EFFECT OF PARTICLE SIZE ON PACKED BED BIOMASS COMBUSTION

G.D.M. RAJAPAKSHA

149263P

Degree of Master of Science

Department of Chemical and Process Engineering

University of Moratuwa
Sri Lanka

March 2018

EFFECT OF PARTICLE SIZE ON PACKED BED BIOMASS COMBUSTION

G.D.M. RAJAPAKSHA

149263P

Thesis submitted in partial fulfilment of the requirements for the degree
Master of Science

Department of Chemical and Process Engineering

University of Moratuwa

Sri Lanka

March 2018

Declaration

I certify that this is my own work and this thesis does not incorporate without recognition any previously submitted material for a degree or diploma at any other higher education university or institution and as far as I know and believe it does not contain any previously published material or written by another person, except in cases where recognition is made in the text.

Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute my thesis/dissertation, in whole or in part in print, electronic or other media. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date:

The above candidate has carried out research for the Masters/MPhil/PhD thesis/Dissertation under my supervision.

Signature of the Supervisor: Date:

Abstract

In this thesis, particle size effect on biomass (rubber-wood) combustion in a packed bed reactor was investigated in experimentally. Mass loss rate, bed shrinkage rate, temperature profile at different bed locations and gas compositions in the out-of-bed flue gases were measured at a constant primary air flow rate. In this study used a fixed batch of biomass. An external heat source was used to ignite the biomass initially and after ignited the biomass, removed the external heat source. Rubber-wood cubes were fired with size ranging 25mm, 38mm, 50mm and 63mm. As time pass, the height of the packed bed is decreasing due to shrinkage of the bed and also the weight of biomass is reducing with time. It is found that at the operating condition of the current study, burning rate of biomass particle is higher with smaller fuel size; and also smaller biomass particles are faster to ignite than the large biomass particles and have unique combustion stages; on the other hand, larger biomass particles produced a higher flame temperature. Larger particles also cause the combustion process becoming more transient where the burning rate varies for the most part of the combustion process. And also biomass combustion time (operational time) is increased with increasing biomass particle size. And here calculate the percentage of excess air, when increased the particle size, amount of excess air release is high. Therefore, need to control the amount of primary air supply when increased particle sizes.

Keywords— Biomass, Combustion, laboratory scale packed bed, shrinkage of the bed,particle size, mass loss, temperature gradient, gas composition, excess air.

Acknowledgement

I am deeply thankful to my supervisor Dr. Mahinsasa Narayana, Senior Lecturer, Department of Chemical & Process Engineering University of Moratuwa, Sri Lanka for his valuable guidelines, suggestions to initiate this research work and development. Further, I extended my sincere thanks to Dr. Narayana for his great service done as course coordinator during the course period.

I am thankful to all academic and non-academic staff of the Department of Chemical and Process Engineering for their sincere support and appreciation to complete this task.

I would like to express my immense gratitude to my parents, for giving me life in the first place and for educating me with all parts of life.

Last I wish to express my sincere thanks to my loving husband for his support, silent motivation and sustained patience during the many long hours I spent working on this research and thesis at the university.

Table of Contents

List of Figures

List of Tables

Nomenclature

Symbol	Description
Ω	Stoichiometric coefficient
ΔH_{evap}	Latent Heat of Evaporation
$X_{M,\ fsp}$	fiber saturate moisture point
X_M	saturate moisture point

Abbreviations

BFB	Bubbling fluidized Bed
CFB	Circulating Fluidized Bed
CHP	Combined Heat & Power
IEA	International Energy Agency
LHV	Lower Heating Value
HHV	Higher Heating Value
FC	Fixed Carbon
VM	Volatile Matters
CV	Calorific Value
wt	Weight
mm	millimeter (unite)
cm	centimeter (unite)
min	minutes (unite)
FG	flue gas
SGS	solid gas surface
G	grate

1 INTRODUCTION

1.1 Background of biomass combustion

Biomass energy is one of humanity's earliest energy source. The total energy consumption and pollutant emissions of the world have doubled in the last 40 years[1]. Worldwide biomass energy consumption is approximately 14% of the world's energy needs[2]. All human and industrial processes produce wastes, which are, normally unused and unwanted products of a specific process. The most of this waste is biomass. Biomass can be efficiently burned to produce electricity and heat in combined heat and power plants (CHP). The International Energy Agency (IEA) predicts that biomass usage in power generation will grow from the current level of 54 GW to 82 GW by the end of 2020[3].

Combustion is the main technology of biomass converted to the bioenergy. Combustion process is fulfilled the more than 90% of the world's primary energy requirement like food preparation, transportation, space heating, electricity, ventilation and cooling. Also, the fuel is burnt with the oxygen from the air to release the stored chemical energy as heat in burners, boilers, internal combustion engine and turbines.

On one hand, the versatile nature of biomass enables it to be utilized in all parts of the world, and on the other, this diversity makes biomass a complex and difficult fuel. Currently, both packed beds and fluidized beds are used for biomass combustion in the industrial sector. Instead of generating steam, oil is heated to transfer energy from the packed bed to application areas. Even the packed beds which are currently in use have numerous issues including the design of the packed bed, pre-processing of biomass, selecting the best type of biomass and oil, the rate of fuel supply etc.

Recent experimental and theoretical studies have discovered the importance of considering shrinkage for a more realistic analysis of combustion phenomena. But the concern on shrinkage and the changes in structural properties on prevailing packed bed models is very low. Therefore, the shrinkage of packed beds in biomass combustion is not well understood yet. Therefore, the present study is carried out experimentally to understand the bed shrinkage of a packed bed combustion.

1.2 Biomass

Biomass is organic materials derived from plants which include animal and plant material such as wood from forests, material left over from forestry and agricultural processes, organic industrial, human and animal wastes. Biomass comes from a variety of sources such as:

- Wood from natural forests
- Forestry residues
- Forestry plantations
- Municipal solid waste
- Food processing wastes
- Sewage
- Animal waste
- Agricultural residues such as straw, cane trash, Stover and green agricultural wastes
- Agro-industrial wastes such as rice husk and sugarcane
- Industrial wastes (black liquor from paper manufacturing)

Biomass will take a very long way in time to release energy in naturally. Then its store energy releasing is occurred very slowly. But quickly way of releasing its store of energy is burning biomass and often in a useful way. Biomass is a carbon neutral fuel. This means that the carbon released during consumption is balanced by the carbon consumed by photosynthesis during plant growth. Thus, the net contribution to atmospheric CO_2 is zero.

1.3 Biomass conversion process

The conversion of biomass into energy is done using the main three technologies mentioned below,

Thermochemical: Combustion, Pyrolysis, Gasification & Liquefaction

Biochemical / biological: Digestion and Fermentation

Mechanical: etherification and trans-esterification

1.4 Biomass combustion

Biomass combustion is one of the oldest methods of thermal conversion. It is a complex process involving heat and mass transfers, fluid dynamics, homogeneous as well as heterogeneous reactions. When a biomass particle is exposed to heat flux, it undergoes three stages: drying, pyrolysis, and char burnout. For small particles, e.g. pulverized fuel particles, drying, pyrolysis, and char burnout occur sequentially, and the char burnout period lasts much longer than the pyrolysis and drying stages. For larger particles, drying, pyrolysis, and char burnout occur simultaneously.

Of the different thermochemical conversion techniques, combustion is the most extensively used and developed technique for the utilization of biomass[4]. Thus, to increase combustion development, the whole process needs to be optimized in terms of efficiency and cost. Because of this necessity, developing research has focused on three main aspects: fuel properties, boiler characteristics, and emissions. Biomass combustion is the main focus of this study and is discussed in more details in chapter 02.

1.5 Environment benefits of biomass combustion.

Utilization of Biomass fuel provides substantial benefits further the environment is concerned. Due to increasing environmental concerns especially related to the use of fossil fuels, new solutions to limit the greenhouse gas effect are continuously sought. Among the available alternative energy sources, including solar, wind, hydro etc., and biomass is the only carbon-based sustainable option to mitigate greenhouse emissions. Thus, biomass is used to reduce carbon footprint. When using biomass as the energy carrier, there is always a closed CO_2 cycle. That means that in the case of energy generation from biomass, there is no growing content in the atmosphere when crops are planted continuously. Biomass absorbs CO_2 during growth and emits it via combustion. The use of biomass as fuel for power production offers a renewable and CO_2-neutral fuel.

The heavy metal content in biomass raw material is close to zero, therefore there is no or very low heavy metal emission during combustion; the sulphur content in biomass is extremely low. Even in the case of straw, the sulphur content of flue gas is much smaller than that of the light heating oil combustion; Except for some crops of high protein content; the nitrogen content in biomass is also low. In a broad sense, biomass fuels range from pruning waste, industrial and agrarian residuals, waste wood, cultivated crops to sewage sludge from domestic and industrial water treatment plants and paper industry. Thus, combustion of biomass provides a solution to reduce the amount of waste collected as well.

1.6 Important to Sri-Lankan industries

Sri Lanka is on its way to becoming an internationally competitive middle-income country. This energy and energy sector development plan is aligned with the country's drive for development and has been prepared to provide affordable, high quality and reliable energy to all citizens, rich and poor while preserving the valuable natural environment of the country. In 2013, the total energy requirement of the country was around 11,125 kilotonne of oil equivalent. Biomass contributed 43% of total energy consumption. Sri Lanka has no reserves of oil or natural gas, then Sri-Lanka has to import fossil fuel to fulfil energy requirement and it’s very costly. Country Sources of supply and minimize regional disparities in the provision of energy services. The vision of the energy and energy sector is to harness the full potential of all renewable resources and other indigenous resources for Sri Lanka to become a self-sufficient energy nation by 2030[5].

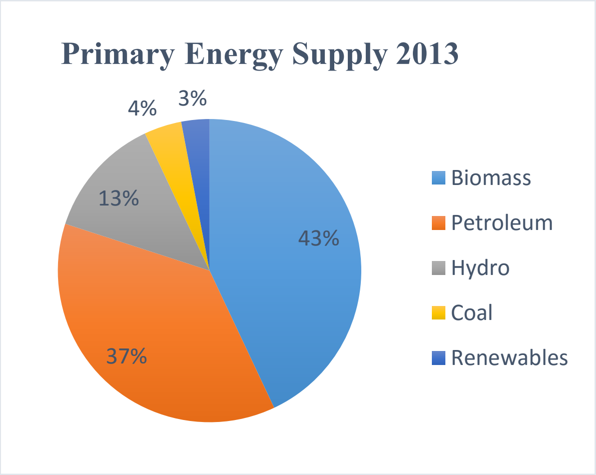


Figure 1-1 : primary Energy Supply 2013

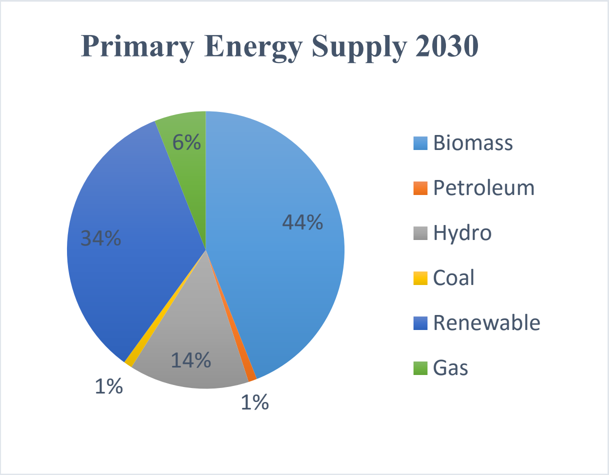


Figure 1-2 : primary energy Supply 2030

Biomass is playing an important role for domestic heating and power generation. In Sri Lanka, biomass consumption is focused on industrial energy requirements. Nowadays biomass is used in packed bed combustion to cover up all the heat energy requirements in industries like rubber product, tea, sugarcane, corn industries etc. This energy generation through biomass combustion is mostly available in tea and rubber industries using their own waste including plant particles. As per the current situation, industrial sector energy requirements are fulfilled using biomass up to 40% in Sri Lanka.

1.6.1 Advantages and disadvantages

Advantages;

- Biomass is readily available and can be used as a renewable resource
- Biomass used as a fuel reduces the need for fossil fuels for the production of heat, steam, and electricity for residential, industrial and agricultural use.
- Biomass fuel from agriculture wastes may be a secondary product that adds value to the agricultural crop.
- Growing Biomass crops use CO_2 and produce O_2
- Utilization of waste materials reduce landfill disposal.
- CO_2 which is released when biomass fuel is burned is taken in by plants.
- Steady, reliable clean power and heat.
- Reduced reliance on fossil fuels and less money spent on foreign oil.

Disadvantages;

- If the basic crop is no longer grown, the agricultural wastes will not be available
- Additional work is required in areas such as harvesting methods.
- Land used for energy crops may be in demand for other purposes, such as farming, conservation, housing, resort or agricultural use.
- Some Biomass conversion projects are from animal wastes and that is relatively small and limited.

1.7 Objectives of present research

- To analyse the thermochemical process in the fixed bed particulate biomass combustion, with the effects of biomass particle size.
- The biomass packed bed shrinkage, mass loss, packed bed temperature profile, and flue gas composition variation are evaluated with different size of particulate biomass packed bed combustion.
- To analysis amount of excess air variation with particle size.

1.8 Dissertation Outline

Chapter 1: It has a brief introduction of biomass, combustion, Sri Lankan energy balance and also has a brief description of research objectives of this research project.

Chapter 2: In this section, Theory and literature review is presented about biomass, its properties combustion technologies, types of combustion and combustion reactions.

Chapter 3: This chapter is explaining the experiment with packed bed biomass combustion.

Chapter 4: This chapter discusses the experiment results of packed bed biomass combustion.

Chapter 5: in this section conclusion and discussion is carried out. And it also contains future work suggestions.

2 LITERATURE REVIEW

2.1 Biomass energy and its scenario

Biomass is a fuel that is developed from organic material. The energy produced from organic materials is called bioenergy which is used to create electricity or other forms of power. Biomass is produced through photosynthesis by plants converting sunlight into plant material and includes all land and water based vegetation, as well as organic wastes[6]. Plants store sunlight energy as chemical energy having strong molecular bonds which when broken up these materials are subjected to some conversion process and then heat is released. And also photosynthesis process utilizes the carbon dioxide in the atmosphere and suns radiation, therefore biomass balance the carbon dioxide content in the atmosphere.

$$\mathbf{6CO_2 + 6H_2O + Light \rightarrow C_6H_{12}O_6 + 6O_2} \qquad (1)$$

Biomass can be classified into two major types i.e. crop biomass and wood biomass. The origin of other biomass sources like municipal waste or animal waste can be traced back to the above two types. Crop biomass mainly contains carbohydrates, glucose, starch or oils. Wood biomass contains cellulose, hemicellulose, and lignin[7].

The major contribution for the renewable energy sources is given by biomass. Two third of the energy supplied by biomass is used for cooking and heating in developing countries. Power generation consumes about 13 % of the biomass energy while the industrial sector about 15 % and the transport sector about 4 %[8].

Biomass has been a major source of energy and it contributes 10-14% of the whole world's energy supply[6]. However, from last few years it has got major attention which might be due development in conversion technology of biomass, lower prices, surplus food generation, especially in European countries, climate change due to the adverse effect of fossil fuel emission on the environment, increased energy demand and sustainability. We know that biomass was the main source of energy for heat from early days but with the introduction of fossil fuels in the form of coal, petroleum oil and natural gas, the world became dependent on these fossil fuel sources. Currently, the main energy source in the world is fossil fuel[9]. Increases in fossil fuel demand are also due to the utilization of by-products at a very high rate in daily life. Still, it has not been confirmed how much fossil fuel is remaining. With the high consumption rate, it is approximated that depletion is fast. Further, these fuels have no even distribution on the globe and therefore many countries are dependent on others. This increasing consumption trend of fossil fuel with its by-products combining with other factors was the main barrier in the commercialization of biomass. Now realization in terms of a non-renewable state of fossil fuel and high depletion rate give the opportunity to think seriously about other resources and biomass energy is one of them. It has been estimated that the global biomass potential is 91-675 EJ/year for the years 1960 to 2060[9]. Total worldwide energy potential from biomass on a sustainable basis is about 100 EJ/year, In which woody biomass 40.1%, energy crops 37.4%, and straw constitute 17.2 % [2]. Still, biomass and its products need to grow in the market, and it needs awareness in local communities. Currently, the total global energy demand is about 470 EJ/Year[9].In the United States, without any changes in land use and without interfering with the production of food grains, nearly 1 billion tons of biomass can be harvested each year on the sustainable basis for biofuel production[10]. It is approximated that 1.3 billion tons of biomass equivalent to 3.8 billion barrels of oil in energy content[9]. The energy shift with time is shown in Figure 2-1.

