysis which is comprehensive analysis and composition of the fuel is expressed by means of its basic elements except of moisture.

Equation 5

$$C + H + O + N + S + ASH + M = 100\%$$

Here C, H, O, N, S are weight percentage of Carbon, Hydrogen, Oxygen, nitrogen, Sulphur and M is known as moisture.

### **2.8 Proximate Analysis**

The "proximate" analysis gives moisture content, volatile content (when heated to 950 C), the free carbon remaining at that point, the ash (mineral) in the sample and the high heating value (HHV) based on the complete combustion of the sample to carbon dioxide and liquid water. (The low heating value, LHV, gives the heat released when the hydrogen is burned to gaseous water, corresponding to most heating applications and can be calculated from the HHV and H<sub>2</sub> fraction.) (Prabir Basu, 2012)



## **2.9 Biomass Gasification theory and Technology**

Conversion of solid or liquid feed stock into useful gaseous fuel or chemical feed stock is called gasification and this producer gas can be used to burn to release energy or can be used to production of value added chemicals.

In gasification processes following steps are included

1. Drying
2. Pyrolysis
3. Partial combustion of gasses
4. Gasification

### **2.9.1 Drying**

For any of thermochemical process Moisture content is one important characteristic to be evaluated as every kilogram of moisture will take 2260 KJ of energy from gasifier or combustor to vaporize water, and that energy is not recoverable. Typically, in freshly cut woods, moisture content to be varied from 30-60% while in some of situation it will high as 90%. Therefore, any of design moisture content must be a concern especially in energy applications. In a process surface moisture is addressed but have limitations in removing inherent moisture. Due to these factors limited pre-drying is recommended in gasification especially before fed into combustor or reactor. Final drying is taken place under the gasifier and required heat is taken from the hot zone downstream and which releases the loosely bounded water from surface. When temperature rises low molecular weight, contaminants are volatilized and process will continue temperature of the zone will reach approximately 200 °C (Prabir Basu, 2012)

### **2.9.2 Pyrolysis**

In Pyrolysis, carbonaceous material is decomposed by applying heat in absence of oxygen. In this process biomass is decomposed into gas, liquid and solid. (Czajczyńska *et al.*, 2017)

Based on time of reaction pyrolysis is defined in two different variations

- Slow pyrolysis – the oldest form of pyrolysis is known as slow pyrolysis. The aim of slow pyrolysis is to form of charcoal or char. Here biomass is slowly heated in oxygen restricted

environment to a lower temperature approximately 400 °C. In Conventional pyrolysis there are three types of products are generated which are gas liquid and char.

- Fast pyrolysis – in maximizing of generating bio fuel production it is used fast pyrolysis. In fast pyrolysis biomass is rapidly heated till it reaches the peak pyrolysis temperature. The heating rate can be as high as 1000 to 10,000 °C/s. (Prabir Basu, 2012)

The product of pyrolysis is depending on the various parameters including

- Design of pyrolizer
- Physical and chemical characteristics
- Operating parameters (heating rate, Pyrolysis temperature & residence time)

The relative yields of solid, liquid and gaseous product of pyrolysis will be varied along with pyrolysis temperature and heating rate. Compare to low heating rates, in higher heating rates maximized the volatiles and more reactive char.(Brownsort, 2009)

Composition of biomass is having greater impact on pyrolysis yield especially depend on the Hydrogen to Carbon (H/C) ratio. Each of three major constituents of a lingo-cellulosic biomass has its preferred temperature range of decomposition. Kumar and pratt researched that analyzing data from thermogravimetric apparatus (TGA) and differential thermogravimetric (DTG) on some selected biomass having temperature ranges for initiation of pyrolysis (Kumar, J.V.Pratt, 1996; Roddy and Manson-Whitton, 2012)

Hemicellulose : 150 – 350 °C

Cellulose : 275-350 °C

Lignin : 250-500 °C

Which means that individual constituents will contribute in differently for the end product yield. Apart from the composition particle size also having impact on the product yield. Smaller size of particles having lesser resistance to escape of condensable gasses as a result it will increase the liquid product yield similarly for the larger particles which they may have higher resistance to escape gasses hence will impact on secondary cracking. But it was found by practical results with the increase of particle size increasing gas production but results were not remarkable. (Feng *et al.*, 2015)

## **2.10 Effect of Pyrolysis Temperature and Heating Rate**

Pyrolysis temperature is the maximum temperature that is maintained inside the reactor. Fuel particles kept hold under same temperature till the process is completed. Both yield and composition are affected by pyrolysis temperature.

Varying the temperature of pyrolysis and the heating rate, pyrolysis product yield will be varied. Increasing temperature, the liquid yield increased significantly up to 500 °C at a product yield of 51 wt%. The solid (Char) yield decreased rapidly from 62 wt% (at temperature of 200 °C) to 44 wt% (at temperature of 400 °C). As operating temperature increases from 400 °C to 600 °C, the char yield decreased sharply from 44 wt% to 28 wt%, and gradually reduced to 20 wt% at 800 °C. This research was done for 7 different types of biomass materials (Adebisi; Akinola, 2016).

## **2.11 Gasification**

### **2.11.1 Gasification System**

There are three different gasification processes with different reactant resulting in product gas with different calorific values and compositions.

Direct gasification - An oxidant gasification agent is required to partially oxidize the feedstock

Indirect gasification - No oxidizing agent is required

Oxygen gasification - produces synthesis gas

The calorific value of the producer gas is depending on the gasification medium. For direct gasification 4-7 MJ/Nm<sup>3</sup> and for oxygen gasification it is ranged around 10- 12 MJ/Nm<sup>3</sup> while for indirect gasification it much higher as 15 MJ/NM<sup>3</sup>. (Belgiorno *et al.*, 2003).

A wide range of gasifier designs have been developed depending on the end use of gasification product and the type of feedstock. Generally gasification process is design is developed based on four parameters temperature, pressure, reactant gases and method of contacting. (Khor, 2006)

## 2.12 Types of Gasifiers

Gas – solid contacting mode and gasifying medium are the primary classification factors of gasifiers. Gasifiers are further categorized into three principal types based on gas –solid contacting mode as entrained flow, fixed or moving bed, and fluidized bed. Each type of those three subdivides into specific categories as shown in Figure (Prabir Basu, 2012)

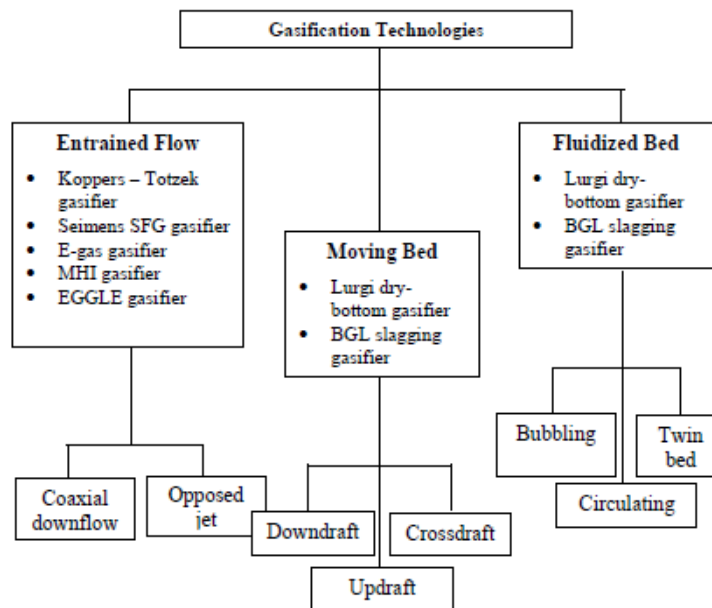


Figure 6 Gasification Technologies

### 2.12.1 Fixed/moving bed gasifier

In fixed/moving bed gasifier, fuel particles keep stationary on grate, which is designed according to relative motion with fuel particle for ash removing and better contact between char and gases. There are three different reactors such as updraft, downdraft and cross draft in fixed/moving bed gasifier. (Couto *et al.*, 2013)

One of the main feature of fixed bed/moving bed gasifier is clearly separated zones as drying, pyrolysis, combustion and gasification (char burning). This type of reactor is not effective for large scale power requirement for the reason that poor heat and mass transfer across the cross section of reactor. However, construction of this type of gasifier is relatively not expensive and less complex.

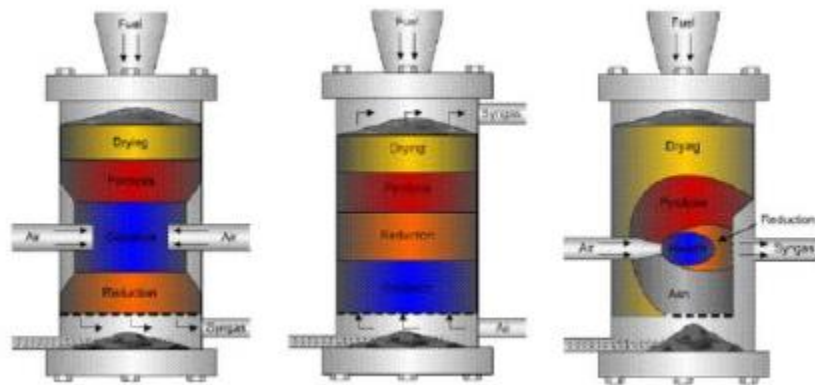


Figure 7 Different Constructions of Fixed Bed / Moving Bed Gasifier (Left to right: Downdraft, Updraft, and Cross Draft)

### 2.12.2 Updraft gasifier

Updraft gasifier is also called as counter current gasifier, which is the oldest and simplest of all of designs. Fuel feeds at the top of gasifier while gasification agent feeds at the bottom of reactor. Then, the gasification agent passes through hot char, combustion zone, pyrolysis zone and drying zone respectively. Produced gas removes at the top of the updraft reactor. Updraft gasifier is appropriate for biomass having higher ash amount (up to 25%) and higher moisture content (up to 60%) (Prabir Basu, 2012). Higher tar production is the main drawback of this gasifier since it causes a significant damage for downstream equipment in plant such as, internal combustion engines and gas burners. All the micro scale cooking gasifier are updraft gasifiers, and dry ash gasifier and slagging gasifier are examples for commercially available large scale applications.(Weiland, 2015)

### **2.12.3 Cross draft gasifier**

Cross draft gasifier is another simple gasification design. Unlike co-current or counter current gasifier, air (gasification agent) enters from side direction of reactor and produced gas removes from opposite side direction of wall, which air enters. However, fuel entry from upper part of the gasifier is alike other fixed bed/moving bed gasifier. Cross draft has the most light power capacity, where output gas directly connects to the internal combustion engine after gas is cleaned (*Cross Draft Gasification / Biofuels Academy*; Prabir Basu, 2012) Low respond time for load change and low tar generation are the main advantages of this type, thus, it is required a simple gas cleaning system. Cross draft gasifier is not suitable for fuel contents higher ash amount, but it can handle fuels having higher moisture.