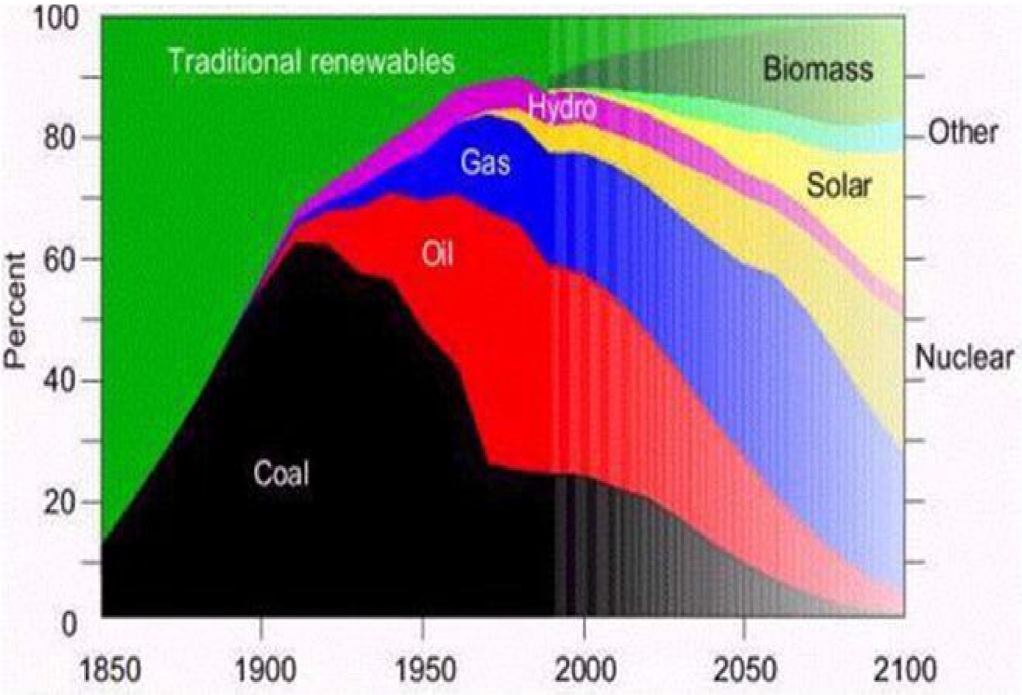


Figure 2-1: Energy shift with time [11](Source: Ageneal. Energias renováveis [Internet]. 2006. Available from: http://www.ageneal.pt/content01.asp?BTreeID=00/01&treeID=00/01&newsID=8)

Figure 2-1 clearly depicts that with the passage of time how energy trend will shift globally and around 2050 biomass will be tycoon of the energy sector. Other renewable sources such as solar, wind will also participate but their contribution looks much less than biomass. Biomass has the advantage over traditional fossil fuels that it replenished quickly, renewable and environmentally friendly. Currently, biomass constitutes 10% of the worldwide primary energy production, as shown in Figure 2-2, equating to 1.277 Gt of oil equivalent (Gtoe) (53.47 EJ) of primary energy consumption of total biomass in 2012[11]. The contribution of fossil fuels to energy production amounted to more than 80% of the primary energy production in 2011,337 TWh of electricity has been produced from combustible renewable energy sources and waste generation.

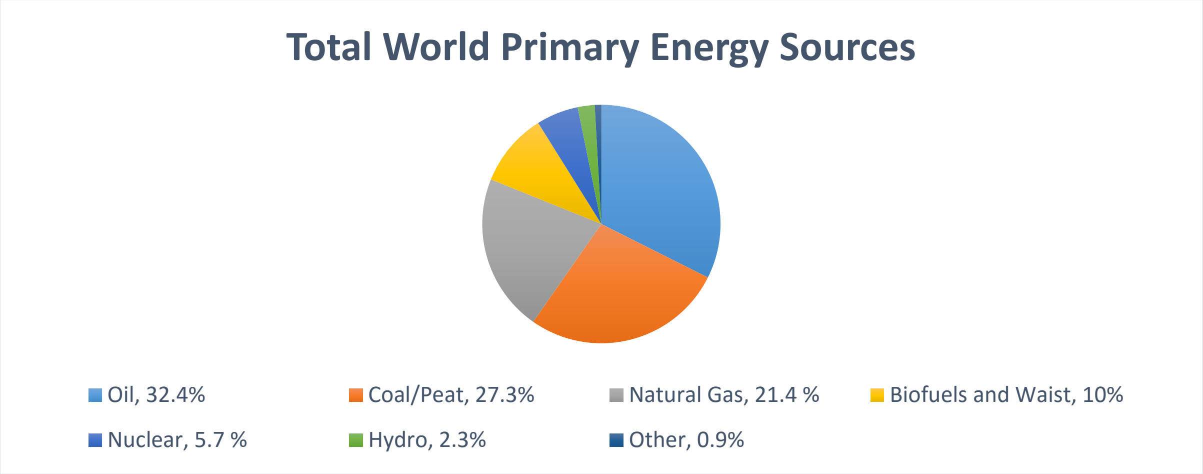


Figure 2-2: Total world primary energy source [12]

2.1.1 Sri Lanka biomass energy scenario

Presently a major portion of thermal energy requirement in Sri Lanka is fulfilled by firewood. Biomass usage groups in Sri Lanka are the household sector, commercial sector, industrial sector, and private power plants. In Sri Lanka, 53.9 % of the primary energy is supplied by biomass in 2012. The largest consumer of biomass is the household and commercial sector which is 77.7 %. Tea and Brick & Tile Industries are the major consumers of biomass in the industrial sector and it accounts for 71.8 %. Wood log burning is a popular and conventional method in Sri Lankan industries. With the reduction of subsidies given to fuel oil converting large industrial thermal systems emerged in Sri Lanka. Recently various types of wood chip combustion technologies have been introduced to improve the combustion efficiency of combustors especially related to the tea industry[13].

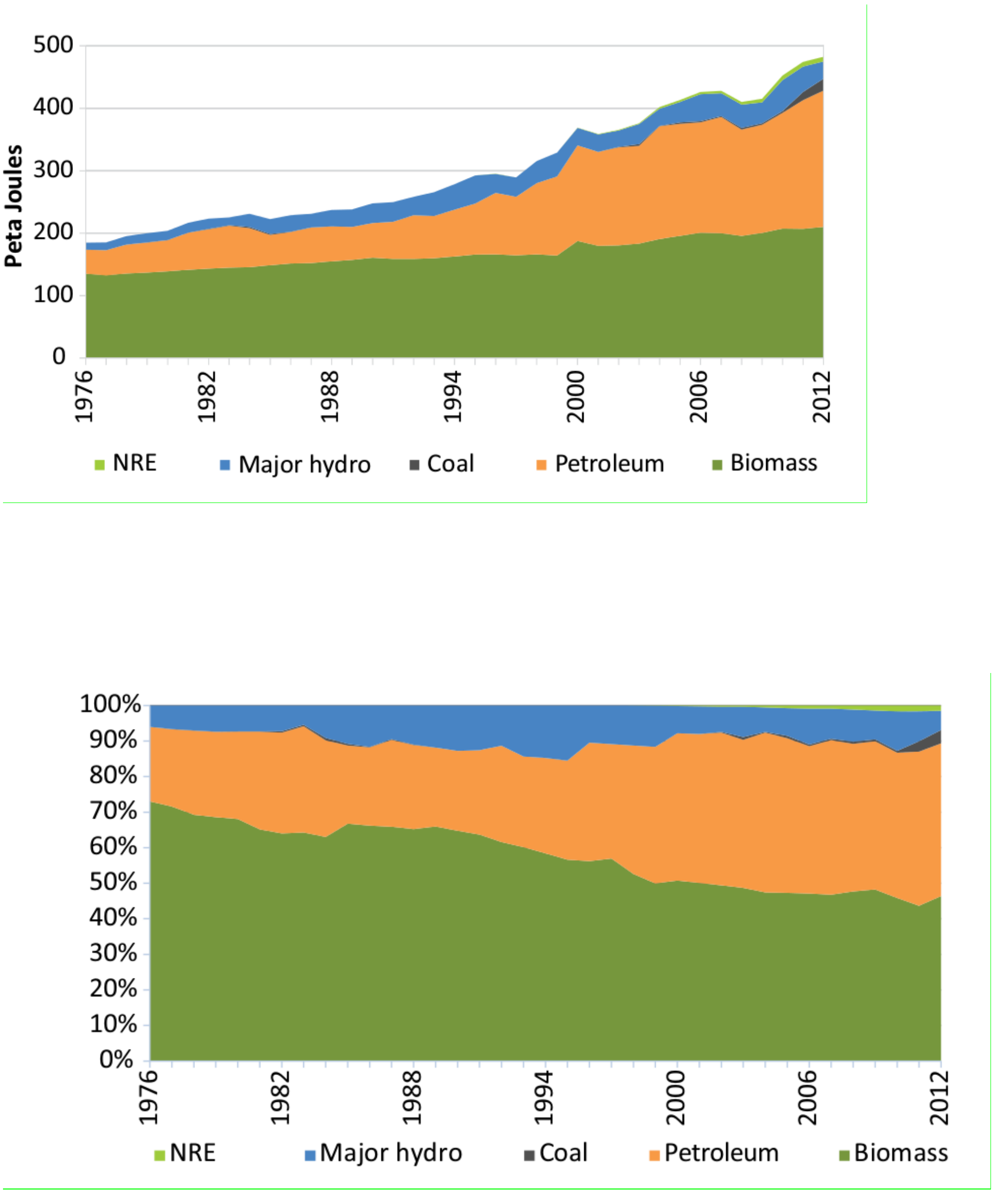


Figure 2-3: Evolution of energy supply forms with time

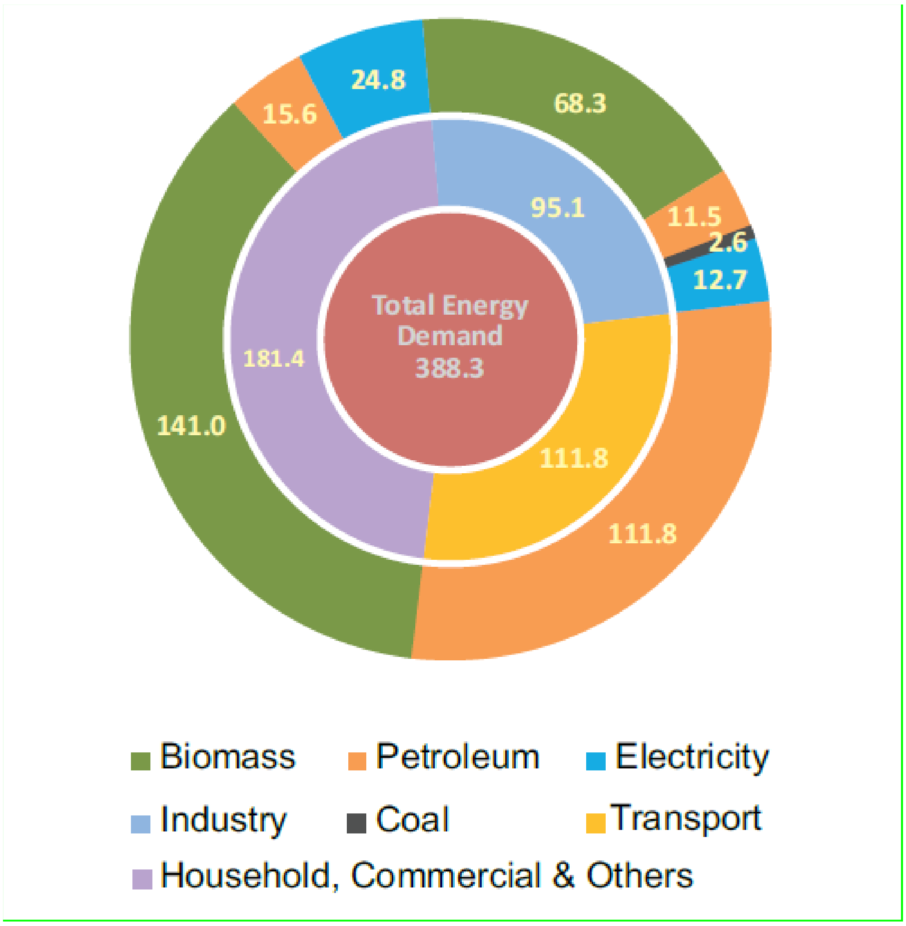


Figure 2-4: Energy balance for year 2012

2.2 Biomass materials

Biomass materials classification has been done by many researchers and still it's being developed and improved to find out a better new one but basically, as at to date all have agreed on wood species. Peter classified it as woody plants, herbaceous plants and grasses, aquatic plants[14] While [15] have classified stating more clearly that biomass material can be wood, herbaceous, and agricultural, aquatic, human and animal wastes, contaminated and industrial waste.

2.3 Biomass properties and selection

The development of biomass combustion technologies is mainly focused on understanding the characteristics of biomass as a fuel and using it to design combustion facilities. Biomass fuels have a wide range of different physical and chemical properties.

2.3.1 Physical properties

The main physical properties are:

- Particle size distribution
- The shape of the particles
- The porosity of the particle

Particle size affects the reaction rate considerably, therefore, it influences all the aspects of combustion and the combustion technology. The range of the particle size of woody biomass is huge, from spanning wood log to ground powders after milling. There are three dimensions for these particles including particle length, width, and thickness. For the current study considered four different size of particles.

Particle shape is another important factor which affects the gas-solid reactions. Mainly reactions between char and other gases depend on the surface area available for the reactions. A particle which has a larger surface area for a certain volume offers higher reaction rates. Pores inside the particle and the mass transfer rates additionally influence the process and makes the process complex.

Porosity is the ratio between the volume occupied by the pores inside the particle and the total volume (including the volume of the pores) of the particle. This can be calculated by two densities of the particle i.e. apparent density and the real density. Apparent density is the mass of the particle divided by the volume of the particle which is including the volume of its internal pores. The real density is the ratio between the mass of a particle to and the volume of the particle excluding the internal volume of the pores.

2.3.2 Chemical properties

The following properties of biomass are important when selecting the biomass.

- Heating value
- Proximate analysis
- Ultimate analysis

The important biomass properties include the following (a) heating value (b) proximate analysis and (c) Ultimate analysis. The proximate analysis includes determination of moisture contents, ash contents, volatile matters, fixed carbon by the percentage while ultimate analysis is to determine the presence of the percentage of carbon, nitrogen, oxygen, hydrogen, and sulphur. Other characterization would include describing its compositional contents such as lignin, cellulose and hemicelluloses, carbohydrates and fat contents.

2.3.3 Calorific value

The Calorific value (CV) of biomass is crucial to determine its energy that can be recovered during thermo-conversion. The CV is usually measured in terms of energy contents per unit mass or volume; hence MJ/Kg for solids, MJ/l for liquids and MJ/Nm^3 for gasses[6]. The chemical reaction is typically a hydrocarbon reacting with O_2 to form CO_2, H_2O and release heat. This CV can be divided into two according to the way it calculated.

- Higher heating value (HHV)
- Lower heating value (LHV)

2.3.4 Proximate analysis

- **Moisture contents**

There are two types of moisture contents associated with biomass one is called intrinsic moisture while other is known as extrinsic moisture. In the first category, there is no impact of weather conditions while in later one weather condition has an impact especially during harvesting and this is the additional moisture added to the material. In respect of the prevailing weather conditions at the time of harvesting, is the potential contamination of the harvested biomass by soil and other detritus, which can, in turn, have a significant negative impact on other ‘material’ properties during subsequent treatment or processing. The parameters of interest that area affected by such contamination is the ash and alkali metal content of the material.

Thermal conversion requires low moisture content feedstock (typically<50%), while bio-conversion can utilize high moisture content feedstock. Thermal conversion technologies can also use feedstock with high moisture content but the overall energy balance for the conversion process is adversely impacted[6].

❖ Fixed Carbon and volatile matters

Fuel analysis has been developed based on solid fuels, such as coal, which consists of chemical energy stored in two forms which are fixed carbon and volatiles:

- The volatiles content, or volatile matter (VM) of a solid fuel, is that portion driven-off as a gas (including moisture) by heating (to 950 ^{0}C for 7 min)
- The fixed carbon content (FC), is the mass remaining after the releases of volatiles, excluding the ash and moisture contents[6].