### **2.12.4 Downdraft gasifier**

Downdraft gasifier is a co-current reactor where air enters to gasifier at a certain height below the top. Product gas flows downward as implies from the name and leaves through a bed of hot ash as shown in figure 8. Since it passes through high-temperature zone of hot ash, tar in the product gas finds favorable conditions for cracking. Therefore, downdraft gasifier has the lowest tar production rate ( $0.015\text{-}3\text{g/nm}^3$ ) among all those types (*Cross Draft Gasification / Biofuels Academy*; Prabir Basu, 2012; Mendiburu *et al.*, 2014)]. It is the main reason of downdraft gasifier for well performance as internal combustion engine. The engine suction draws air through the bed of fuel, and gas is produced at the end. Furthermore, ignition and required time for reactor to get active temperature for downdraft gasifier is shorter than updraft type.

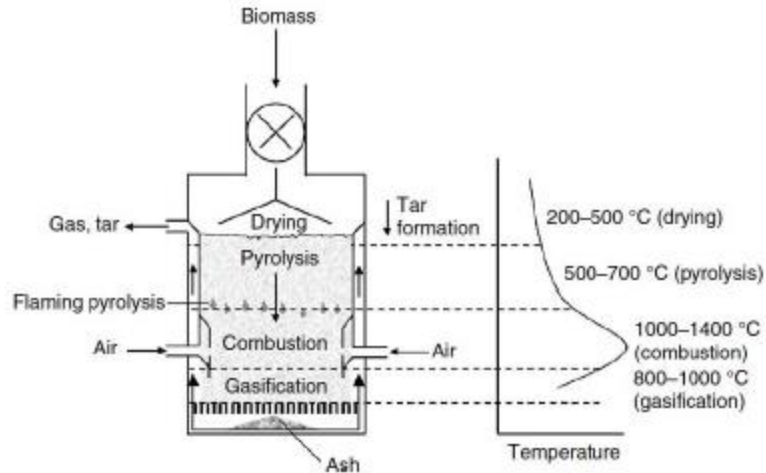


Figure 8 Schematic of Downdraft Gasifier and Temperature Gradient with Height(Prabir Basu, 2012)

According to geometrical shape, there are two types of downdraft gasifier; Downdraft Imbart gasifier and Stratified Downdraft gasifier.

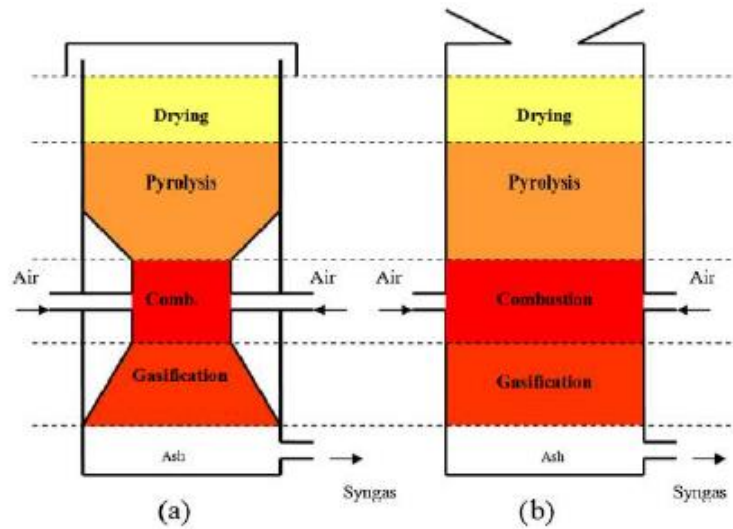


Figure 9 a) Imbert Downdraft Gasifier, (b) Stratified Downdraft Gasifier (Mendiburu et al., 2014)

### **2.12.5 Stratified gasifier**

Stratified gasifier is also called as open top, or throttles, where the top is exposed to the atmosphere, and there is no narrowing in gasifier vessel because walls are vertical. Conical groove type fuel flow is avoided in this construction. Therefore, it is better for low shrinkage fuel (light weight and finer). Moreover, best performance is in pelletized fuel rather than fine light biomass, however, additional cost is added for fuel pelletizing. Moreover, moisture content of fuel must not exceed 25%. Similarly, another negative point is that large amount of residual as ash and dust in the product gas. And lower gasification temperature is resulted due to higher temperature at the exit.(Mangre, Vyas and Pandey, 2017)

Georges Imbert invented the original design of throated or constricted gasifier in 1920s, which is popularly known as an Imbert (Prabir Basu, 2012). It has a cross-sectional area that is reduced at the throat and expanded afterwards.

Here, fuel is fed at the top, and then descended along the cylindrical section that serves as storage. At the height of about one-third of way up from the bottom, air is injected just above the constriction through nozzles. Air pyrolysis the biomass and all of those pyrolysis gas is forced to pass through the narrow passage, because oxidation (combustion zone) facilitates at the narrowest part of the throat. There, pyrolysis products are burnt. A uniform temperature distribution, char gasification and cracking of the most of tar are appeared because the entire mass of pyrolysis product moves through this hot and narrow zone, over the cross-section. However, throated downdraft gasifiers are not advantageous when scale-up to larger sizes because they do not allow for uniform distribution of flow and temperature in the constricted area.

### **2.12.6 Fluidized –bed gasifier**

Fluidized - bed is prepared using granular solids, known as bed materials where those materials are kept in fluidized state (semi-suspended condition) by the passage of gasifying medium through them at appropriate velocities. Excellent mixing and temperature uniformity are the key features of the fluidized-bed gasifiers. However, this type of gasifier is relatively insensitive to fuel's quality because of this excellent gas–solid mixing and the large thermal inertia of the bed (Prabir



Basu, 2012) Hence, risk of fuel agglomeration is reduced significantly by the temperature uniformity. The fluidized-bed design is specially evidenced that it is beneficial for biomass gasification. Tar production rate of this type of gasifier is usually around  $10 \text{ g/nm}^3$ , which lies between downdraft ( $\sim 1 \text{ g/nm}^3$ ) and updraft ( $\sim 50 \text{ g/nm}^3$ ) gasifiers. (Prabir Basu, 2012)

## 2.13 Gasification medium and kinetics

### 2.13.1 Overall kinetics of gasification

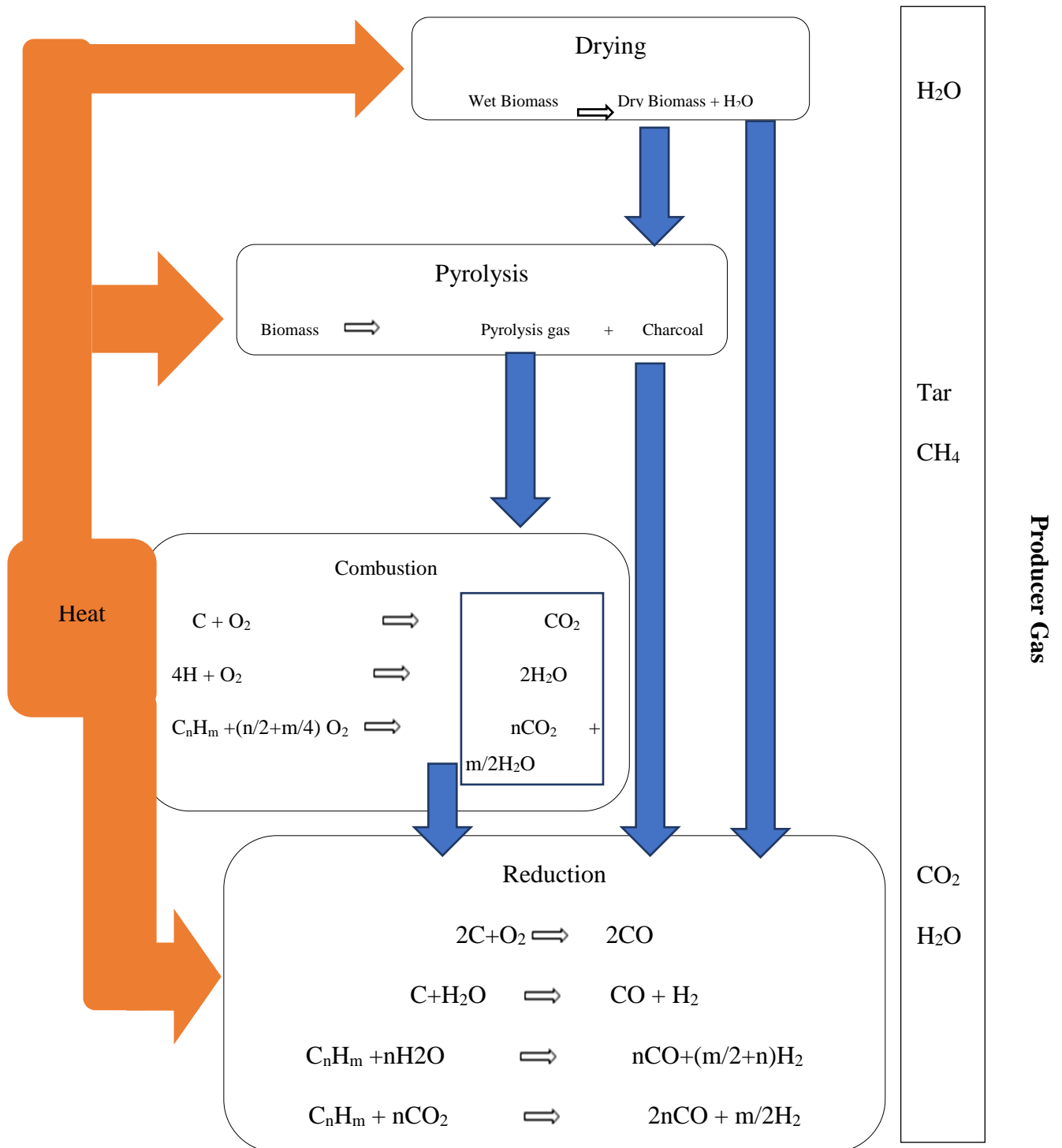


Figure 10 Overall kinetics of gasification

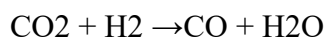
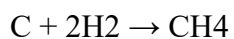
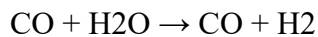
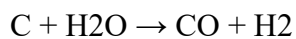
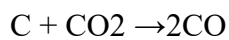
### 2.14.1 Combustion zone reactions

The following reactions occur in combustion zone and released significant amount of heat energy (401.9 KJ/mol and 241.1 KJ/mol) that increase the temperature inside the gasifier to 900 - 1,200 °C. This assists with burning off a substantial part of tars that would otherwise condense further downstream.(Prabir Basu, 2012)



### 2.14.2 Reduction zone

The products of partial combustion, water, carbon dioxide and un combusted partially cracked pyrolysis products now pass through a red-hot charcoal bed where the following reduction reactions take place (Prabir Basu, 2012)



The above reactions are endothermic, and it will reduce the temperature of gas released from oxidation zone. Producer gas in its final chemical composition is formed in this zone. The final temperature of the gasifier at the point of leaving the gasifier will reach around 250- 500 degrees of Celsius.

## 2.15 Gasification medium

For the gasification air, steam, carbon dioxide and a steam oxygen mixture can be used and different behaviors are resulted in tar formation and conversion. The ratio of fuel to medium is key parameter which make different results and make performance variations. This parameter is expressed differently for different mediums. Table 2. (Prabir Basu, 2012)

Medium	parameter
Air	ER = ratio of air used to stoichiometric air
Steam	Steam to biomass (S/
CO <sub>2</sub>	CO <sub>2</sub> to Biomass Ratio
Steam and oxygen	Gasifying ratio (GR) :( Steam + O <sub>2</sub> ) to biomass ratio

Table 2 Gasification Mediums and Characteristic Parameters

### 2.15.1 Gasification in air

Increasing ER will result in decreasing of yield and concentration of tar. Since with higher ER excess oxygen is fed into chamber and which allows volatiles to fire in pyrolysis zone. Above an equivalence ratio of 0.27 phenols are nearly all converted and less tar is formed. This decrease is greater at higher temperatures. With higher ER reduces the tar, it reduces the quality of the gas as well. Heat value of producer gas is getting reduced with higher ER because of nitrogen dilution.(Ojolo and Ogunsina, 2012)

### 2.15.2 Gasification in steam:

When steam reacts with biomass to produce H<sub>2</sub>, the tar-reforming reaction reduces the tar.



A large reduction in tar yield was seen over an Steam to Biomass ratio range of 0.5 to 2.5 (Prabir Basu, 2012)

### 2.15.3 Gasification in a steam–oxygen mixture

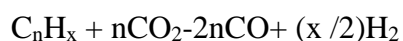
The addition of oxygen with steam further improves tar reduction. Additionally, it provides the heat needed to make the gasification reaction auto thermal. The tar yield reduces with an increase in the gasifying ratio. For example, an 85% reduction in tar is obtained when the GR is increased from 0.7 to 1.2. (Prabir Basu, 2012)

Medium	Operating condition	Tar yield (g/Nm <sup>3</sup> )	LHV (Mj/Nm <sup>3</sup> dry)	Tar yield (g/kg BM)
Steam	S/B = 0.9	30-80	12.7 – 13.3	70
Steam and oxygen	GR=0.9, H <sub>2</sub> O/O <sub>2</sub> =3	4-30	12.5-13.0	8-40
Air	ER = 0.3; H/C = 2.2	2-20	4.5-6.5	6-30

Table 3 Comparison of tar production in three gasification mediums (Gil et al., 1999)

### 2.15.4 Gasification in carbon dioxide

The tar may be reformed on the catalyst surface in a carbon dioxide medium. Such a reaction is called dry reforming and is shown here



Sandeep K has done comprehensive analysis with CO<sub>2</sub> injection in air gasification has come out below results inside a down draft gasification.

Introduction of CO<sub>2</sub> as a gasifying medium contributes to better char conversion in reduction zone. The increase of CO<sub>2</sub> fraction and increase in CO fraction in producer gas with time can be clearly seen in the Figure.

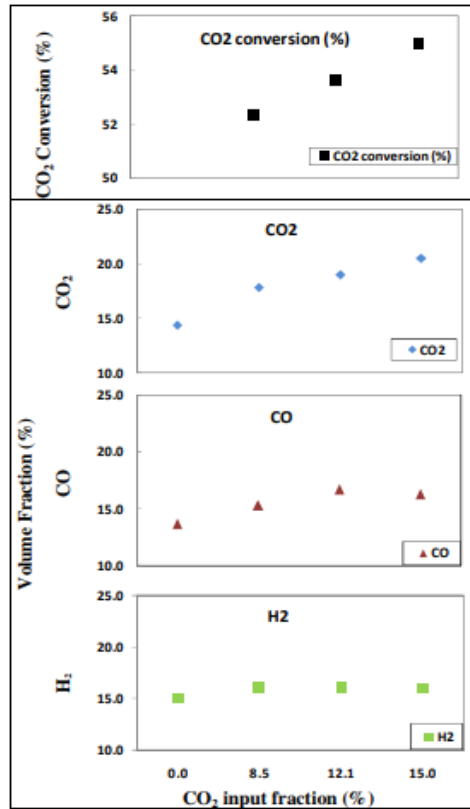


Table 4 Experimental results with varying CO<sub>2</sub> input fractions

Induction of CO<sub>2</sub> in input gasifying medium increases the fraction of CO<sub>2</sub> in the gas passing through the reduction zone, resulting in further drop in bed temperature of the reduction zone owing to endothermic reaction with char. Passing 20% of air through bottom nozzle helped in maintaining the bed temperature and thus enhancing the CO<sub>2</sub> conversion process. (K, S and Dasappa, 2012)

# CHAPTER 3: EXPERIMENTAL SETUP OF UPDRAFT GASIFIRE UNIT

## 3.1 Design parameters of the gasifier

### 3.1.1 Diameter of the reactor

The selected gasifier is originally designed to have 25 KW of thermal energy rate for the fuel calorific value of 18 MJ/kg. Hence overall power is redefined on below with the new wood chip having calorific value of 19.9 MJ/kg.

Therefore, below its re calculated for rated efficiency.

Diameter of Reactor

The diameter of the reactor is a function of fuel consumption rate and specific gasification rate. Specific gasification rate normally lies in the range of 110-210 kg /m<sup>2</sup>.hr (Ojolo and Ogunsina, 2012). For this research it has kept gasification rate 110 kg /m<sup>2</sup>.hr as an arbitrary. Diameter of the reactor is calculated by following equation

Equation 6

$$D = \left( 4 \times \frac{FCR}{SGR \times 3.14} \right)^{0.5}$$

Where

D=diameter of cylinder, m

FCR= Fuel consumption rate, kg/hr

SGR=Specific gasification rate= kg /m<sup>2</sup>.hr

Here the diameter is set to be 0.28 m, hence it can be calculated that FCR = 6.9 kg/hr

### 3.1.2 Fuel Consumption Rate

#### Equation 7

$$FCR = \frac{Q}{HV_f \times \xi_g} \quad (\text{Ojolo and Ogunsina, 2012; Prabir Basu, 2012})$$

Where:

FCR – Fuel consumption rate, kg/s

Q – Rated thermal energy, kW

HV<sub>f</sub> - heating value of fuel, MJ/kg

ξ<sub>g</sub> - gasifier efficiency (Taken as 70% )

Hence Rated thermal power can be calculated as 26.7 kW.

### 3.1.3 Height of the reactor

The height of a typical gasifier lies upon several parameters and determines how long would the gasifier be operated in one loading of fuel. Basically, it is a function of the required time to operate the gasifier (T), the specific gasification rate (SGR), and the density of biomass. This gasifier is designed to have 4 hr operational time for a batch.

#### Equation 8

$$H = SGR \times T / \rho$$

Where

H= Height of reactor

SGR= Specific gasification rate

ρ =Density of fuel= 350 kg/m<sup>3</sup>

Hence height of the reactor 1.26 m.