❖ Ash contents

The chemical breakdown of a biomass fuel, by either thermochemical or biochemical processes, produces a solid residue. When produced by combustion in air, this solid residue is called ‘ash’ and forms a standard measurement parameter for solid and liquid fuels. The ash Content of biomass affects both the handling and processing costs of the overall, biomass energy conversion cost. During biochemical conversion, the percentage of solid residue will be greater than the ash content formed during combustion of the same material. For a biochemical conversion process, the solid residue represents the quantity of non-biodegradable carbon present in the biomass. This residue will be greater than the ash content because it represents the recalcitrant carbon which cannot be degraded further biologically but which could be burnt during thermo-chemical conversion.

2.4 Biomass Conversion Technologies

Biomass can be converted into different energy forms through various processes. The choice of the conversion process is depended on the type and quantity of biomass feedstock, desired energy form, environmental standards, economic conditions, and project-specific factors. In many situations, biomass conversion process route determines by the available type and quantities of biomass.

Biomass can be converted into three main type of products: electrical/heat energy, transportation fuels, and chemical feedstock. Conversion of biomass to energy is undertaken using the main two types of process technologies which are thermochemical and biochemical. Four process options are available under thermo-chemical conversion; combustion, pyrolysis, gasification, and liquefaction. Within bio-chemical conversion, two process options are available; digestion and fermentation. Biomass conversion technologies are shown in following tree chart. Amongst the options of these energy conversions; the thermo-chemical process is the main focus in this study.

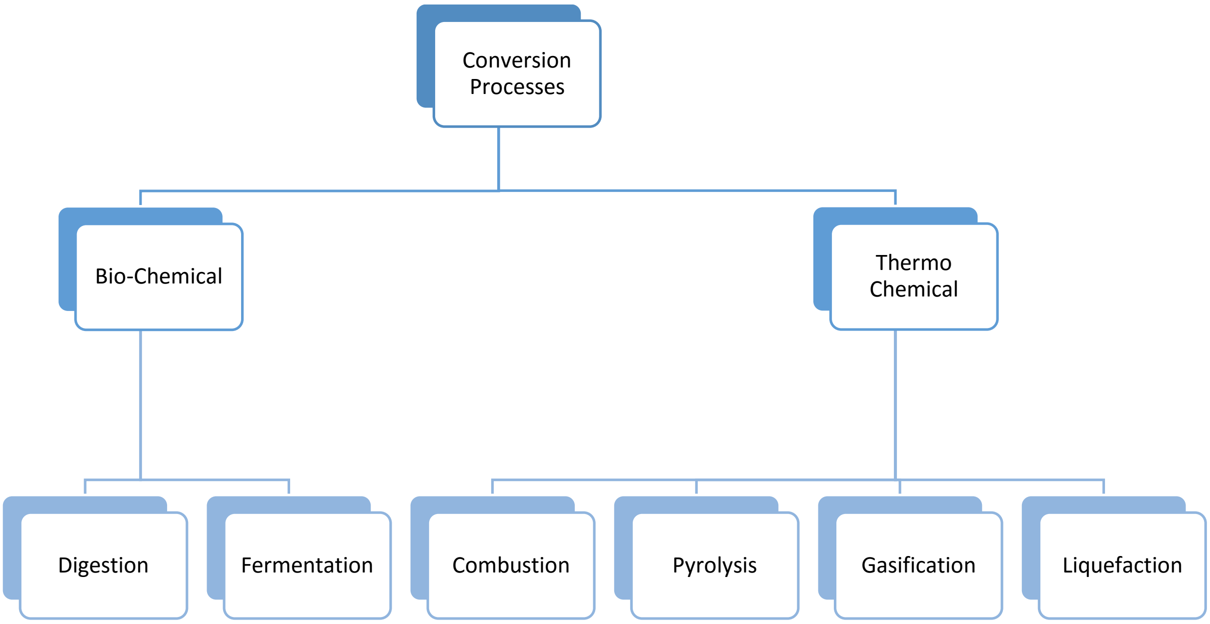


Figure 2-5: Biomass Conversion Technologies

2.4.1 Thermal conversion process

The thermochemical conversion of thermally degradable fuel, such as biomass and coal, involves a number of different processes. Which are drying, pyrolysis, gasification, and combustion

2.4.1.1 Drying

Drying will occur below the boiling point due to diffusion of water vapor from the particle, Moisture in the fuel-wood will evaporate at lower temperatures absorbing the heat released from the combustion process. This reduces the temperature in the combustion chamber. Therefore, wet fuels cannot sustain combustion. The optimum moisture content of biomass for combustion varies from 15 %- 25 %[16].

2.4.1.2 Pyrolysis

Conversion of biomass into liquid, solid and gaseous fraction by heating the biomass in the absence of air and around 500 ^{0}C temperature is called as pyrolysis. Fuel type, composition, temperature, pressure, heating rate and reaction time affect the pyrolysis process.

Based on the time of reaction pyrolysis is defined in three 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 ℃. In Conventional pyrolysis there are three types of products are generated which are gas liquid and char.
- Fast pyrolysis – in maximizing of generating biofuel 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[1].

Pyrolysis can be used to produce predominantly bio-oil if flash pyrolysis used, enabling the conversion of biomass to bio-crude with an efficiency of up to 80% [14]. Below chart shown that possible yield of pyrolysis energy products.

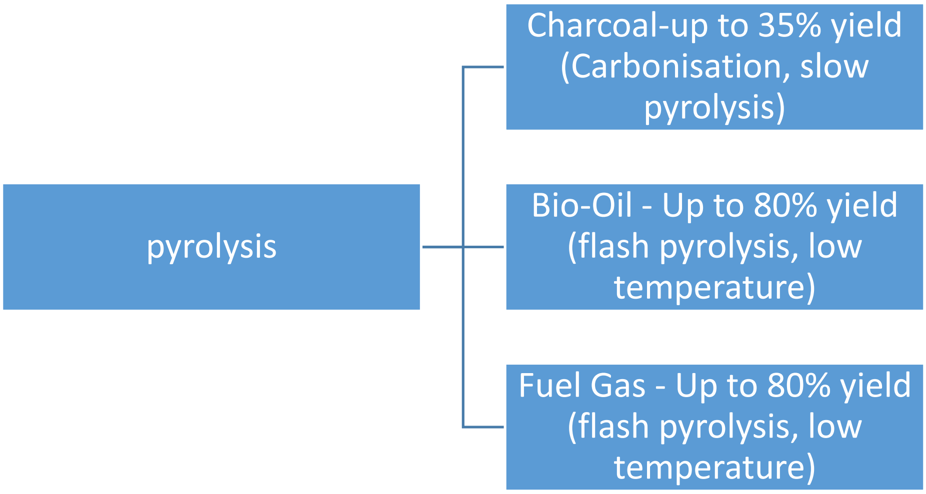


Figure 2-6 : Energy Products From pyrolysis

2.4.1.3 Gasification

Gasification is the conversion of biomass into a combustible gas mixture by the partial oxidation of biomass typically at 800–900 °C. The low calorific value (CV) gas produced (about 4–6 MJ/N m^3) can be burnt directly or used as a fuel for gas engines and gas turbines[14]. The product gas can be used as a feedstock (syngas) in the production of chemicals (e.g. methanol)[6]. Carbonaceous materials like biomass are convert into useful convenient gaseous fuels or chemical feedstock through gasification[17]. When biomass gasification, incomplete combustion of biomass is happen which is resulting in production of combustible gases consisting of Carbon monoxide, Hydrogen and traces of Methane. This mixture is called producer gas. Producer gas can be used to run internal combustion engines (dual fuel), can be used as substitute for furnace oil in direct heat applications and can be used to produce methanol in an economically viable way which is useful both as fuel for heat engines as well as chemical feedstock for industries . This process is much more attractive as any biomass can undergo gasification than biogas or ethanol production where only selected biomass materials can produce the fuel.

2.4.1.4 Combustion

Combustion is a reaction which produces heat and luminescence in which the reaction is preceded by the generated heat. The combustion process is defined by the fuel properties and combustion application. Combustion is the complete oxidation of the fuel. In this step, oxygen reacts with the solid char or other combustible gases This will occur at temperatures 800°C-1000°C[18]. Combustion process proceeds through some major steps are Drying, Pyrolysis and char burnout. This is discussed in the next section.

2.5 Combustion of biomass

Combustion is the main conversion technology bioenergy production. It is considered to be the most economical and simplest method of conversion technology and is being used around 90 % in the world[19]. It is a process involving heat and mass transfers, fluid dynamics, homogeneous as well as heterogeneous reactions. When a biomass particle is exposed to heat flux, it undergoes three stages: drying, pyrolysis, and char burnout. For small particles, e.g. pulverized fuel particles, drying, pyrolysis, and char burnout occur sequentially, and the char burnout period lasts much longer than the pyrolysis and drying stages. For larger particles, drying, pyrolysis, and char burnout occur simultaneously. The following sections describe the stages involved in the combustion of the biomass particles. The scheme of combustion approach is shown in Figure 2-7.

- Drying
- Pyrolysis
- Char burnout
    - ✓ Char gasification
    - ✓ Char oxidation

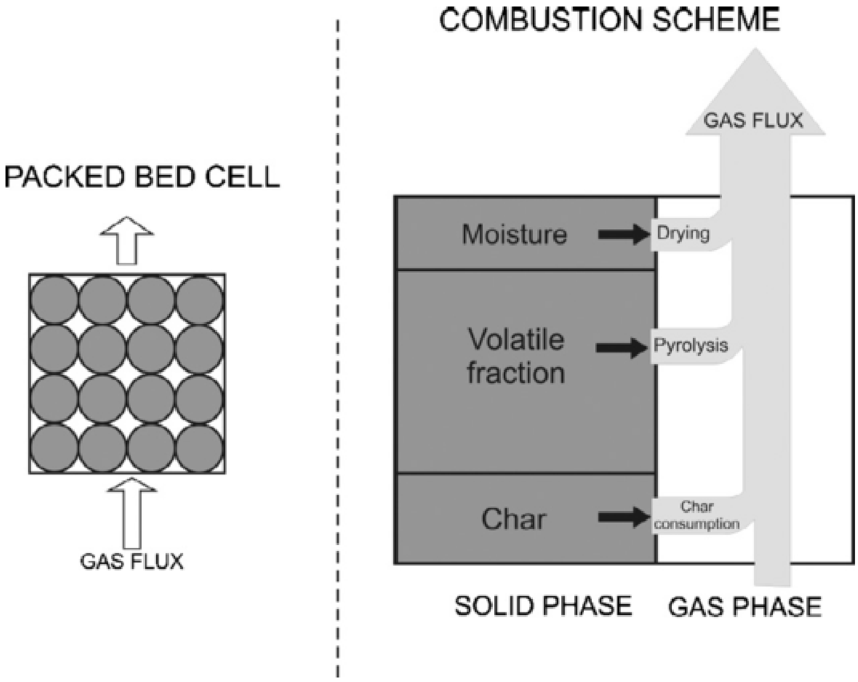


Figure 2-7 : Representation of the combustion approach [20]

Solid biomass from different sources has different characteristics. Therefore, combustion behaviour varies considerably. Biomass has a high moisture content, high volatile content, ash formation characteristics, and high oxidation reactivity. The following mechanisms show separate stages of the thermal degradation of a wood particle. In here each process has been shown separately for clarity. In reality, different stages may overlap.

Heterogeneous reactions	
$C + O_2 \longrightarrow CO2 + CO$	(R1)
$C + H2O \longrightarrow CO + H2$	(R2)
$C + CO2 \longrightarrow 2CO$	(R3)
Homogeneous reaction	
$C + O_2 \longrightarrow CO2$	(R4)
$C_iH_j + O_2 \longrightarrow CO2 + H_2O$	(R5)
$C_nH_mO_n + O_2 \longrightarrow CO + H_2$	(R6)
$H_2 + O_2 \longrightarrow H_2O$	(R7)
$CO + H_2O \longrightarrow CO + H_2O$	(R8)

Table 2-1 : Combustion Reaction Equations [21]

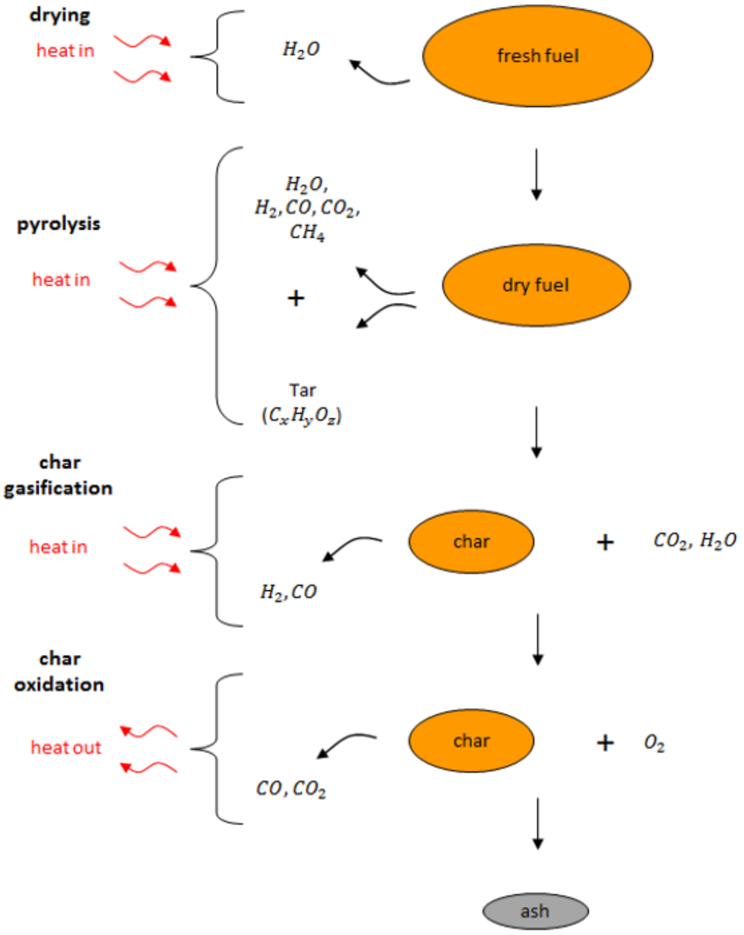


Figure 2-8 : Separate stages of the thermal degradation of a wood particle [22]

2.5.1 Drying

The typical moisture content of fresh wood very between 30 to 60 %, and for some biomass, it can be exceeded 90%. Moisture in the fuel-wood will evaporate at lower temperatures absorbing the heat released from the combustion process and this energy cannot be recovered. This reduces the temperature in the combustion chamber. Therefore the total energy efficiency of the system may be reduced significantly. Therefore wet fuels cannot sustain combustion. The optimum moisture content of biomass for combustion varies from 15%-25%. A certain amount of pre-drying is necessary to remove moisture from the biomass as much as possible before it is fed into the combustion chamber.

In wood, this water is present in three different forms[22].

- Free (liquid) water

The fiber saturation point,$X_{M,fsp}$, for wood is approximately 30%wt db. Above this point, X_M > 30%wt db, free or liquid water occupies voids within the wood structure. Transport is due to capillary flow through the voids. The energy required to evaporate the water is the latent heat of evaporation (ΔH_{evap}).

- Bound water

Bound water is water which is adsorbed and believed to be hydrogen-bonded to the cellulose and hemicellulose fibers. Below the fibre saturation point, $X_M \leq 30\%$ db, all moisture is believed to be bound to the wood fibers. Transport occurs due to diffusion of the water. The energy required to evaporate the water will have to overcome the latent heat of evaporation in addition to the heat of adsorption.

- Water vapour

This is the result of the evaporation of bound and liquid water within the solid.
Transport is due to convection and diffusion.

Solid fuels are typically injected into furnaces at relatively low temperatures to prevent premature fuel loss due to pyrolysis. Upon entry to the combustor, the fuel is then heated to the surrounding temperature. Drying will initially occur due to diffusion of water from the particle surface but will increase rapidly once the evaporation temperature, approximately 100°C, is reached. Drying will initially occur at the outer boundary of the particle where the temperature is highest, but the drying front will move inwards due to heat and mass transport.

2.5.2 Pyrolysis

Pyrolysis is a chemical process which is the major decomposition process occurring in a biomass particle and involves a large number of reactions. In this process large hydrocarbon chains are broken down into shorter chains. This process is complex and having some influence factors, which include; heating rate, temperature history, particle size and shape, pressure, moisture content, and chemical composition[22].

Several studies have been carried out to determine product yields in terms of char, tar, and gas. Detected yields for biomass under combustion conditions ranged from 5-25 wt% for char, 10-40 wt% for gaseous and 30-60 wt% for tars[23].

Char: the solid residue which remains after pyrolysis. The organic material and ash are the main component of char. Its organic material is mostly carbon, but it can also contain some oxygen and hydrogen.