Volume of the reactor

Volume of the reactor is given by equation 9

**Equation 9**

$$V = \pi r^2 \times H$$

V=volume of reactor (m<sup>3</sup>)

R=radius of reactor (m)

H=height of reactor (m)

Hence the volume of the reactor is set to be 0.076 m<sup>3</sup>

### **3.1.4 Total working height of reactor**

Total working height of gasifier means to make provision for grate, ash chamber, plugs and socket accommodation. This height fixed value is taken as 37.75%. So the total designed as follows

$$\text{Height} \times \text{Fixed Value} = 1.25 \times 0.37 = 0.46 \text{ m}$$

**Equation 10**

$$\text{Total Height} = 0.46 + 1.25 = 1.71 \text{ m}$$

### **3.1.5 Time required to consume fuel:**

This defines total maximum time required for gasification of biomass inside the reactor(Ojolo and Ogunsina, 2012) This time is a combination of startup time and operational time. This is calculated by formula given below.

**Equation 11**

$$\text{Time} = \rho \text{ of Fuel} \times V / \text{FCR}$$

$$T = 350 \times 0.076 / 6.9 = 3.9 \text{ hr}$$

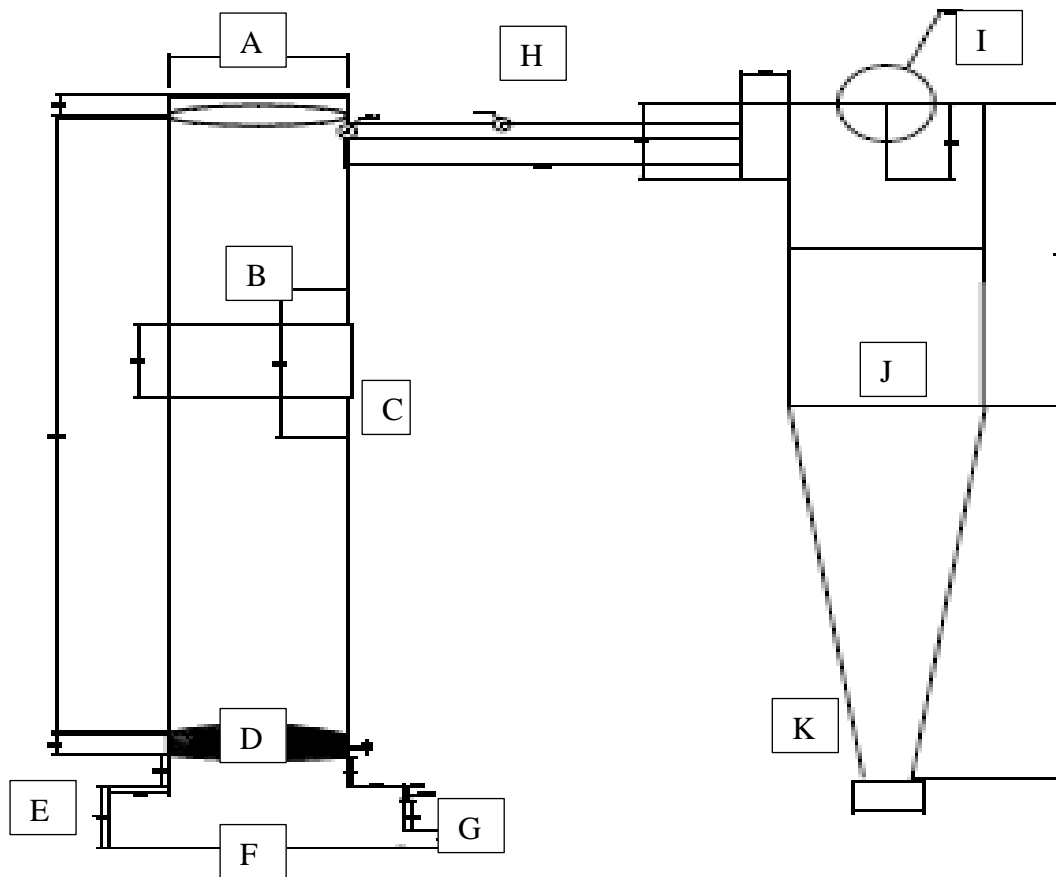


Figure 11 Model of Updraft Gasifier with Cyclone separator.

(A) Feeding Provision ; (B) Reactor Main Body; (C) Packing plate Provision; (D) Grate; (E) Ash Window; (F) Ash Chamber;(G) Air blowing line;(H) Gas Exit pipe ; (I) Gas exit pipe with sampling port; (J) Cyclone separator; (K) solid particles and Condensate collector

### 3.2 Reactor Fabrication and Material selection

This reactor has been designed with mild steel and stainless steel which is to withstand at elevated temperatures. Three thermocouples have been set into body to measure the temperatures of each zone. The grate has placed in the bottom of the reactor which allows fire the biomass and keep passage to ash removal. Also, ash chamber has set up below the grate unit which is to be used to remove ash generated during firing.

Cyclone has set to remove solid particles and tar to improve the quality of produced gas. Also end of the cyclone unit gas sampling point has set up to take samples for analysis. Digital temperature monitors also fixed onto a board which is equipped with selector switch. Unit has

correctly insulated from Rockwool having thickness of 4 inch and which is designed to minimize heat loss and outer temperature to be designed to have as below 60 °C while inside is above 800 C

### **3.2.1 Air Supply to unit**

Air inlet passage has fabricated on unit and 2.0 Ampere, 1.5” diameter size blower fan is used while its flow can be controlled from 0 – 5 m<sup>3</sup>/hr.

Air flow was measured using hotwire Anemo meter and ensured that control the air flow which is fed into reaction chamber.

## **3.3 Feed Stock Preparation, Analysis and Operation**

### **3.3.1 Biomass feed stock**

Rubber wood is selected as fuel which was chipped into size of 2”x1” using a chipping machine. Wood chip was processed outside chip processing plant hence the size is controlled through the machine itself.

### **3.3.2 Fuel property Analysis**

#### **2.4.1.4 Ultimate Analysis**

Fuel wood was tested on reputed laboratory externally for ultimate analysis and results were obtained as ASTM standard test methods.

Test/Parameter	Method
Total Moisture	ASTM D 2961 : 11
Ash (on dry basis)	ASTM D 3174 : 12
Ash (As received basis)	ASTM D 3174: 12
Volatile matter (on dry basis)	ASTM D 3175 : 11
Volatile matter (as received basis)	ASTM D 3175 : 11
Fixed Carbon (on Dry basis)	ASTM D 3172 : 13
Fixed Carbon (As Received basis)	ASTM D 3172 : 13
Gross Calorific value (on Dry basis)	ASTM D 5865 : 13
Gross Calorific value (on As received basis)	ASTM D 5865 : 13
Sulphur (on Dry basis)	ASTM E 775-87 Reaff 2008
Sulphur (on As received basis)	ASTM E 775-87 Reaff 2008
Carbon (on Dry basis)	ASTM D 5373 : 2014
Carbon (on As received basis)	ASTM D 5373 : 2014
Hydrogen (on Dry basis)	ASTM D 5373 : 2014
Hydrogen (on As received basis)	ASTM D 5373 : 2014
Nitrogen (on Dry basis)	ASTM D 5373 : 2014
Nitrogen (on As received basis)	ASTM D 5373 : 2014
Sulphur (on Dry basis)	ASTM D 5373 : 2014
Sulphur (on As received basis)	ASTM D 5373 : 2014
Ash (on Dry basis)	ASTM D 5373 : 2014
Ash (on As received basis)	ASTM D 5373 : 2014
Oxygen (on Dry basis)	ASTM D 3176 : 2015
Oxygen (On As received basis)	ASTM D 3176 : 2015

**Table 5 Fuel test standard**

In addition to above tests Moisture content was checked just before the fuel feed into gasifier reactor.

#### **2.4.1.5 Determination of moisture contents.**

Samples were weighted accurately in a Petridis spreading evenly over the dish surface. These samples were then introduced into an oven for 1 hour at 100 °C. After removing samples from oven, they were placed in a desiccator for 10 minutes to cool and then weighted.

### 3.4 Overall equipment setup



Figure 11 Overall Arrangement A- Combustor, B - Temperature Display, C - CO2 Cylinder, D - Air blower



Figure 12 Orsat equipment set up

### 3.5 Test procedure flow chart

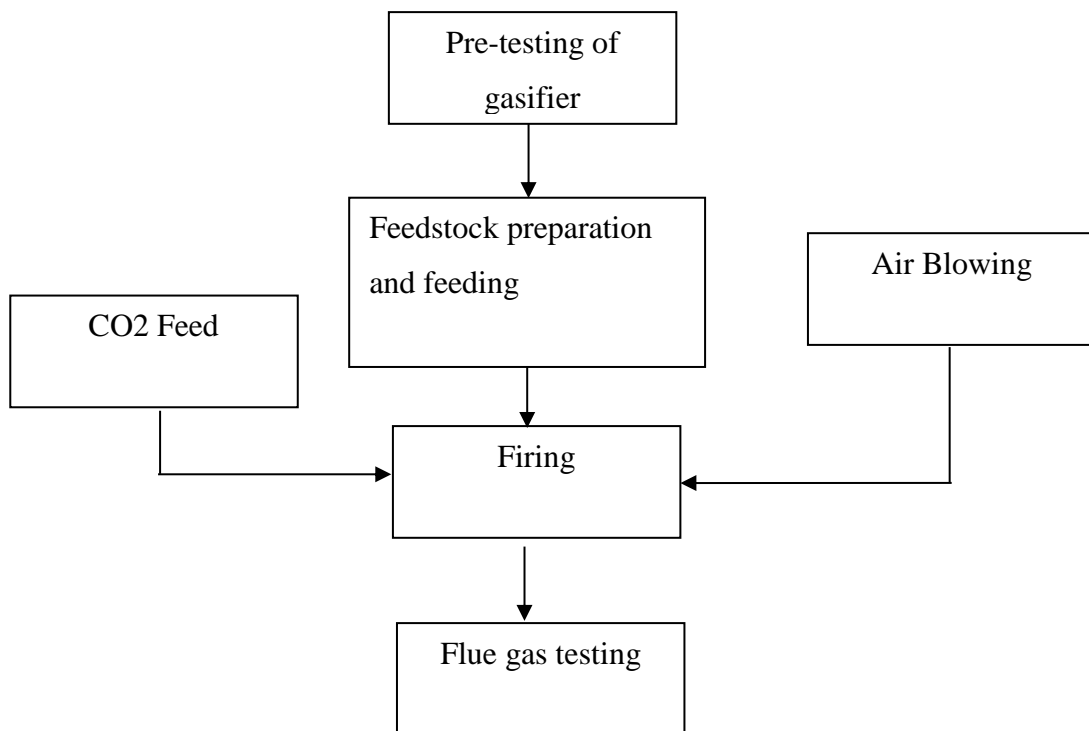


Figure 13 Test procedure

#### 3.5.1 Pre Testing

Gasifier reactor was pre-tested prior to trial start for the leak preparation on gas piping and ensured that no leak condition and appropriate insulation condition.