Tars: high molecular weight organic products that are condensable at room temperature while these products are gaseous at the higher temperature. Tar is the largest mass fraction of the pyrolysis product.

Gases: lower molecular weight products, such as CO, CO2, H2o, CH4, etc....

2.5.3 Char burnout

Char is a porous, carbon-rich solid and which carbon constitutes over 90% of the char[22].and also presented small amounts of hydrogen, oxygen, nitrogen, sulphur, and inorganic matter or ash.

There is two type of char burnout: char oxidation and gasification. The char oxidation with O2 and gasification with CO2, H2O, and H2 are considered as the char conversion reactions: The char conversion reactions are assumed to occur at the interface between char and ash layer.

$\Omega C + O_2 \longrightarrow 2(\Omega-1)\, CO + (2-\Omega)\, CO_2$ (R9)

$C + CO_2 \longrightarrow 2CO$ (R10)

$C + H_2O \longrightarrow CO + H_2$ (R11)

$C + 2H_2 \longrightarrow CH_4$ (R12)

For most of the combustion applications the reaction of char with oxygen is much faster than char gasifications with carbon dioxide, water vapour and hydrogen[23]. Where the oxygen is depleted, these gasification reactions become important.

2.6 Biomass Combustion Technologies

There are three main technologists used for the biomass combustion; fixed bed, fluidized bed, and pulverized bed. Classification of principal combustion technologies can be presented as below. The configurations of furnaces are described briefly in Figure 2-9. The Main focus of this study is the fixed bed conversion and it is discussed in detail in the section 2.7.

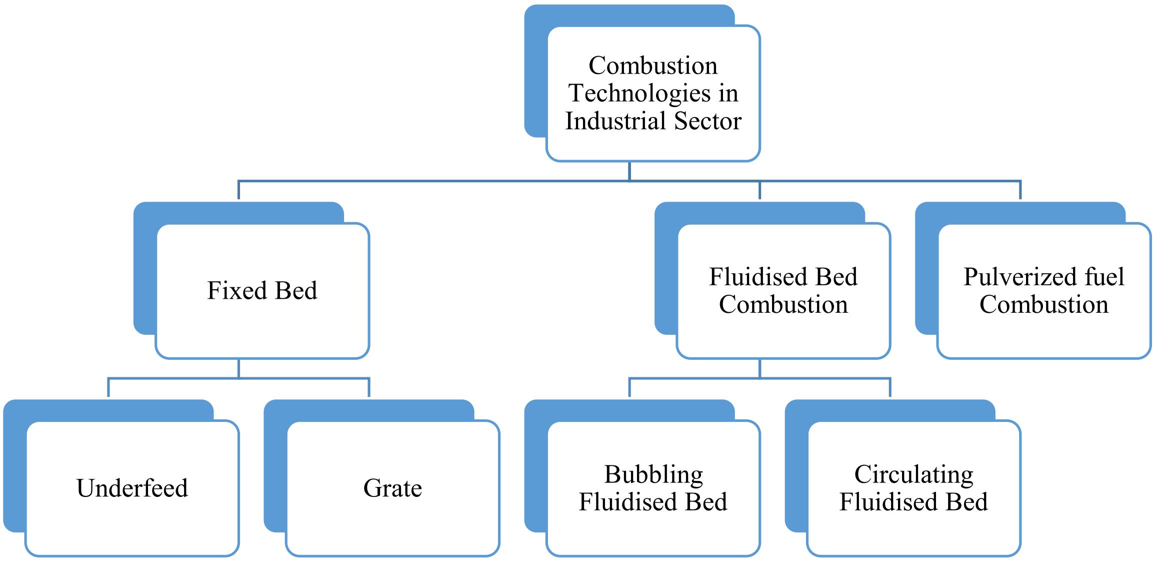


Figure 2-9: Biomass Combustion Technologies

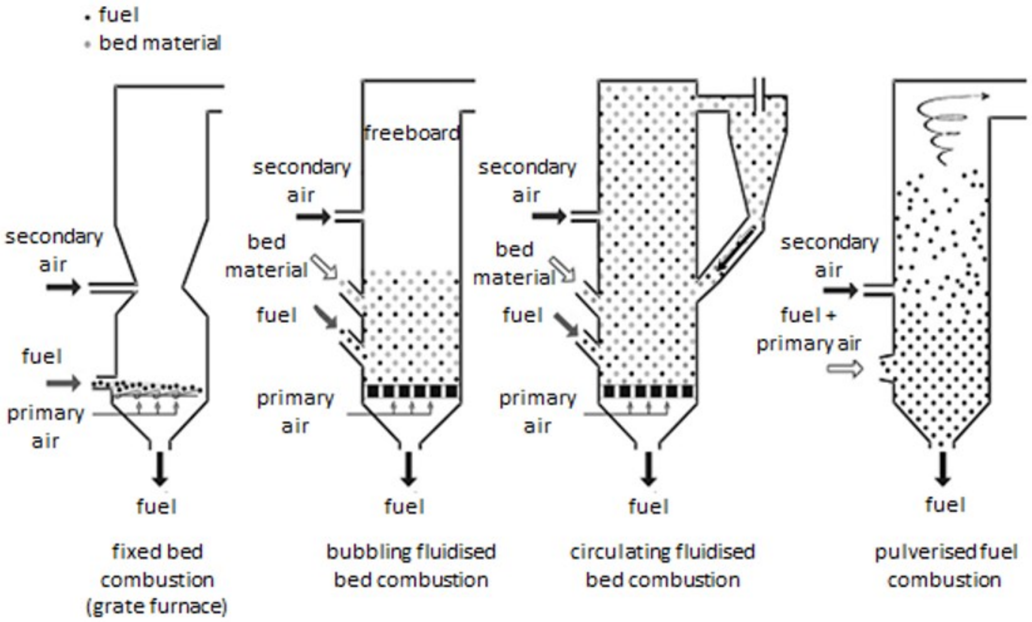


Figure 2-10 : Principal Combustion technology for biomass

2.6.1 Fixed bed Combustion

Fixed bed combustion is the most common and simplest method of converting chemical energy stored in biomass to a more useful form of energy. Drying, gasification and charcoal combustion occur in the bed and the combustion of the gaseous product occurred outside the fuel bed. Grate furnaces and underfeed stockers are included for the fixed bed combustion systems. Grate furnaces can be categorized into fixed grates, moving grates, traveling grates, rotating grated and vibrating grates. Fuels with high moisture content, different particle sizes, and high ash content can be burnt in grate furnace.

Fixed bed furnaces are mostly used for the small-scale applications and have the lowest investment cost of all conversion technologist. When comparing Operational costs of fixed bed combustion are lower than other systems due to grate furnaces are capable of burning untreated, moist fuel, ranging in size from pellets (6 – 10 mm) to wood logs[22].

2.6.2 Fluidized bed Combustion

In the fluidized bed system biomass fuel is burned in a self-mixing suspension of gas and solid bed material. A perforated plate at the bottom keeps the hot, inert and granular material and fluidized bed made as a cylindrical vessel. Silica and dolomite are used as common bed materials. The primary air enters through the perforated plate at the bottom of fluidizes the bed and fluidized the bed. Therefore, it becomes a bubbling mass of particles and bubbles. About 90-98% of the mixture of fuel and bed material is represented by the bed material. The vertical speed of the inlet air is sufficient to cause the bed material to become suspended, effectively making the entire mass of solids behave like a fluid; the different gas speed encountered are shown below figure 2-11. Better contact between particles and the air and good mixing conditions provide space for complete combustion with low excess air demand. The combustion temperature has to be maintained usually between 800-900°C to prevent ash sintering in the bed. This can be achieved by internal heat exchanger surfaces, by flue gas recirculation, or by water injection.

Fluidized bed combustion plants deal flexibly with various fuel mixtures (e.g. mixtures of wood and straw can be burned) to achieve the good mixing. But it is limited when it comes to fuel particle size and impurities contained in the fuel. Therefore, appropriate fuel pre-treatment system covering particle size reduction and separation of metals is necessary for fail-safe operation. Fluidized bed combustion can be divided into two main categories i.e. Bubbling Fluidized Bed and Circulating Fluidized Bed. These beds are depending on the fluidization velocity.

2.6.2.1 Bubbling fluidized bed (BFB)

The main principle of a BFB furnace is that the fuel is dropped down a chute from above into the combustion chamber where a bed, usually of silica sand, sits on top of a nozzle distributor plate, through which air is fed in to the chamber with a velocity of between 1 and 3.5 m/s. The vertical air-speed is high enough to cause fluidization of the fuel bed but low enough to prevent solid particles from escaping the bed.

The main two advantages of BFB's are fuel size and type over more traditional fixed bed systems. First, they can cope with fuel of varying moisture content and particle size with little problem, and then, they can burn mixtures of different fuel types such as straw and wood.

2.6.2.2 Circulating fluidized beds (CFB)

CFBs have higher air-speed than BFBs and air velocity is increased to 3.6-10 m/s then a CFB system can be achieved. In CFB the sand is carried upwards by the flue gases and a more in-depth mixing of the fuel and bed material takes place. A cyclone is required downstream to separate these particles from the flue gas for their return to the fuel bed. The cost is relatively high due to their larger size compared to other combustion methods and there are problems involved with fuel size, which must be very small, and the difficulties involved in running them at partial load.

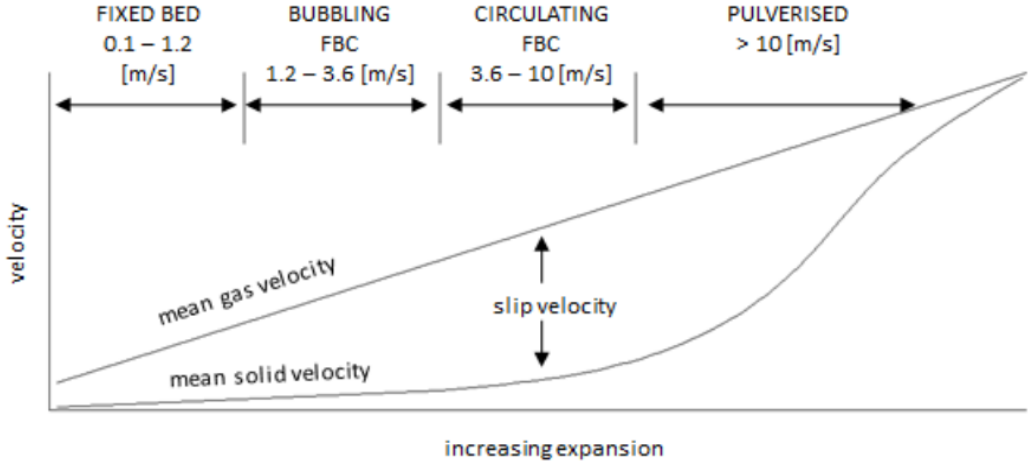


Figure 2-11 : Fluidizing Velocity of air for various bed system[22]

2.6.3 Pulverized Fuel Combustion

Small size fuel particles (average diameter smaller 2 mm) are suitable for pulverized fuel combustion. In pulverized combustion, sawdust and fine-wood particles are injected pneumatically into the furnace, while the transportation air is used as primary air. Fuel moisture contains should be less than 20% and should maintain maximum fuel particle size between 10-20 mm range. At the start-up auxiliary burner initiates the combustion which is then transferred to the biomass. Fuel quality should be kept constant and the fuel injection to the system has to be carefully controlled due to the explosion like the behaviour of biomass particles entering the system. Since fuel gasification and charcoal burning occur simultaneously, quick load changes and efficient load control can be achieved.

2.7 Fixed bed conversion

Fixed-bed combustion system can be classified into two categories which are grate furnace and underfeed stokers. With these methods of combustion primary air passes through a fixed bed, in which drying, gasification, and charcoal combustion occurs. The combustible gases produced are burned in another chamber, usually in a combustion zone separated from the fuel bed where secondary air addition has taken place.

2.7.1 Underfeed stokers

Underfeed stokers are relatively cheap and operationally safe technology for small-scale and medium-scale systems. They are suitable for biomass with small sizes fuel particle (particle dimension up to 50mm) and low ash content such as wood chips, sawdust, pellets. Then, need a more efficiency ash removal system for the ash-rich biomass fuels like bark, straw, and cereals. Furthermore, sintered or melted ash particles covering the upper surface of the fuel bed can cause problems in underfeed stokers due to unstable combustion conditions.

There are many advantages of underfeeding stokers. They have good partial-load behaviour and simple load control than other technologies since load change can be achieved quickly and more easily than in grate combustion plants due to fuel supply can be controlled more easily. Fuel is fed into the furnace by screw conveyor from below and then forced upwards on the inner or outer grate.

2.7.2 Grate furnaces

Grate furnaces are well proven and reliable and can tolerate wide variations in fuel quality like the variation in moisture content, varying particle sizes and fuels with high ash content. Mixtures of wood fuels combustion like a mixture of wood fuel and straw, cereals and grass, do not allow due to their different combustion behaviour, low moisture content and low ash melting point. When designed a good and well control grate furnaces consider the homogeneous distribution of the fuel and the bed of residues over the whole grate surface. And also the homogeneous distribution of fuel is very important for the equal primary air supply over the various grate areas. If has an inhomogeneous air supply through the grate, it may be caused slagging, higher fly-ash amounts, and may increase the excess oxygen needed for the compete combustion. Therefore, homogenous air flow through the grate is more important to avoid the formation of holes, to keep the bed of embers calm and homogeneous and to avoid the elutriation of fly ash and unburned particle as much as possible. There is various type of grate furnace technologies available which are fixed grates, moving grates, traveling grates, rotating grates and vibrating grates. And also grate furnaces can be classified into three categories according to both fuel and air flow direction to the fixed bed. Classification of grate furnace categories illustrated in figure 2-12.

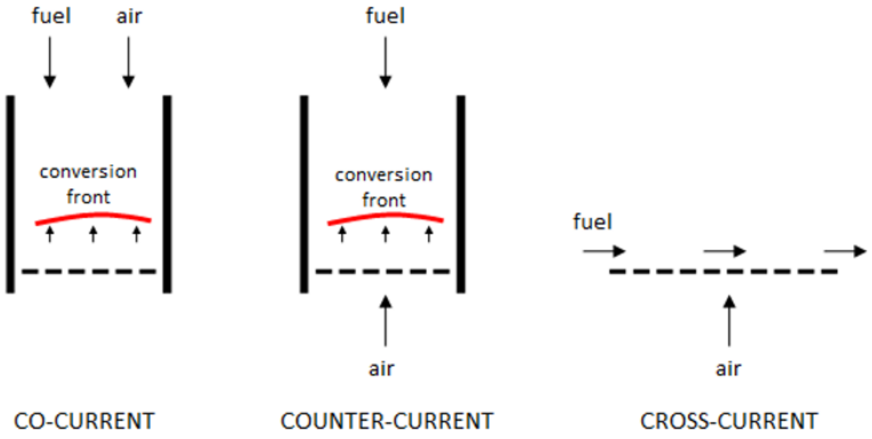


Figure 2-12: Classification of grate combustion technologies

2.7.2.1 Co current flow

Co-current flow is suitable for fuels with low moisture content or systems where the preheated primary air is used. And this method is mostly used for modern small-scale boilers and gasifies, due to it provides a stable conversion front, which travels in the opposite direction to the air supply. The residence time of the unburned gases increases in this system and NO_x emission is reduced due to enhanced contact of flue gas with the charcoal bed. Higher fly ash entrainment can occur.

2.7.2.2 Counter current or updraft

This method is used in a less sophisticated system, such as open fire or old boiler, primarily due to its simplicity. And also this method is suitable for fuels with low heating values. Hot flue gases pass over the fresh fuel entering the combustion chamber allowing the moisture in the fuel to be vaporized. Counter-current flow fuel beds produce colder gases with more tar content than the co-current flow.

2.7.2.3 Cross flow

Cross-flow combustion is applied in combustion systems with vertical secondary combustion chambers. In this type of furnaces, a mixture of counter-current flow and co-current flow occurs. Cross-flow furnaces are used with coarse particle sizes. The fuel is transported by a moving grate. In different parts of the bed, the air supply can be changed [24].

3 METHODOLOGY

3.1 Experimental method

Experiments were performed in a lab scale packed reactor with consists of vertical combustion chamber, grate, air supply system and weighing scale as shown in Figure 3-1. The packed bed is made from mild steel having a bed height around 800cm and a side length of 300cm. it has three measuring ports installed on the wall for access of K-type thermocouples and sampling probes, and they are located near the grate, gas-solid surface, and flue gas zone. The junctions of thermocouples are aligned along the core of the reactor. Air was supplied through a blower with a constant flow rate at room temperature and air introduced through a porous plate at the bottom. A gas analyser measures the O2, CO, and CO2 concentrations by using an Orsat's apparatus. The reactor is suspended from weighing scale having four load cells in order to measure the mass loss of the fuel bed. The weighing scale has a resolution of 20g, while the initial sample feed is 3-4 kg depending on the bed height. Bed height is measured by using meter rule and initial bed height is about 20 – 25 cm. The data record the temperatures, mass loss, and bed height every 2 minutes time. And collected one or two gas samples per every batch. The time duration required for total combustion of the bed depends on the particle size. Hence the experiments carried out different time interval.

3.2 Experimental conditions

Table 3-1 lists the bulk density, bed height and operating conditions for the rubber-wood samples of different particle sizes. The air flow rate was fixed at 16.5 m/s at room temperature. The initial bed height was 20 -22.5 cm. the bulk density of the fuel bed was about 175 – 225 (kg/m^3). The particle size of the rubber-wood did not affect the bulk density, which indicates that the fuel bed with larger particles have similarly void fraction but bigger voids than with smaller particles.

Samples	Bulk density (kg/m^3)	Bed height (cm)	Air flow rate m/s
Size 1 (25 mm × 25 mm × 25 mm)	192.8	22.5	16.5
Size 2 (38 mm × 38 mm × 38 mm)	222.5	20	16.5
Size 3 (50 mm × 50 mm × 50 mm)	210.6	20	16.5
Size 4 (63 mm × 63 mm × 63 mm)	177.8	22.5	16.5

Table 3-1 : the bulk density, bed height and operating condition for the rubber wood samples of different particle sizes.

3.3 Experimental setup

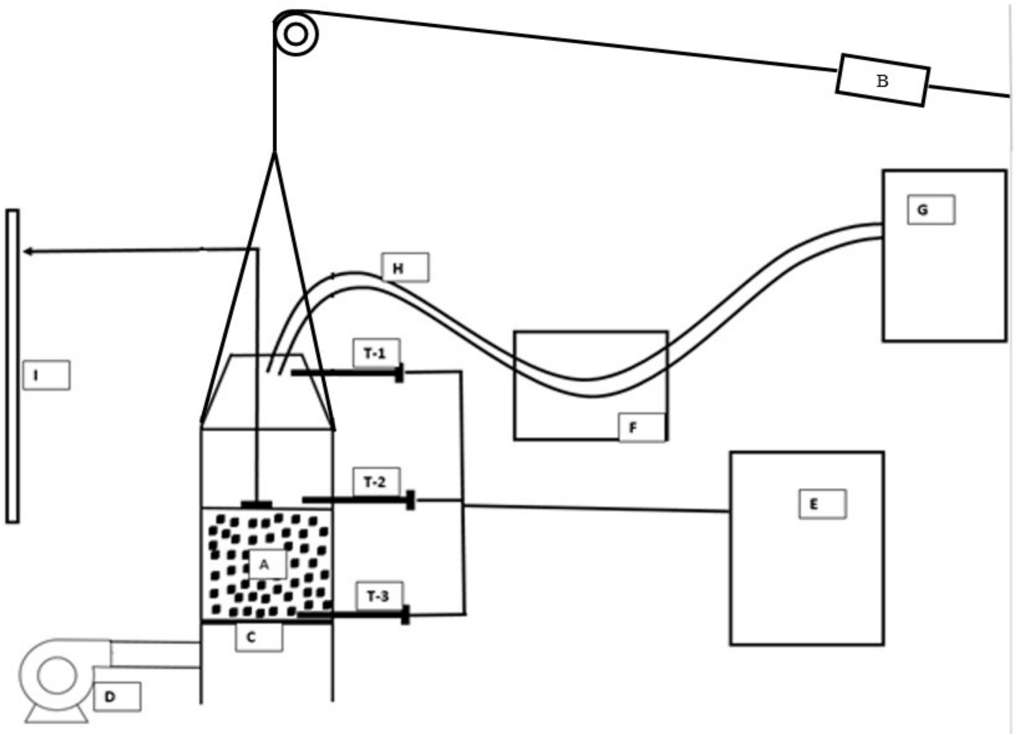


Figure 3-1 : Schematic diagram of the experimental fixed bed combustion reactor. (A) Rubber wood initial bed; (B) weight scale; (C) Grate; (D) blower; (E)Temperature Reader; (F) Water bath; (G) The Orsat apparatus; (H) copper tube; (I) Ruler; (T-1, T-2, T-3) Thermocouples

3.4 Equipment

The following equipment was used for taking measurements.

3.4.1 Thermocouples

K-type thermocouples were used to measure the temperature in different sections. Three thermocouples were installed in reactor body as shown in below figure to measure the temperature of the bottom surface, gas-solid surface and flue gas.

Figure 3-2 : Picture of the Thermocouples with Reactor

3.4.2 Temperature panel

The temperature panel consists of two digits meter for temperature reading. For this study, used only large digital meter for temperature measurement. A regulator was installed, and three thermocouples connection were made via this regulator to the digital meter. The regulator numbers 1, 2 and 3are for bottom surface, solid gas surface and flue gas temperature reading respectively. A stopwatch was used to monitor the temperature measurement with time.

Figure 3-3 : Picture of the Temperature Panel of Unit

3.4.3 Air supply and velocity measuring

A blower of 75mm outlet at 3600 rpm was used to supply air. The air blower was connected to the supply line of 3.175cm diameter and measures the air velocity by using a digital anemometer. By measuring the velocity and with the known diameter of the pipe we can calculate air flow rate. Specifications of the instrument are given below in Table 3-2.

Anemometer [Hot wire with temperature sensing probe]	
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

Table 3-2 : Specification of Instrument

Figure 3-4 : Picture of the Digital Anemometer

Figure 3-5 : Picture of the Primary air Supply Blower

3.4.4 The Orsat's apparatus

To analyse the composition of flue gas and calculate air/fuel ratio in a combustion process. There are three types of chemical-solution used for this apparatus:

- Solution no. 1 - 140g of KOH dissolved in 350 cm^3 of distilled water.
- Solution no. 2 - 22g of pyrogallol dissolve in 75 cm^3 of distilled water and 100 cm^3 of con.HCl acid.
- Solution no. 3 - 20g of cuprous chloride dissolve in 100 cm^3 of water and 100 cm^3 of con.HCl acid.

These three solutions were used to measure the flue gas composition of CO_2, O_2, and CO respectively.

Figure 3-6 : Picture of the Orsat's Apparatus

3.4.5 Collecting gas sample

While doing the experiment collected gas sample directly to the Orsat’s apparatus by using a copper tube and suction valves. When collecting the gas sample, the copper tube goes through a water bath to reduce gas temperature as shown in figure 3-7.

Figure 3-7 : Picture of Water Bath

3.4.6 Measuring mass loss

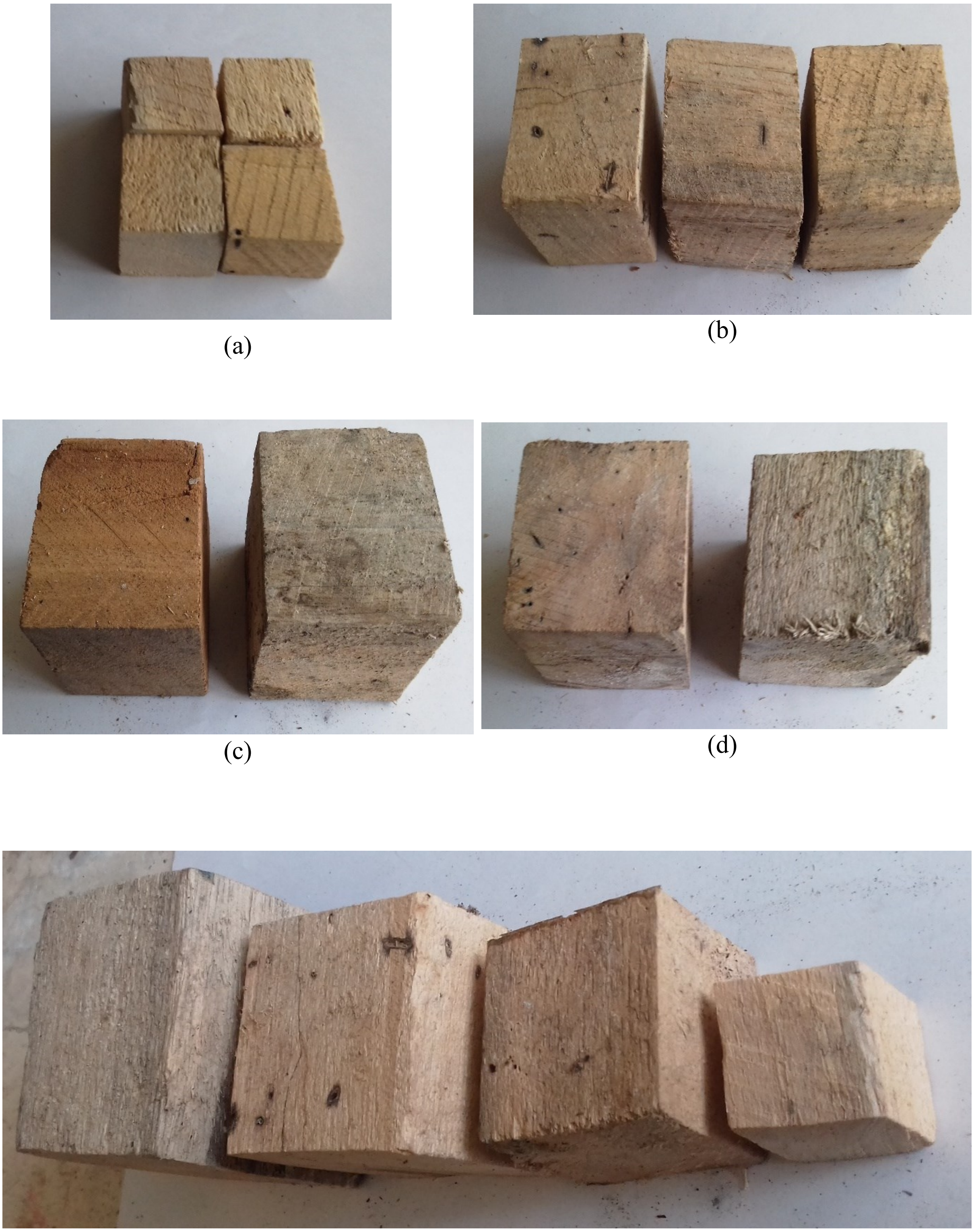
OCS-F- 50 series portable crane scale was used to measure the mass loss (see experiment setup, figure 3-1). The bed reactor has carried by wire using a pulley. Here one end of the wire connected to the bed reactor and other end connected to the weight scale.

3.4.7 Measuring moisture level

Samples were weighted accurately in a Petridis spreading evenly over the dish surface. These samples were then introduced into an oven for 24 hours at 100 +/- 5 °C. After removing samples from the oven, they were placed in a desiccator for 10 minutes to cool and then weighted.

3.5 Selected biomass sample

Rubber is the main type of biomass in Sri-Lank and also a lot of industries used rubber wood to full fill their energy requirements. In the present study selected rubber-wood as biomass raw material. Rubber-wood as it was collected in large pieces, desired particles were obtained by using a wood cutting machine. Rubber samples were cut into cubes with four different sizes (25mm, 38mm, 50mm, and 63mm) in order to investigate the effect of particle size. All raw materials were fairly sun-dried to reduce moisture content less than 5% for the number of days and then packed to prevent it from environmental impacts.



(a)

(b)

(c)

(d)

(e)

Figure 3-8 : Picture of different size Rubber wood samples; (a) particle size 25mm, (b) particle size 38mm, (c) particle size 50mm, (d) particle size 63mmand (e) all particle size together.

3.6 Operational procedure

Operational procedure for each batch was the same. And only difference was the changing the biomass particle size (four different sizes of rubber-wood samples used as the biomass). The Operational procedure was carried out as follows.

- The reactor was suspended from weighing scale having four load cells to measure the weight loss.
- Temperature panel and blower were set in the ready mode by plugging switches in the socket.
- The Orsat's aperture was set to analyse the flue gas composition.
- Set the water bath and copper tube to collect the flue gas samples.
- Set the measurement rule by using supporter to measure the biomass bed shrinkage.
- Blower switch was turn on and measure the primary air flow rate and outer air flow rate by using anemometer and noted these air flow rates.
- Blower switch was turned off.
- Weight scale reading was adjusted to zero.
- Biomass material was introduced into the reactor through a grate.
- Noted the initial bed height (at t=0) and initial mass weight of biomass (at t=0).
- Temperature panel was turned ON and initial temperatures (at t=0) of three thermocouples were noted which was ambient air temperature.
- Ignited the biomass particle by using external heat source through a grate and closed the grate.
- The blower was turned on.
- Immediately after starting black smoke was observed coming out. A few minutes later noted that fire was coming out to the top of the reactor.
- During operation, the temperatures of each thermocouples were noted at every 2 minutes interval.
- The highest temperature recorded was 860-degree °C near the grate during in all batches while operation.
- During operation mass of biomass bed, and height of the biomass bed were recorded at every 2 minutes interval.

- During the operation, for the analysis flue gas composition, collected sufficient amount of flue gas sample to the orsat's apparatus which was connected to the copper tube at one end and the remaining end of the copper tube was placed to existing flue gas zone. The copper tube was passed through a cold-water bath to reduce the gas temperature.
- Flue gas composition was analysed two times per batch. And how-to determinate the flue gas composition discuss later.
- After the constant weight of the biomass bed. Stopped the recoding readings.
- Temperature panel and blower were turned off.
- The unit was left for the cooling
- Before starting each batch remaining residual was removed manually.
- Thermocouples were removed for cleaning and reinstalled before starting again for the next batch.
- After cleaning the unit is verified to see whether it is ready for another batch operation.
- For the next batch procedure was carried out in the same manner.

3.6.1 Flue gas analysis procedure

The solution to the apparatus:

- Solution No.1 - 140g of KOH dissolved in 350 cm^3 of distilled water.
- Solution No.2 - 22g of pyrogallol dissolve in 75 cm^3 distilled water and 125 cm^3 of solution No.1.
- Solution No.3. - 20g of cuprous chloride dissolve in 100 cm^3 of water and 100cm^3 of con.HCl acid

Preparation

- Assemble the apparatus as shown in figure 3.9.
- All stopcocks should be lubricated with good quality grease. No grease should be left in the capillaries or the bore of the stopcocks.
- The levelling bottle "A" which is attached to the lower end of the burette "B" by means of rubber tubing of sufficient length to enable the bottle to be raised above the apparatus which shall be filled with confining liquid. (5% sulphuric acid solution coloured with methyl orange).

- The absorption vessels shall be filled with the correct reagent of the appropriate strength. The quantity required is about 200 cm^3 in each case.
- G1 - contains 40% aqueous solution of KOH.
- G2 - contains 30% aqueous solution of pyrogallol with 40% of aqueous solution of KOH in the ratio of 1:2.
- G3 - contains acidic cuprous chloride solution of 20g of pure cuprous chloride in 100 cm^3 of distilled water and 100 cm^3 of con. HCL acid.
- As it is undesirable to have the reagent in contact with air, the open limp of each absorption tube should be covered with a thin layer of medicinal paraffin.
- By lowering the levelling bottle "A" and opening the appropriate stopcock, draw up the reagent in G1, G2, and G3 to the level mark "B".
- Fill "E" with the confining liquid by placing the liquid level in "A" against the burette mark "C" and opening stopcock "D" to waste.
- In all these adjustments, do not bring the reagent above the mark "B"
- Test the apparatus for leaks by filling the burette with the confining liquid closing the stopcock "D" and lowering the level bottle. On standing, the level of confining liquid will not fall.

Method of drawing 100ml sample:

- Connected the gas sample supply to "J" and draw up sample of gas into "E" by suitable turning stopcock "D".
- Discard this to waste by raising "A" and adjusting "D".
- Then, lower "A" below the zero level in "E" and draws in more than 10cc of gas and close "D".
- Place the liquid level in "A" against the burette zero mark and momentarily opening of "D".
- Release the gases to atmosphere until the liquid level in "E" is at zero.
- Keep "D" closed during the analysis.

Determination of CO_2:

- Open "F_1" and transfer the gas slowly to air from the absorption vessel "G_1" by raising and lowering "A". after 2 or 3 passes, draw up the reagent to "B_1" and close "F" and place the liquid in "A" against the liquid level in "E" and note that the reading.
- Repeat the transfer of gas to and from "G_1" until the burette readings remaining constant.
- The reading on burette gives the percentage of CO_2.

Determination of O_2.

- Transfer the gas to "G_2" and repeat as for CO_2. The difference between the final reading and the reading for CO_2 gives the percentage of O_2.