#### 3.5.2 Feedstock preparation and feeding

Rubber woods was brought from reputed industrial biomass supplier and chips were cut in to 2” x 0.5 “sized and size distribution was randomly checked.

Biomass was stored under normal room condition and before using it was solar dried and moisture content was measured as described. Then sufficiently dried biomass was weighed, and measured batch was fed through the top part of the reactor.

Tightly close the top cap of the reactor inserting packing material to avoid further leaks through fuel feeding cap.

### **3.5.3 Firing**

Air was blown through the chip bed using 1.5" diameter having blower and flow rate was set to 7 m<sup>3</sup> per hour. Initial firing was done from liquid petroleum gas (LP gas) also ensure than gas exhausted lines are fully opened.

Gas burner was used for initial firing and flame was introduced through the bottom of the reactor. Once the fire started air blower closed the ash window and switched ON the blower fan to provide air for the combustion.

Air velocity was measured using Anemo meter and flow rate was adjusted accordingly.

Temperature of each zone was recorded in every 15 min interval and flue gas was tested through Orsat apparatus. (Test procedure under 3.5.5)

### **3.5.4 Flue gas testing**

Before samples were taken out from the exhaust line, it was ensured that sufficient CO is produced while taking temperature at pyrolysis zone as well as burning the exhaust flue gas.

Flue gas sampling line was directly connected to Orsat apparatus through copper tubes and passes through the water bath.

Measured the O<sub>2</sub>, CO, CO<sub>2</sub> gas compositions through orsat apparatus.

After taking reference samples of three, CO<sub>2</sub> was fed through air blow line at different flow rates and measured the performance change of gas composition.

Trials were repeated for 4 reference samples and 8 samples were taken with CO<sub>2</sub> feeding.

### **3.5.5 Orsat Operation**

Orsat Apperatus is used to analyze gas samples drawn from flue gas.

### 2.4.1.6 Apparatus

As shown in Figure 12, the Orsat apparatus consists of a water-jacketed 100-ml burette B connected at its top to a glass manifold M and at its bottom to a leveling bottle L. The glass manifold M is connected to three reagent bulbs called pipettes P<sub>1</sub>, P<sub>2</sub> and P<sub>3</sub> via three cocks C<sub>1</sub>, C<sub>2</sub> and C<sub>3</sub>. Each tube is filled with its own absorbing chemical solution:

P<sub>1</sub>: potassium hydroxide (30 % w/v) to absorb CO<sub>2</sub>

P<sub>2</sub>: alkaline pyrogallol to absorb O<sub>2</sub>

P<sub>3</sub>: cuprous chloride in hydrochloric acid to absorb CO.

Pipettes P<sub>1</sub> and P<sub>2</sub> are partly filled with glass tubes to increase the contact surface area between liquid and glass. P<sub>3</sub> contains copper wire to protect acid against possible oxidation. The 3-way cock C<sub>4</sub> is used to connect manifold M to the atmosphere (via suction pump SP), to connect it to the sampler tube or to isolate the trapped gas.

### 2.4.1.7 Procedure

#### a) Preparatory Steps

-Fill the system with water & chemicals as applicable.

-By opening one of the cocks C<sub>1</sub>, C<sub>2</sub>, C<sub>3</sub> at a time and keeping all other cocks close, and manipulating bottle L bring the solution in each pipette to the top mark on the stem of the pipette. Then close the isolating cock.

-Now connect the sampler line to suction pump SP by turning the 3-way valve C<sub>4</sub>. Operate the pump to purge all air from the sampler line.

#### b) Trapping the Gas Sample

-By turning the cock C<sub>4</sub> connect the glass manifold M to the sampler line.

-Lower bottle L slowly until the water level in burette B is slightly below the zero mark on the scale. Then close C<sub>4</sub> and disconnect the sampler line.



-Slightly lift cock C<sub>4</sub> off its seat to equalize the pressure inside burette B with the ambient pressure. Then raise bottle L gently until water level in the burette coincides with the zero mark. This ensures that the burette now contains 100 ml of exhaust gas at atmospheric pressure.

### c) Absorption of Gas Constituents

The following steps should be done for each pipette, one at a time, in the order P<sub>1</sub> then P<sub>2</sub> then P<sub>3</sub>.

-Open cock C<sub>1</sub>, and slowly raise bottle L to allow the gas to flow into pipette P<sub>1</sub> until water in the pipette reaches the (100)-mark.

-Slowly lower bottle L to let gas leave pipette P<sub>1</sub> and re-enter burette B until the chemical solution in pipette P<sub>1</sub> reaches the top mark on its stem. Close C<sub>1</sub>.

-Bring the levels of water in burette B and bottle L to coincide. Read the scale on burette B to get the volume of CO<sub>2</sub> absorbed, measured at atmospheric pressure.

-Repeat this procedure a few times until the reading becomes constant which means that all CO<sub>2</sub> has been absorbed. Then close cock C<sub>1</sub>.

-For the next pipettes, the volume absorbed is obtained as the difference between the current scale reading and the one just preceding it.

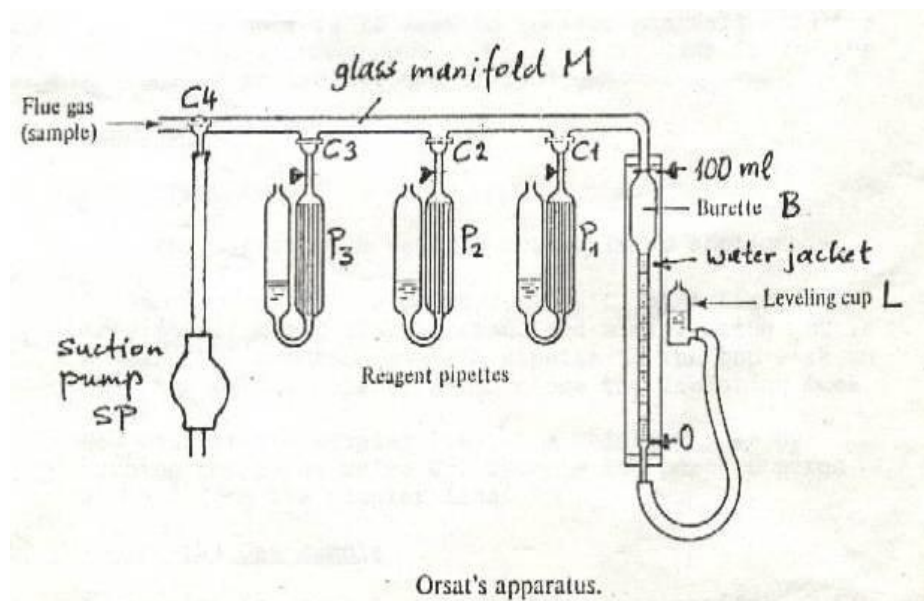


Figure 14 Orsat setup

## 3.6 Supportive Calculations

### 3.6.1 Specific gas production: Gas to Fuel Ratio

Carbon balance is used to calculate Gas to fuel ratio

Equation 12

$$C_f = C_g + C_{c-a} + C_t$$

Where

$C_f$  = Rate of carbon entering the gasifier with fuel (kg/hr)

$C_g$  = Rate of carbon leaving with Producer gas

$C_{c-a}$  = Rate of carbon leaving with char-ash

$C_t$  = Rate of carbon leaving with tar

With Air feeding

It can be assumed that carbon in char ash and tar is negligible compared to carbon in the producer gas then equation can be modified into

Equation 13

$$C_f = C_g$$

$C_f$  is carbon in fuel;

Equation 14

$$C_f = C \text{ wt \% in fuel} \times FCR$$

Where

FCR - Fuel consumption rate in kg/hr. therefore equation 12 can be re written into

Equation 15

$$C \text{ wt \% in fuel} \times FCR = C_g$$

Volumetric fraction of carbon in the producer gas is computed as follows

Equation 16

$$C_{gv} = \sum \frac{(\% \text{ of C comp} \times \rho \text{ of C comp} \times \text{C wt. per mole})}{\text{Molecular weight of component}}$$

However

Equation 17

$$C_g = C_{gv} \times G$$

Where  $G$  = Producer gas flow rate ( $\text{m}^3/\text{h}$ ), from Eq15 and we get the following