Determination of CO.

- Transfer the gas to "G_3" and repeat as for CO_2. The difference between the final reading and the reading for O_2 gives the percentage of CO.

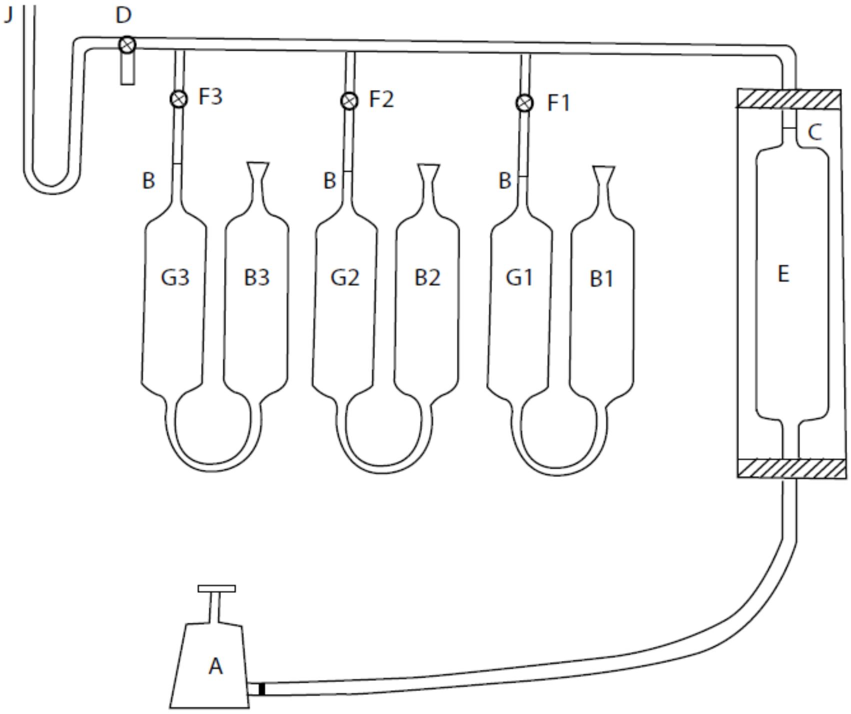


Figure 3-9: The Orsat's Apparatus. (A) Levelling bottle; (E) Burette; (G1, G2, G3) Solutions contains; (D) Stopcock; (J) Gas sample supplier.

Pictorial view of operation is presented below in figure 3-10.

Figure 3-10 : pictorial view of operation

4 Results and Discussion

4.1 Mass loss with time

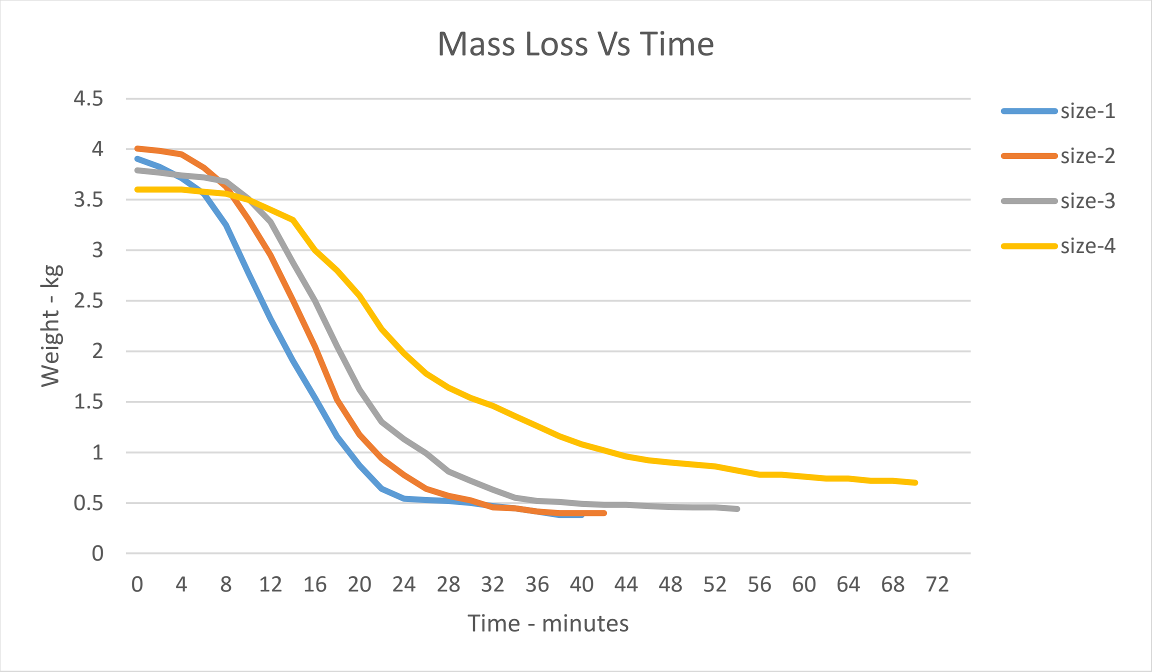


Figure 4-1: Mass Loss curves for four different size biomass fuel.

Figure 4-1 show the mass loss history of fuel (rubber-wood samples with different particle size) as expressed as remaining mass on the bed as a function of reaction time. Three different periods can be distinguished based on mass loss curves.

1st period – Initial ignition (drying) period in combustion with pyrolysis without ignition of volatiles.

2nd period – ignition of volatiles periods, most of the volatiles are released from biomass and the mass of the packed bed sharply declines with an almost constant rate.

3rd period – char oxidation period, during this period the mass of the packed bed gradually decreases, as the char burnout rate is slower than the pyrolysis rate.

There was an initial ignition (drying) period before a steady stage was reached. For the 25 mm rubber wood fuel, the initial mass loss was quick, reaching steady state at t= 3 min. for the 38 mm rubber wood cubes, the initial mass loss was slightly slower, reaching a steady state at t= 6 min. for the 50 mm particle size, it was only after t=10 min that the mass loss reached a steady state. The 63 mm rubber-wood the longest initial ignition (drying) period about 14min before a fully steady combustion stage was reached. As seen from the initial stage of conversion of the bed, the reaction front reaches a steady state very rapidly in the small particle bed, whereas in the large particle bed it takes more time. Therefore, initial ignition (drying) period increase with increasing particle size.

After the initial ignition (drying) period, a sharply declines with the almost constant rate the total mass of the fuel bed was observed. Depending on the particle size, for the smallest particle size, 25 mm is having the largest mass loss rate while largest particle size 63 mm is having the shortest period of constant burning. The biomass consumption rate is inversely proportional to the size of the biomass particle.

Further on as the reaction time increased, the rate of the mass loss slowed down. For the small rubber wood cubes of 25 mm, this final period of combustion was about 18 min before the whole combustion completed. For the 38 mm, it increased to 22 min and for the 50 mm fuels, the final burning period further increased to 26 min. the largest fuel size, 63 mm, featured the longest final burning period of 42 min. it was noticed that the total burning time increased with an increase in the fuel particle size. The obtained value was 40, 42, 54, and 70 min respectively for the rubber-wood of 2.

4.2 Bed Shrinkage with time

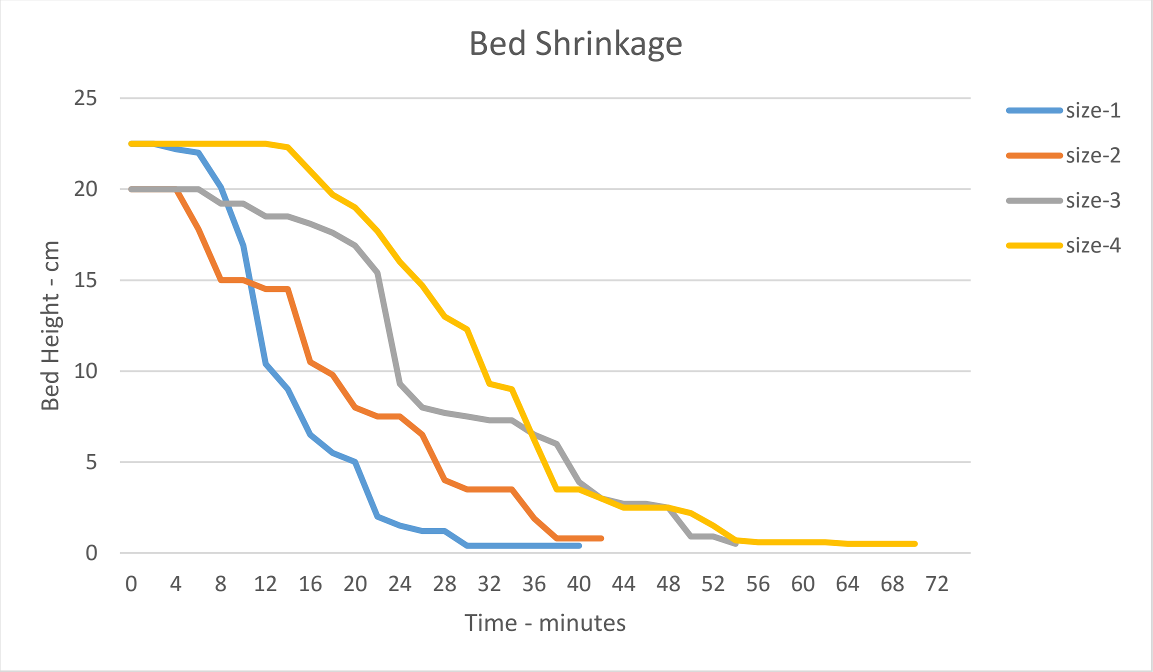


Figure 4-2 : Bed shrinkage curves with time for four size biomass particles.

Figure 4-2 is shown that a change of the bed height of the fuel bed over time. The surface of the fuel bed is not flat during the combustion of pack bed because of the uneven consumption of the fuel. Therefore, in always the centre point of the bed on the bed surface has been considered. At the beginning of combustion bed height remaining constant some time period. According to the above figure 4-2 shows that for the 25 mm rubber-wood bed height was remaining constant at about t = 4 min. for the 38 mm bed height was remaining constant at about t= 6 min. for the 50 mm rubber-wood bed, it was only 8 min remaining constant bed height. For the 63 mm rubber-wood bed height was having constant for the longest time period at t = 16 min. then, the initial bed height constant time period is increased with increasing particle size. And during the drying period, the size of particle remaining constant.

Further, as the above figure 4-2, it can be seen bed shrinkage starts with pyrolysis. The bed shrinkage rate is depended on the particle size. For the smallest rubber-wood bed is having the largest bed shrinkage rate and for the largest rubber-wood bed, 63 mm, is having the smallest bed shrinkage rate.

The bed height decreasing is not smooth. The uneven bed shrinkage can be interpreted as a bed collapse. Since the movement of the particle is only considered in the gravity direction, it leads to an unrealistic shape of the ash layer on the grate at the end of the combustion. Moreover, as it can be seen in the figure 4-2, at test runs at the end of the combustion an ash layer with a height is depending on the particle size and its height only a few millimetres and mass of about 0.35 – 0.7 kg was remaining.

4.3 Temperatures profile

4.3.1 Flue gas temperature profile.

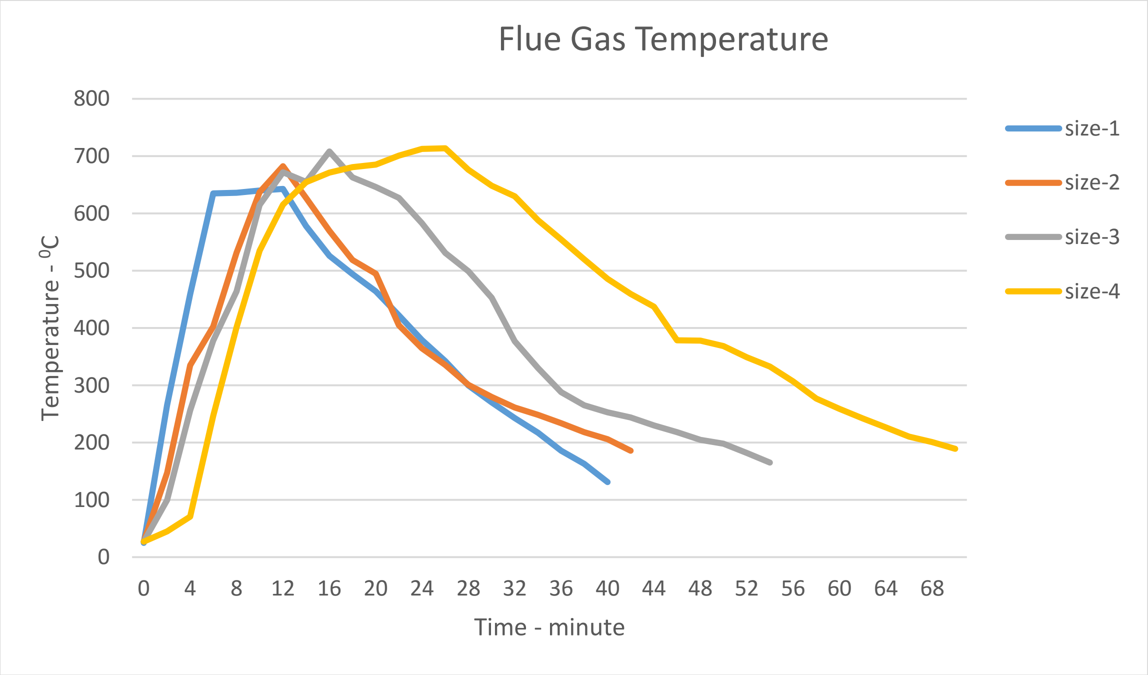


Figure 4-3 : Flue gas temperature with time

Figure 4-3 shows the flue gas temperature against time for different particle sizes of rubberwood. For the smaller particle (size 25 mm), the maximum temperature is about 635°C and the shorter time duration was span for rising of flue gas temperature from room temperature to the peak temperature. That time was recorded as 6 min. According to the graph, the peak temperature is increasing with increasing particle size, the peak temperatures were recorded as

682ºC, 708ºC, and 714ºC for the particle size 38 mm, 50 mm & 63 mm respectively. Also time duration which is for rising of flue gas temperature from room temperature to peak temperatures were recorded as 12, 16 and 26 min, for particle size 38 mm, 50 mm & 63 mm respectively. Then, the peak temperature of flue gas increased with increasing particle sizes in the bed and time duration also increase with increasing particle size.

4.3.2 Solid gas surface temperature

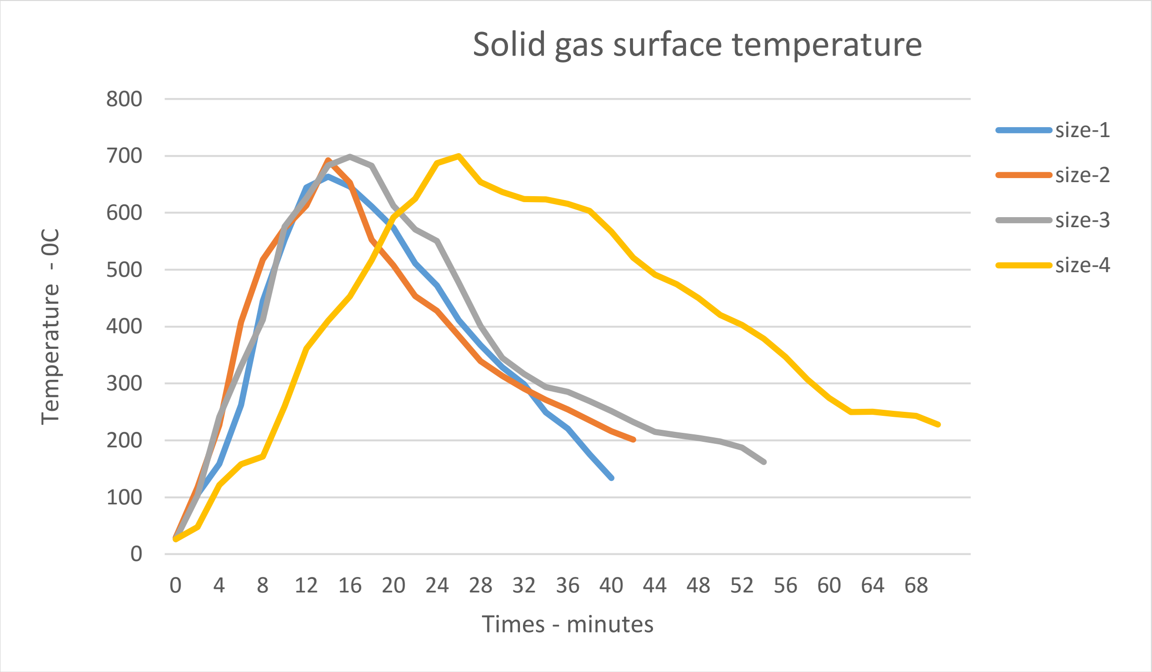


Figure 4-4 : Solid gas surface temperature

Figure 4-4 shows the solid gas surface temperature against time for different particle sizes of rubber-wood. The maximum temperatures of biomass samples are mostly similar and did not affect the particle size for the peak temperature of the solid gas surface. And also time durations which are for rising of solid gas temperature from room temperature to peak temperature were recorded as 14, 16 and 26 min, for particle size 38 mm, 50 mm & 63 mm respectively. Then, the peak temperature of the solid gas is similar for all particle sizes in the bed and time duration also increase with increasing particle size.

4.3.3 Grate temperature profile.

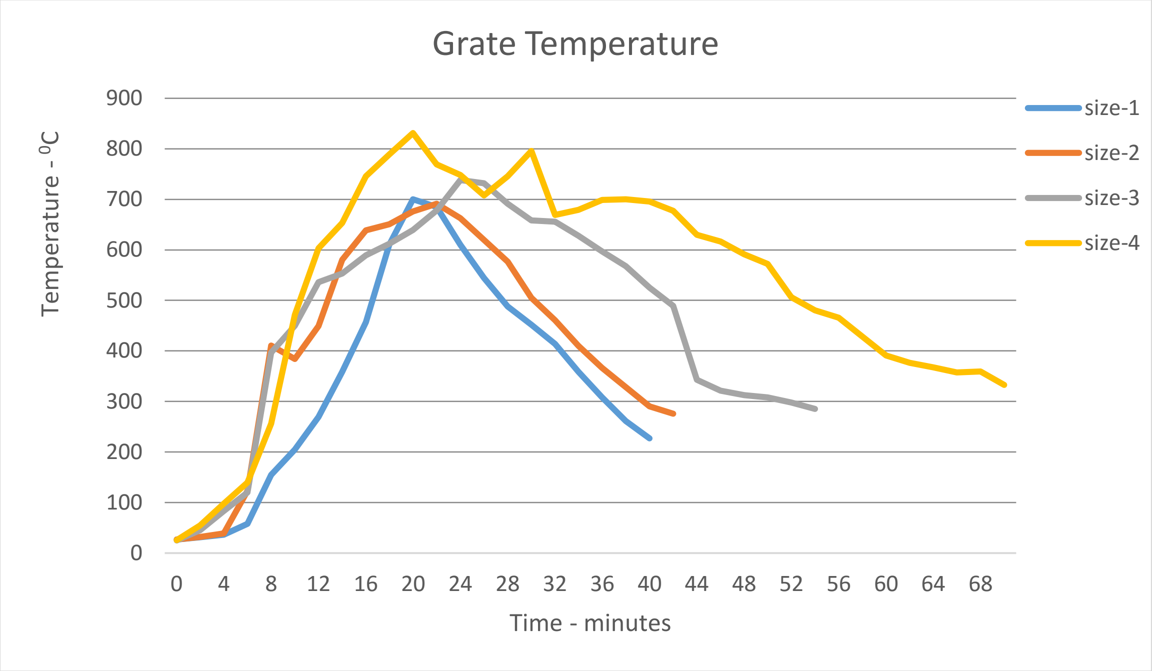


Figure 4-5 : Grate temperature with time

Figure 4-5 shows the grate temperature against time for different particle sizes of rubber-wood. There is no uniform temperature gradient for large particle while smaller particle has a uniform temperature gradient. For the larger particle size has a higher peak temperature which is about 831°C. The peak grate temperature increases with increase particle sizes. And also time duration which is for rising of grate temperature from room temperature to peak temperature were not visible linear relationship between particle sizes.

4.3.4 Temperature profile in the fixed bed reactor

The measured reactor temperature against time at different locations in the bed for particle sizes of 25 mm, 38 mm, 50 mm & 63 mm, shown in figure 4-6, figure 4-7, figure 4-8 and figure 4-9 respectively. For the smaller rubber-wood (Figure 4-6), flue gas temperature rose sharply from room temperature to a peak value is 645°C and kept temperature stable level for the several minutes, then reduced the temperature slowly. The peak value of the solid gas surface temperature is 664 C and the temperature gradient is less than flue gas temperature gradient and it took 16 minutes to reach the peak temperature and then, dropped the temperature. In the beginning, did not visible the more temperature variation for the grate temperature. After several minutes, the grate temperature increased slowly to a peak value at 700ºC and the longest time span for the rising of grate temperature from room temperature to the maximum temperature point.

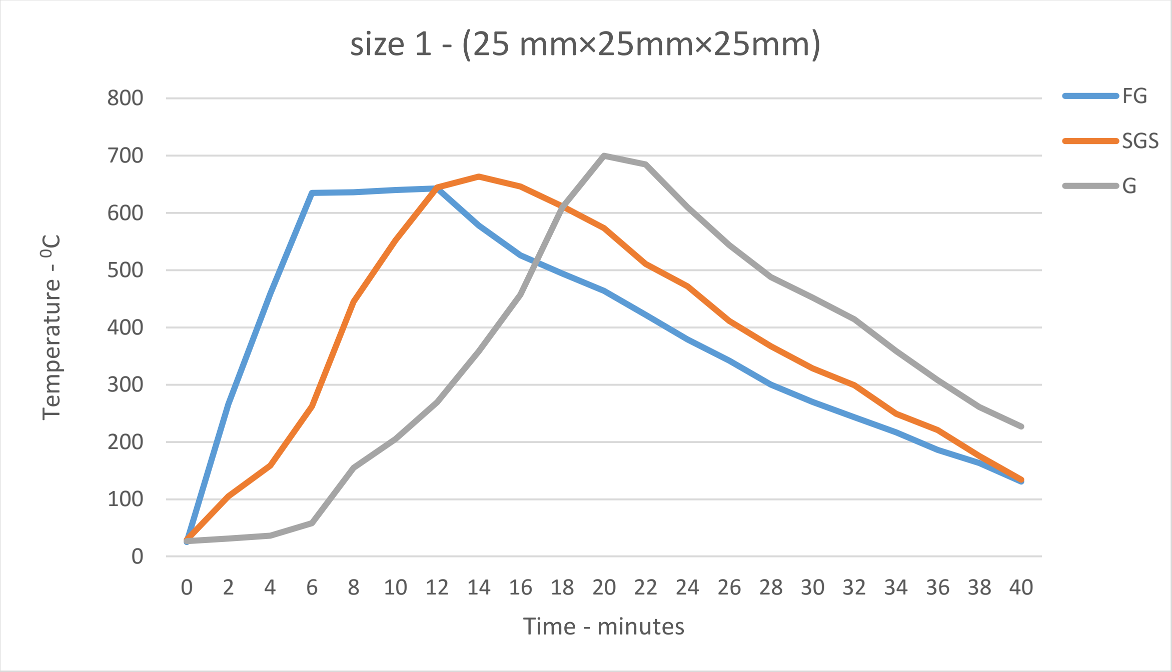


Figure 4-6: Bed temperature vs. reaction time at different bed heights above the grate for 25 mm particle

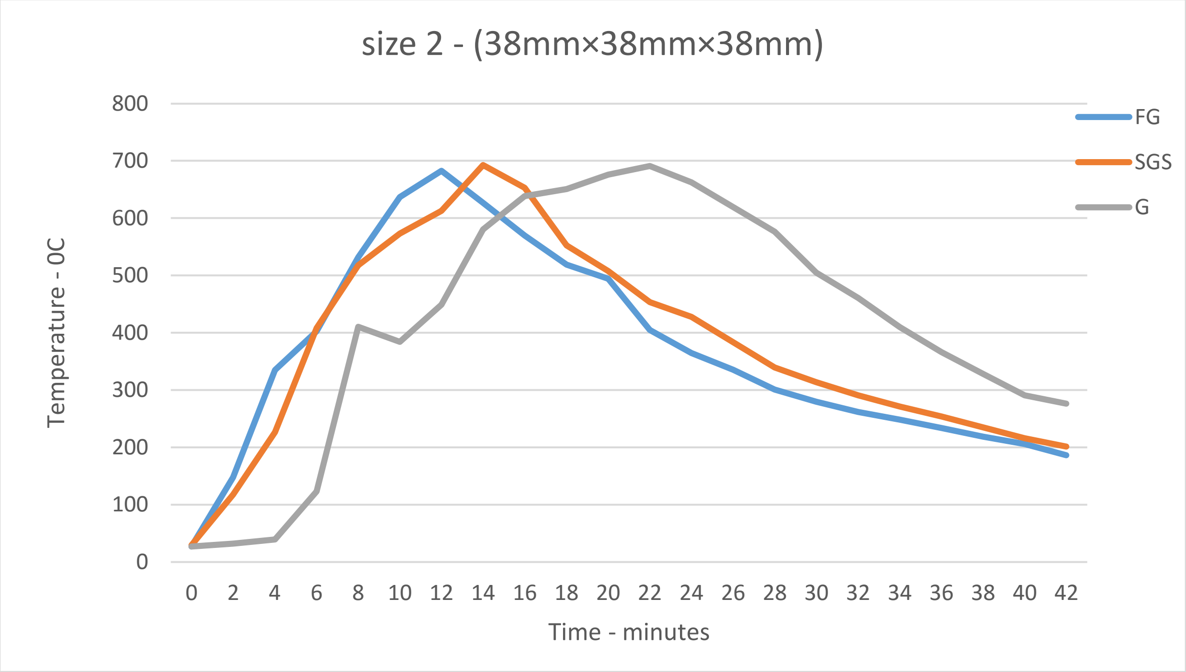


Figure 4-7: Bed temperature vs. reaction time at different bed heights above the grate for 38 mm particle size.

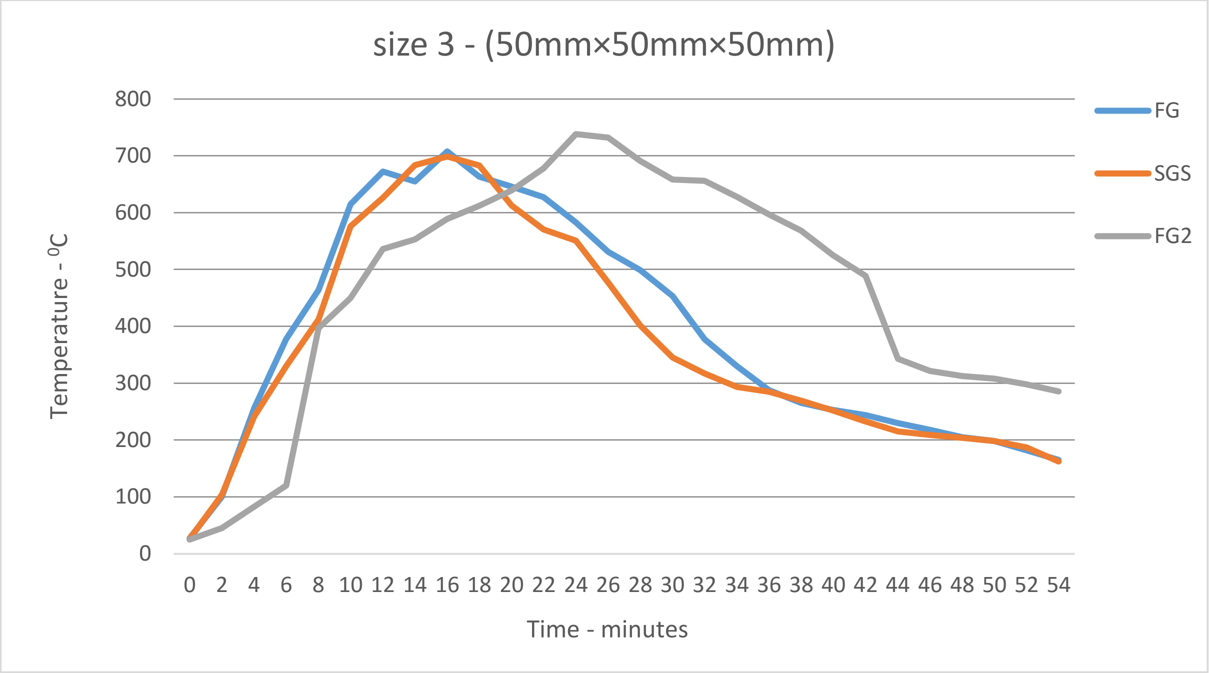


Figure 4-8: Bed temperature vs. reaction time at different bed heights above the grate for 50 mm particle size.

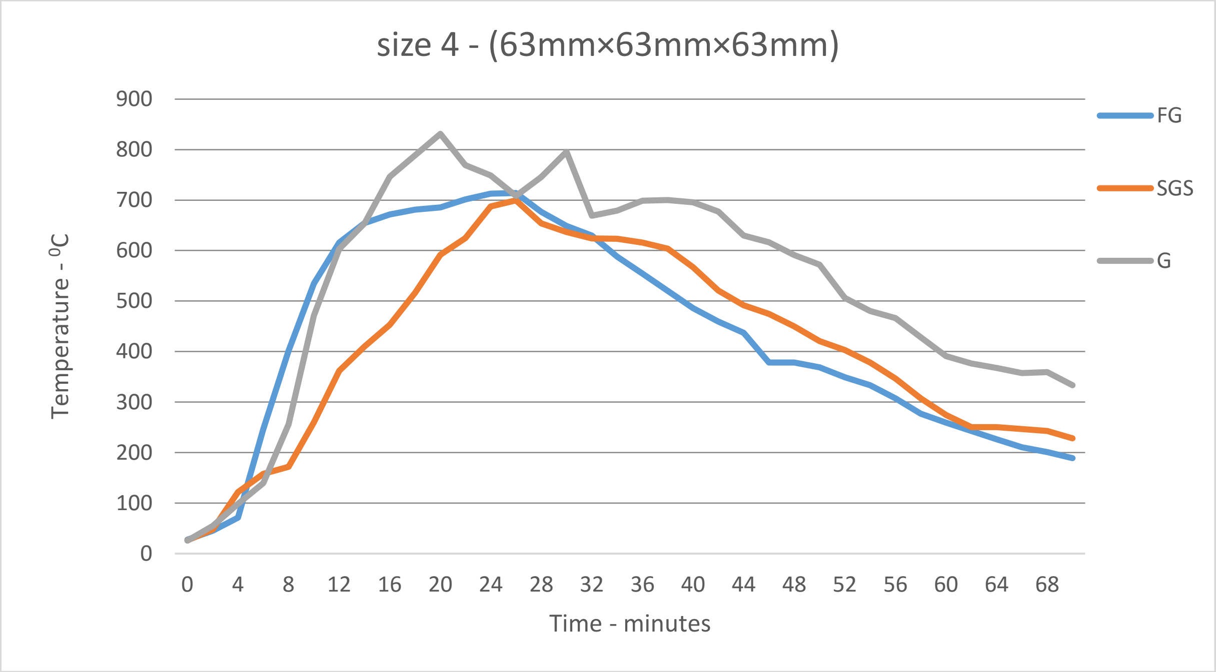


Figure 4-9: Bed temperature vs. reaction time at different bed heights above the grate for 63 mm particle size.

4.4 Excess air calculation

4.4.1 Stoichiometric air to fuel ratio calculation

The formula of rubber wood, only C, H and O, N components were considered while it was assumed that sulphur contents are not present or in very low quantity and was neglected. We assume that nitrogen is leaving without reaction. Balanced Stoichiometric equations for rubber wood biomass material is as follows. This formula is significant because air used for combustion calculation is highly dependent on this. Therefore, in this study, A/F $_{\text{stoic}}$ ratio used was based on these formulas presented below.

Rubber wood formulas: $C_{53.4}H_{6.5}N_{3.1}O_{36.8}$ [25]

$$C_{17.23}H_{2.1}NO_{11.87} + 11.82O_2 \rightarrow 17.23CO_2 + 1.05H_2O + 0.5N_2$$

$$C_{17.23}H_{2.1}NO_{11.87} + 11.82(O_2 + 3.76N_2) \rightarrow 17.23CO_2 + 1.05H_2O + 22.72N_2$$

Stoichiometric air required is calculated,

Molecular weight of Rubber wood biomass = 412.78 kg

Oxygen-Fuel mass ratio= $\frac{11.82\times32}{1\times412.78}$ = 0.916 kg of oxygen /kg of fuel

Oxygen in air by mass percent is 21 so we need

$0.916 \times \frac{100}{21} = 4.36$ Kg of air /kg of fuel

Then, stoichiometric air to fuel ratio = 4.36 Kg of air /kg of fuel

4.4.2 Burning rate

Figure 4-10 shows the burning rate during the ignition propagation period for different particle sizes of rubber-wood. Smaller particles have higher burning rates and burning rate decreases with increasing particle sizes.