Equation 18

$$C \text{ in fuel} \times \text{FCR} = C_{gv} \times G$$

$$\frac{G}{F} = \frac{0.506C \text{ wt \% in fuel}}{C_{gv}}$$

### 3.6.2 Air to Gas ratio (Specific air consumption)

Nitrogen balance is used for calculation of this parameter

Equation 19

$$N_f + N_a = N_g$$

Where

$N_f$  = Nitrogen in fuel (kg/hr)

$N_a$  = Nitrogen in air

$N_g$  = Nitrogen in producer gas

Compare to the Air, Nitrogen content in the fuel is negligible

**Equation 20**

$$N_a = N_g$$

By taking volumetric fraction of nitrogen in air as 0.79;

**Equation 21**

$$N_a = 0.79A$$

Where A = air flow rate (m<sup>3</sup>/h)

By combining Eq19 and the resultant equation becomes as

**Equation 22**

$$0.79A = N_g$$

Volumetric fraction of nitrogen in producer gas can be found from composition so

**Equation 23**

$$N_g = N_{gv} \times G$$

From Eq. 20 and 21 we get the following resultant equation

$$\frac{A}{G} = \frac{N_{gv}}{0.79}$$

### **3.6.3 Biomass formula determination based on elemental analysis**

Determination of biomass formula is done using elementary analysis and C, H and O components are determined while assuming Sulphur content is low. Also, it can be assumed that Nitrogen in Biomass is negligible compared to the Nitrogen in atmospheric Air. Elementary test results attached on Appendix

Formula of biomass (Rubber wood) - C<sub>1.53</sub> H<sub>2.62</sub> O

### 3.6.4 Equivalence ratio

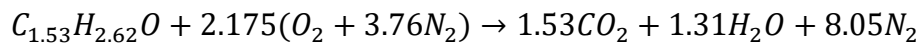
It is the ratio of the actual air–fuel ratio to the stoichiometric air–fuel ratio. This term is generally used for air-deficient situations, such as those found in a gasifier.

Equation 24

$$ER = \frac{\left(\frac{A}{F}\right)_o}{\left(\frac{A}{F}\right)_s}$$

### 3.6.5 Stoichiometric air and gasification air flow rate calculation

Equation 25



Stoichiometric air required is calculated as for Rubber wood.

Molecular weight of Rubber wood = 36.98 kg/kmol

Oxygen-Fuel mass ratio =  $\frac{2.175 \times 32}{1 \times 36.98} = 1.88$  kg of oxygen /kg of fuel

Oxygen in air by mass percent is 21 so we need

$$1.88 \times \frac{100}{21} = 8.95 \text{ kg of air /kg of feed}$$

Equation 26

$$\text{Air flow rate} = \frac{ER \times FCR \times \text{Stoichiometric air fuel ratio}}{\rho \text{ of air}}$$

ER	Air Flow Rate (kg/hr)
0.2	9.5 (7 m <sup>3</sup> /hr)

Table 6 Equivalence ratio and flow rate

# CHAPTER 4: RESULTS FOR UPDRAFT GASSIFIRE PERFORMANCE

## 4.1 Biomass Analysis Results

Biomass Rubber wood chip sample was analyzed in SGS Lanka Private Limited and results are shown below.

### 4.1.1 Proximate analysis

Element	Wight Percentage (w/w%)
Fixed Carbon	17.25
Volatile Matter	81.28
Ash	1.47
Moisture initial	36.7

Table 7 Proximate analysis results

### 4.1.2 Ultimate analysis

Element	Wight Percentage (w/w%)
Ash	1.47
Carbon	48.74
Hydrogen	6.97
Nitrogen	0.35
Sulfur	0.04
Oxygen	42.43

Table 8 Ultimate Analysis Results

## 4.2 Temperature profile variation

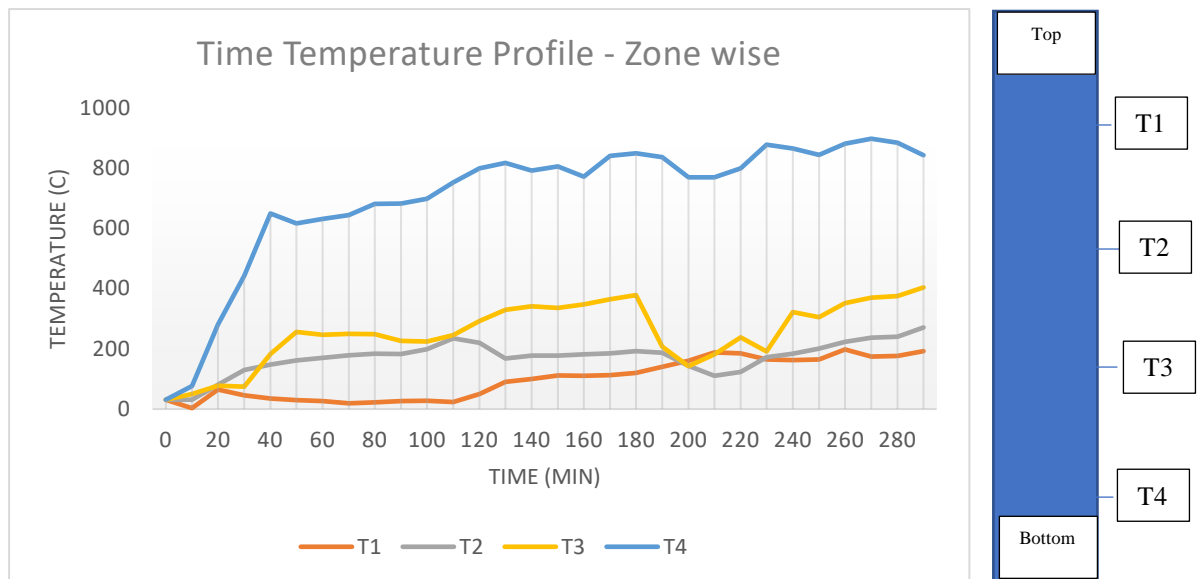


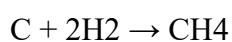
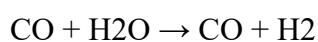
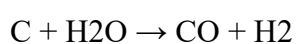
Figure 15 Temperature profile variation

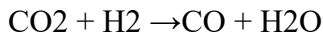
T1 - Temperature of Most top section of updraft gasifier; (subsequently other thermometer locations are indicated in figure 15).

After starting the firing of wood chips at  $t = 0$ , Combustion zone temperature gradually increased and final temperature it reached about  $800^{\circ}\text{C}$ . Special observation noted in T3, once its temperature reached around 170 to  $180^{\circ}\text{C}$ , temperature suddenly reduced by 150 degrees of Celsius.

This can be further explained by reduction reactions

Basically, the products of partial combustion, water, carbon dioxide and un combusted partially cracked pyrolysis products now pass through a red-hot charcoal bed where the following reduction reactions take place.





The above reactions are endothermic, and it will reduce the temperature of gas released from oxidation zone.

### 4.3 Yield variation

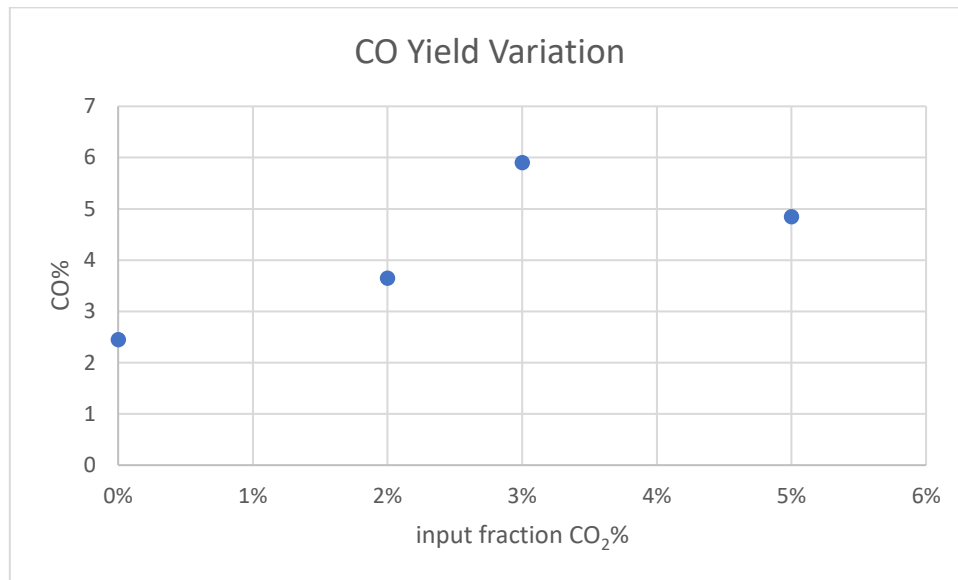


Figure 16 CO yield variation with variable input fraction of CO<sub>2</sub>

Results were obtained by series of trials and it can be clearly seen that increasing of CO<sub>2</sub> fraction in input air will result to increase of CO concentration of producer gas. Also, with increasing CO<sub>2</sub> fraction will cause to reducing of bed temperature since gas is passing through reduction zone because of endothermic reactions which is aligned to the temperature time graph described in figure 12. The CO<sub>2</sub> conversion reaches a maximum at the Carbon Boundary Point (CBP), in which all the solid carbon is transferred to the producer gas. For a higher CO<sub>2</sub> flow-rate, the CO<sub>2</sub> conversion decreases as the CO<sub>2</sub> leaves the reactor without reacting. Therefore at 3% of CO<sub>2</sub> input fraction it maximizes its yield of CO production and gradually decrease.

Since CO<sub>2</sub> is injected into the reactor as a reactive gas, it is difficult to classify CO<sub>2</sub> at the output as being generated during the process by reactions as the unreacted portion from the input stream. Hence, CO<sub>2</sub> concentration plot cannot be used to point out the reactions dominating the process.



#### 4.4 Flame observation



Figure 17 Flame observations

It was observed flame characteristics by burning producer gas. Initially high moisture content having gas released since in initial stage moisture contain with biomass get evaporated. When the reaction zone temperature increased and final temperature of the reaction zone close to 400 °C it was observed blue color flame which indicated that optimum yield.

#### 4.5 Effect of CO<sub>2</sub>/C variation

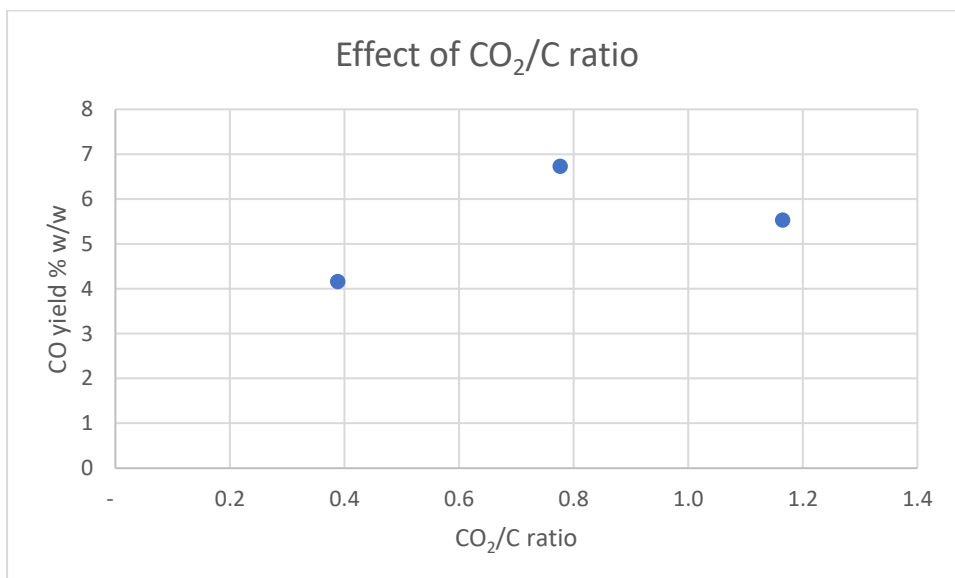


Figure 18 Effect of CO<sub>2</sub>/C Ratio for CO yield

There should be some increase of methane with the temperature increased but the methane dry reforming reactions which is thermodynamically possible only above 640 °C. this reaction should be a reason of increasing CO concentration beyond 790 °C. The change of CO<sub>2</sub>/C ratio affect the yield of CO, H<sub>2</sub> and lower hydro carbons. However, no such significant deviation

observes in this range assumed that possible reason could be the heat loss through bare surfaces of tested gasifier.

(Sadhvani, 2017) has done same test for fixed bed reactor and observed same results that no such significant deviation through 1.04-1.52 range.

#### **4.6 Process influence of Moisture percentage for gasification**

During the testing it was observed that moisture content is greatly impacted for process of gasification and following were observed

1. It took more time for partial combustion with high moisture content fuels
2. Quality of producer gas was affected as almost no CO gained with the fuel fed at above 30% moisture content, hence it will impact on the heating value of the producer gas.
3. Only white colored moisture high gas released through chimney.

Kumar H, has proved same results and concluded that overall gasification efficiency has been affected and quality of producer gas has been drastically reduced with the effect of moisture content. Through the study gasification efficiency has been reduced by 20% by increasing moisture percentage by 35%. (Kumar *et al.*, 2014)

## 4.7 Effect of equipment sensitivity for overall results

There were several limitations during the trial which made impact on overall results

Equipment	Description / Impact to Results	Suggestion for improvement
Air Blower	Air Blower had an adjustable damper to control air flow, it was controlled by continuously measuring air velocity and volumetric flow rate was calculated with diameter of inlet air passage.	Small vortex flow meter to be used for air flow measurement along with control valve
CO <sub>2</sub> Flow Control Valve	CO <sub>2</sub> flow control valve was a factory fitted one on same cylinder head. It has minimum value of 1 Liters per minute. This is not an optimum design and impact on results and some range was not able to measure.	Install Flow meter along with flow control valve
Orsat Equipment	With the limited bed size, firing got fast at gasification phase. At the time it took some time to read the results and very limited number of samples could measure.	Use of different gas analysis technique. (Collection through gas bags/ Digital Gas Analyzer)

Table 9 Effect of equipment sensitivity for overall results

## **CHAPTER 5: CONCLUSION AND FUTURE DIRECTIONS**

### **5.1 Conclusion**

The present study suggests that CO<sub>2</sub> concentration in input air will result in increase of yield of producer gas and which further can be used for re circulation of flue gas into input gas in order to increase the yield. Also, it can be concluded that 3% of input CO<sub>2</sub> mix will result in optimization yield of CO.

### **5.2 Modern Development in gasification**

Though the study focused with injection of CO<sub>2</sub> along with the input air this can be further used to recycling of flue gas fraction in to input air.

Instead of CO<sub>2</sub> feeding externally flue gas recycling gives a definite advantage over conventional gasification process. In 2011 Japan has researched on CO<sub>2</sub> recirculation systems (Oki *et al.*, 2011) and proposed as a solution of existing issues raised on CO<sub>2</sub> capturing due to high steam consumption in absorption .

There are three trapping methods are available in the world on CO<sub>2</sub> capturing

#### **5.2.1 Post-combustion**

In the post-combustion method, CO<sub>2</sub> is separated from the flue gas of the power station by bubbling the gas through an absorber column packed with liquid solvents (such as ammonia) that preferentially take out the CO<sub>2</sub>. In the most commonly-used techniques, once the chemicals in the absorber column become saturated, a stream of superheated steam at around 120 °C is passed through it. This releases the trapped CO<sub>2</sub>, which can then be transported for storage elsewhere.

More experimental techniques to scrub CO<sub>2</sub> from flue gas without the two-step process include using seawater to absorb the gas and then returning the mixture back to the ocean for long-term storage. But, so far, these methods have proved less efficient and reliable.

## **5.2.2 Oxyfuel**

When coal, oil or natural gas is burned in normal air, the amount of CO<sub>2</sub> produced is between 3-15% of the waste gases, depending on the conditions. Separating the greenhouse gas out after combustion requires energy so an alternative CCS method is to burn the fossil fuel in an atmosphere of pure oxygen. In this environment, virtually all the waste gas will be composed CO<sub>2</sub> and water vapour. The latter can be condensed out while the former can be piped or transported directly to a storage facility.

In the oxyfuel system, the air fed into the boiler has to be separated into liquid oxygen, gaseous nitrogen, argon and other trace gases and this process can use up to 15% of the power produced at the station.

## **5.2.3 Pre-combustion**

This method is normally applied to coal-gasification combined cycle power plants. The coal is gasified to produce a synthetic gas made from carbon monoxide and hydrogen. The former is reacted with water to produce CO<sub>2</sub>, which is captured, and more hydrogen. The hydrogen can be diverted to a turbine where it can be burned to produce electricity. Alternatively, some of this gas can be bled off to feed hydrogen fuel cells for cars.


## **5.3 Future Work**

In present study batch operation was carried out for rubber wood chips which only Air and CO<sub>2</sub> volume fraction was the controllable parameter. Further studies are proposed in following areas.

- Input and output online measurement to identify actual behavior and effect of gasification temperature of each zone to have optimum yield.
- As it was observed that moisture content plays an extensive role in biomass gasification its variations can be captured
- Full gas analysis of producer gas and study the behavior of methane re forming and its impact on yield.

# APPENDECIS

## APPENDIX A – SGS Fuel test report



### Test Report

SAMPLE NOT DRAWN BY SGS INDIA PVT. LTD.

**Report No** : CG16-013423.001

**Print Date** : 30/06/2016

**JOE No** : CG16-013423

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**Report Control No** : CGR0000570437

**Sample described by customer as** : WOOD CHIPS

**Customer Name** : SGS LANKA (PVT) LIMITED

**Customer Address** : 1ST FLOOR,140,VAUXHALL STREET

**City** : COLOMBO

**Postal Code** : 2

**Country** : SRILANKA

**Sample Type** : WOOD CHIPS

**Received** : 22/06/2016

**Sample Qty. Recd.** : 1kg

**SGS Internal No.** : 7660016003

**Test Start** : 22/06/2016

**Test End Date** : 30/06/2016

Test/Parameter	Method	Result	Unit
<b>Total Moisture</b>	ASTM D2961 : 11	36.70	% (w/w)
<b>Ash (on dry basis)</b>	ASTM D3174 : 12	1.47	% (w/w)
<b>Ash (as received basis)</b>	ASTM D3174 : 12	0.93	% (w/w)
<b>Volatile matter (on dry basis)</b>	ASTM D 3175 : 11	81.28	% (w/w)
<b>Volatile matter (as received basis)</b>	ASTM D 3175 : 11	51.45	% (w/w)
<b>Fixed carbon (on dry basis)</b>	ASTM D3172 : 13	17.25	% (w/w)
<b>Fixed carbon (as received basis)</b>	ASTM D3172 : 13	10.92	% (w/w)
<b>Gross calorific value (on dry basis)</b>	ASTM D5865 : 13	4753	kcal/kg
<b>Gross calorific value (as received basis)</b>	ASTM D5865 : 13	3009	kcal/kg
<b>Sulphur (as received basis)</b>	ASTM E 775- 87, Reaff:2008	0.03	% (w/w)
<b>Sulphur (on dry basis)</b>	ASTM E 775- 87, Reaff:2008	0.04	% (w/w)
<b>Carbon (on dry basis)</b>	ASTM D5373 : 2014	48.74	% (w/w)
<b>Carbon (as received basis)</b>	ASTM D5373 : 2014	30.85	% (w/w)
<b>Hydrogen (on dry basis)</b>	ASTM D5373 : 2014	6.97	% (w/w)
<b>Hydrogen (as received basis)</b>	ASTM D5373 : 2014	8.52	% (w/w)
<b>Nitrogen (on dry basis)</b>	ASTM D5373 : 2014	0.35	% (w/w)
<b>Nitrogen (as received basis)</b>	ASTM D5373 : 2014	0.22	% (w/w)
<b>Sulphur (as received basis)</b>	ASTM D5373 : 2014	0.03	% (w/w)
<b>Sulphur (on dry basis)</b>	ASTM D5373 : 2014	0.04	% (w/w)
<b>Ash (on dry basis)</b>	ASTM D5373 : 2014	1.47	% (w/w)
<b>Ash (as received basis)</b>	ASTM D5373 : 2014	0.93	% (w/w)
<b>Oxygen (as received basis)</b>	ASTM D3176 : 2015	59.45	% (w/w)
<b>Oxygen (on dry basis)</b>	ASTM D3176 : 2015	42.43	% (w/w)

Page 1 of 2

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## Test Report

SAMPLE NOT DRAWN BY SGS INDIA PVT. LTD.

Report No : CG16-013423.003

Print Date : 30/06/2016

JOE No : CG16-013423

Report Control No : CGR0000570437

Test/Parameter	Method	Result	Unit
Silica (as SiO <sub>2</sub> )	ASTM C : 114 - 2013	87.90	% (w/w)
Aluminum (as Al <sub>2</sub> O <sub>3</sub> )	ASTM D : 6349 - 2013	1.61	% (w/w)
Iron (as Fe <sub>2</sub> O <sub>3</sub> )	ASTM D : 6349 - 2013	1.30	% (w/w)
Calcium (as CaO)	ASTM D : 6349 - 2013	1.41	% (w/w)
Magnesium (as MgO)	ASTM D : 6349 - 2013	0.79	% (w/w)
Sodium (as Na <sub>2</sub> O)	ASTM D : 6349 - 2013	0.07	% (w/w)
Manganese (as MnO)	ASTM D : 6349 - 2013	0.07	% (w/w)
Potassium (as K <sub>2</sub> O)	ASTM D : 6349 - 2013	1.47	% (w/w)
Sodium (as Na)	ASTM D : 6349 - 2013	0.05	% (w/w)
Titanium (as TiO <sub>2</sub> )	ASTM D : 6349 - 2013	0.27	% (w/w)
Phosphorous (as P <sub>2</sub> O <sub>5</sub> )	ASTM D : 6349 - 2013	1.39	% (w/w)
Sulphur trioxide (as SO <sub>3</sub> )	ASTM C : 114 - 2013	0.773	% (w/w)

Per pro SGS India Private Ltd

L\_SIVAKUMAR  
Authorized Signatory

\*\*\*\*End of Report\*\*\*\*

Page 2 of 2

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APPENDIX B

<b>Anemometer [Hot wire with temperature sensing probe]</b>	
Type	Digital RS-232
Model	AVM 714
Circuit	Custom one-chip of microprocessor LSI circuit
Display	13 mm (0.5") super large LCD display (dual function meter's display)
Sampling Time	approx. 0.8 sec.
Operating Temperature	0°C to +50°C
Power supply	1.5V AAA (UM-4) battery x 6 pcs. (alkaline or heavy duty type)
Range	0.2 to 20 m/s
Main Instrument and Telescope Probe Dimension	180 x 72 x 32 mm & round 72 mm dia., L = 250 to 940 mm



## REFERENCES

- Adebisi; Akinola (2016) 'Effect of Temperature on Product Yield of Pyrolysis of Seven Selected Wood Species in South West Nigeria', 9359(6), pp. 176–181.
- Barrio, M. (2002) *Experimental Investigation of Small-Scale Gasification of Woody Biomass*. Available at: <http://www.diva-portal.org/smash/get/diva2:126378/FULLTEXT01.pdf>.
- Belgiorno, V. *et al.* (2003) 'Energy from gasification of solid wastes', *Waste Management*, 23(1), pp. 1–15. doi: 10.1016/S0956-053X(02)00149-6.
- Brownsort, P. A. (2009) 'Biomass Pyrolysis Processes: Review of Scope, Control and Variability', *Biomass*, p. 38. doi: 10.1017/CBO9781107415324.004.
- Couto, N. *et al.* (2013) 'Influence of the biomass gasification processes on the final composition of syngas', *Energy Procedia*. Elsevier B.V., 36, pp. 596–606. doi: 10.1016/j.egypro.2013.07.068.
- Cross Draft Gasification | Biofuels Academy* (no date). Available at: <http://biofuelsacademy.org/web-modules/process/gasification/cross-draft-gasification/> (Accessed: 5 February 2018).
- Czajczyńska, D. *et al.* (2017) 'Potential of pyrolysis processes in the waste management sector', *Thermal Science and Engineering Progress*. Elsevier, 3, pp. 171–197. doi: 10.1016/J.TSEP.2017.06.003.
- Demirbas, A. (2007) 'Combustion Systems for Biomass Fuel', *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. Taylor & Francis Group, 29(4), pp. 303–312. doi: 10.1080/009083190948667.
- Feng, Y. *et al.* (2015) 'The influence of catalyst and temperature on pine sawdust gasification performance by an externally heated gasifier', *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, 37(10), pp. 1033–1038. doi: 10.1080/15567036.2011.588678.
- Hallgren, A. (1996) 'Theoretical and engineering aspects on the gasification of biomass'. Chemical Engineering, Lund University. Available at: <https://lup.lub.lu.se/search/publication/0b01f17f-9c94-4d76-ad11-bdf97435898b>

(Accessed: 5 February 2018).

IEA (2017) *Annual Energy outlook 2017 with projection to 2050*.

Ministry of power and energy (2015) 'Sri Lanka Energy Sector Development Plan for a Knowledge-Based Economy', *CEUR Workshop Proceedings*, 1542, pp. 33–36. doi: 10.1017/CBO9781107415324.004.

K.Srirangan, L Akawi, M.Moo-yong, C. C. (2012) 'Towards sustainable production of clean energy carriers from biomass resources', pp. 172–186.

K, S., S, S. and Dasappa, S. (no date) 'CARBON DIOXIDE CAPTURE THROUGH BIOMASS GASIFICATION', *Indian Institute of Science, Bangalore*. Available at: [http://cgpl.iisc.ernet.in/dasappa/img/pdf/papers/Carbon dioxide capture.pdf](http://cgpl.iisc.ernet.in/dasappa/img/pdf/papers/Carbon%20dioxide%20capture.pdf) (Accessed: 11 February 2018).

Khor, A. (2006) 'Energy from biofuel', (August).

Kumar, J.V., pratt (1996) 'Compositional Analysis of some renewable biofuels', *American Laboratory*, pp. 15–20.

Kumar, H. *et al.* (2014) 'Effect of Moisture Content on Gasification Efficiency in Down Draft Gasifier', *International Journal of Scientific Engineering and Technology*, 413(3), pp. 411–413.

Mangre, M., Vyas, S. and Pandey, M. (2017) 'et Science Downdraft fixed bed biomass gasifier : A review'.

McKendry, P. (2002) 'Energy production from biomass (part 1)- overview of biomass - Peter McKendry 2002 - 2015-07-14', 83(July 2001), pp. 37–46.

McKendry, P. (2002) *Energy production from biomass (part 2): Conversion technologies*, *Bioresource Technology*. Elsevier. doi: 10.1016/S0960-8524(01)00119-5.

Mendiburu, A. Z. *et al.* (2014) 'Thermochemical equilibrium modeling of a biomass downdraft gasifier: Constrained and unconstrained non-stoichiometric models', *Energy*, 71, pp. 624–637. doi: 10.1016/j.energy.2014.05.010.

Ojolo, S. J. and Ogunsina, B. S. (2012) 'Development of a Laboratory Scale updraft gasifier', *International Journal of manufacturing Systems*, IX(June), pp. 1–10.

Oki, Y. *et al.* (2011) 'Development of oxy-fuel IGCC system with CO<sub>2</sub> recirculation for CO<sub>2</sub> capture', *Energy Procedia*. Elsevier, 4, pp. 1066–1073. doi: 10.1016/j.egypro.2011.01.156.

Prabir Basu (2012) *Biomass gasification and pyrolysis, Comprehensive Renewable Energy*. doi: 10.1016/B978-0-08-087872-0.00514-X.

Sadhwani, N. (2017) 'Conversion of Carbon Dioxide and Biomass for Fuels and Chemicals Precursor through Gasification: Experimental and Modeling Approach'.

Sustainable Energy Authority- Sri Lanka-2016 (no date) *Industrial Thermal Applications | SLSEA*. Available at: <http://www.energy.gov.lk/renewables/renewable-energy-resources/biomass/industrial-thermal-applications> (Accessed: 5 February 2018).

Weiland, F. (2015) *Pressurized entrained flow gasification of pulverized biomass, PhD thesis*.

Weragama, T. (2011) 'Fuel wood as an alternative source of thermal energy in the rubber industry in Sri Lanka'. Available at: <http://dl.lib.mrt.ac.lk/handle/123/9952> (Accessed: 23 November 2018).

World Energy Council (2013) *Bio Energy*.

Yaman, S. (2004) 'Pyrolysis of biomass to produce fuels and chemical feedstocks', *Energy Conversion and Management*, 45(5), pp. 651–671. doi: 10.1016/S0196-8904(03)00177-8.