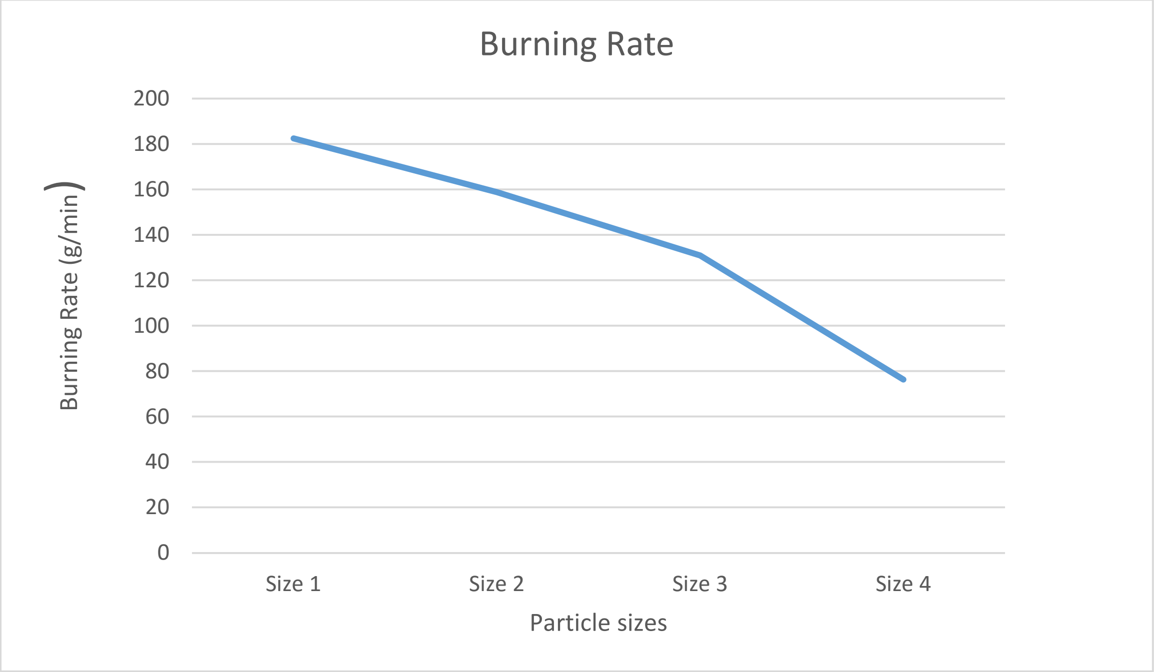


Figure 4-10 : Burning rate Vs Particle size

4.4.3 Actual air to fuel ratio calculation

Inlet air flow rate = 16.5 m/s

Area of bed $= \frac{\pi D^2}{4} = \pi \times \frac{0.045^2}{4}$

Volumetric air flow rate = 0.02625m^3/s

Density of air = 1.225 kg/ m^3

Actual air required per second = 0.02894 kg

For smaller particle size,

Burning rate per second = 0.003042 kg

Then, actual air to fuel ratio = 0.02894/0.003042

=9.513

Similar calculation for other sizes,

	Particle size (mm^3)	Burning Rate (g/min)	Burning Rate (g/s)	Actual air to fuel ratio
Size – 1	25×25×25	182.5	3.042	9.513
Size – 2	38×38×38	158.75	2.646	10.937
Size – 3	50×50×50	130.9	2.182	13.263
Size - 4	63×63×63	76.25	1.271	22.769

Table 4-1 : Actual air to fuel ratio

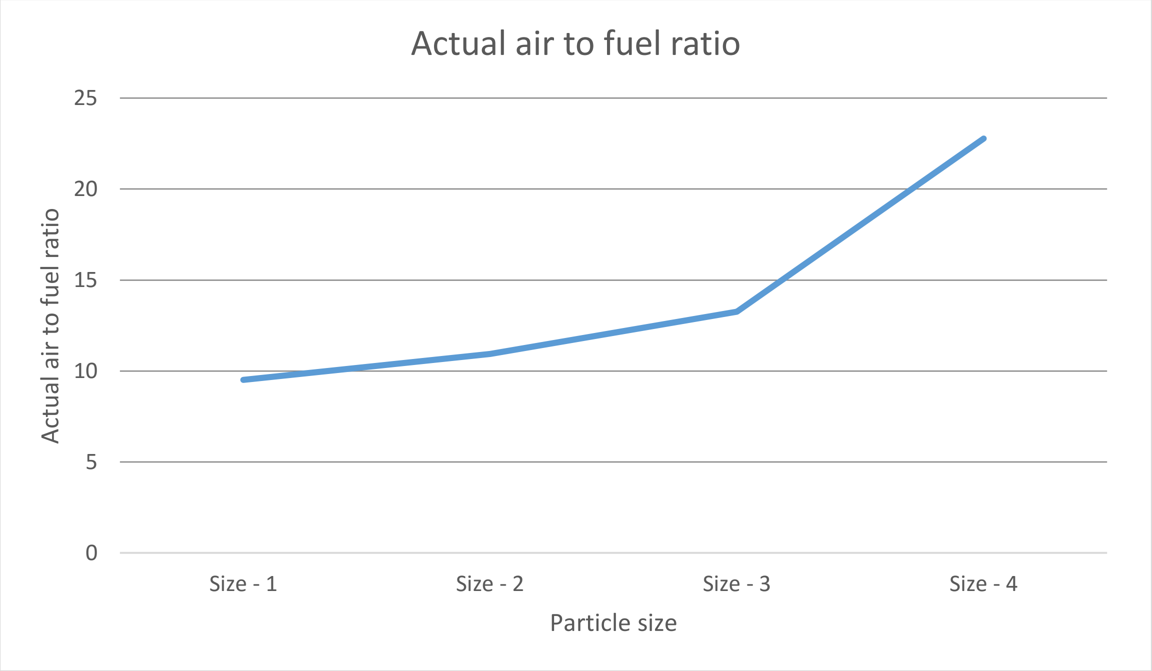


Figure 4-11 : Actual air to Fuel ratio vs particle size.

Figure 4-11 shows, the actual air to fuel ratio variation with particle sizes. Here, smaller particle size has smaller air to fuel ratio than larger particle air to fuel ratio. Then, actual air to fuel ration increases with increasing particle size.

4.4.4 Calculate excess air

For smaller particle size 1,

Actual air can be calculate by using below equation.

$$\%\text{Excess air} = \frac{\text{Actual air used} - \text{Theoretical air}}{\text{Theoretical air}} \times 100\%$$

$$= \frac{9.513 - 4.36}{4.36} \times 100\%$$

$$= 118.19\ \%$$

Similar calculation for other particle sizes,

	Particle size	%Excess air
Size -1	25mm×25mm×25mm	118.19
Size -2	38mm×38mm×38mm	150.84
Size – 3	50mm×50mm×50mm	204.20
Size - 4	63mm×63mm×63mm	422.22

Table 4-2 : Excess air with particle sizes

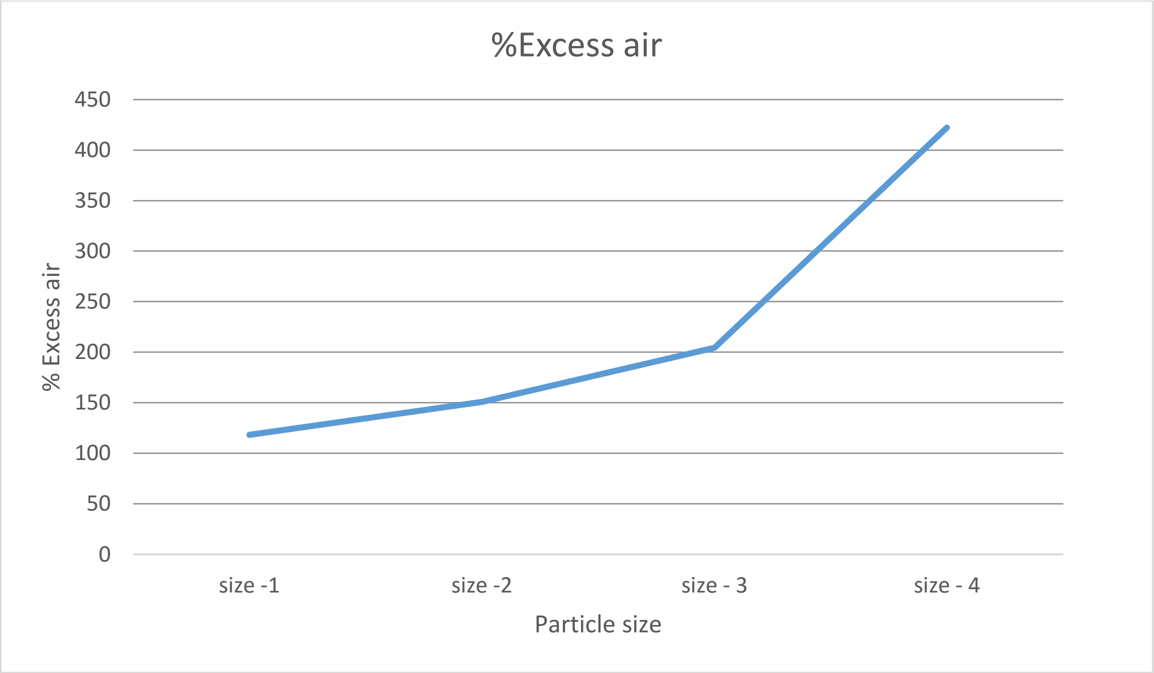


Figure 4-12 : Excess air vs particle sizes

The particle size covered in the calculations ranges from 25mm to 63 mm. Figure 4-10, shows the burning rate as a function of particle sizes. Generally, larger particle size results in a lower burning rate. For instance, 25 mm particles have a burning rate of 3.042 g/s at a primary air velocity, which is 2.4 times of the burning rate with 63 mm particles at the same primary air velocity.

Figure 4-11, shows the actual combustion stoichiometry as a function of particle size. Generally, larger-size particles result in a higher air-to-fuel stoichiometric ratio or less fuel-rich combustion. For instance, 25 mm particles have an air-to-fuel stoichiometric ratio of 9.513 at primary air velocity compared to the ratio being 22.769 with 63 mm particles at the same conditions.

Figure 4-12 shows the percentage of excess air as a function of particle size. Generally, larger size particles result in a higher excess air percentage. For instance, the 25 mm particles have an excess air of 118.19 at primary air velocity, which is 3.57 times of excess air percentage with 63 mm particles at the same condition. Excess air is not a linear function of the air flow rate, due to its effect on the burning rate.

4.5 Flue gas composition

Figure 4-13 shows the gas composition in the flue gases out of the bed top as a function of time for the for a smallest size rubber wood chips. Initially (at t = 14 min) O2 concentration level is less with compared to initial CO2 concentration and CO concentration was lower. Further on at about 10 min (t = 24 min) measured CO2, O2 and CO concentrations, here CO2 concentration was reduced while O2 concentration was increased. And but CO concentration level changed was not visible. At about 30 min, CO2 concentration was dropped further and O2 concentration was remaining same value. For the all period CO concentration was lower during major steady-state burning period.

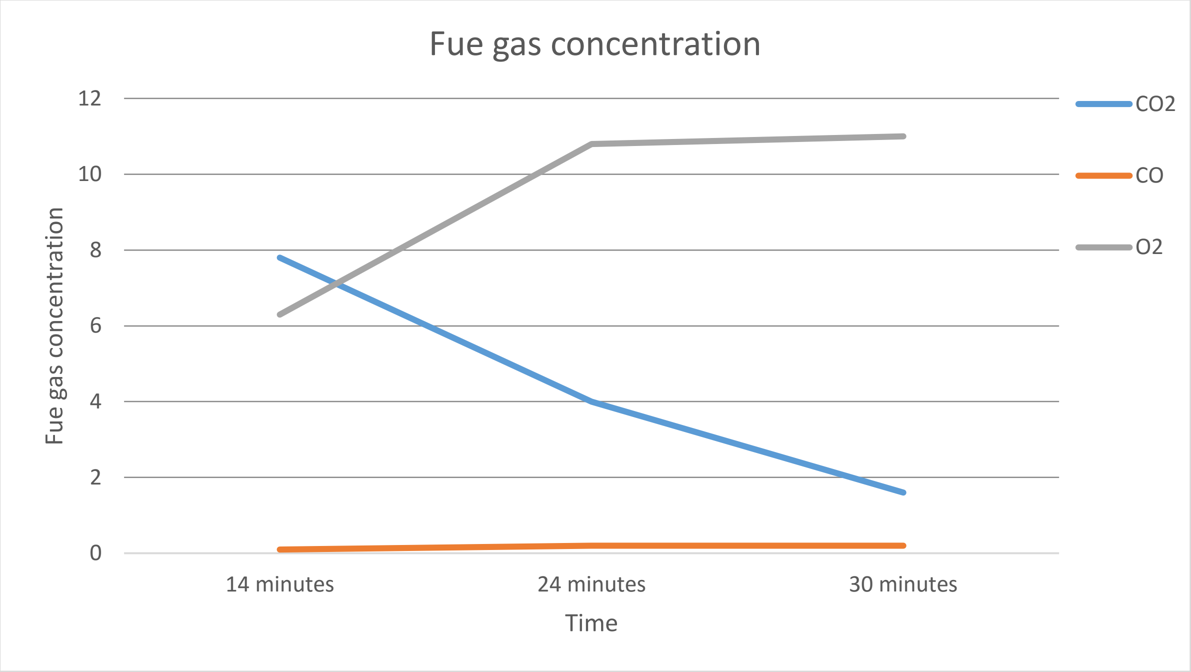


Figure 4-13 : Gas composition in the flue gases out of the bed top as a function of time.

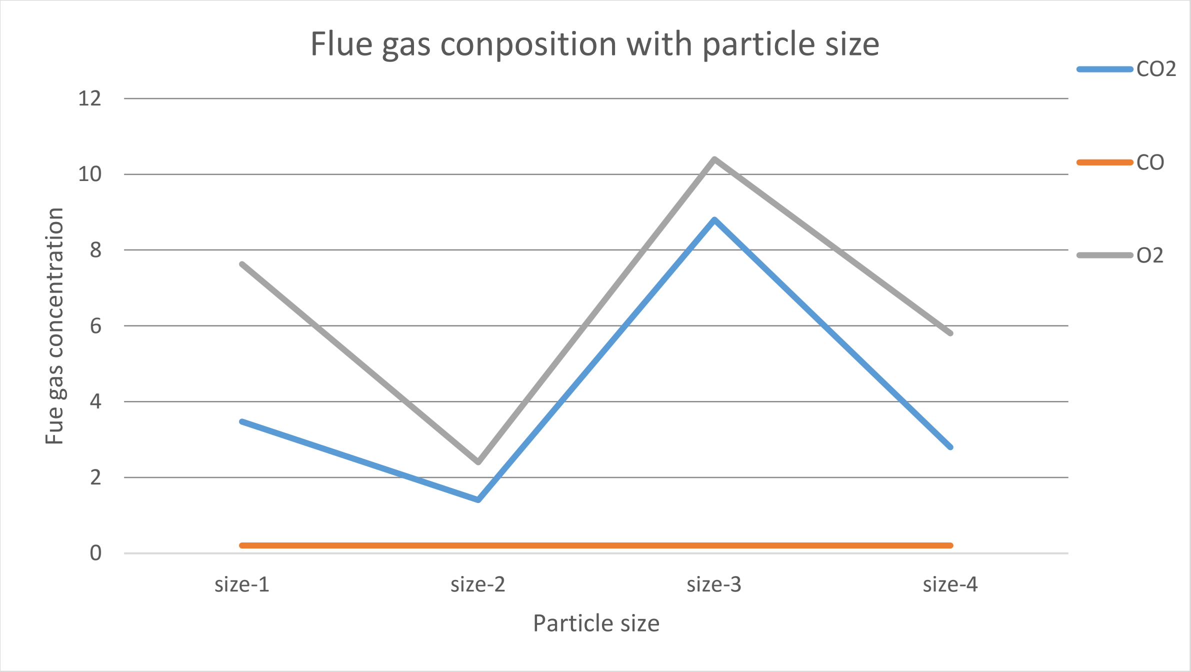


Figure 4-14 : Flue gas concentration vs particle sizes

Figure 4-14 shows, the flue gas concentration variation with particle sizes. Gas sample measured randomly. Here CO concentration has a very small amount for the all particle sizes while O2 concentration is higher than CO2 and CO concentration. Then, there has excess air during the combustion process for all particle sizes.

5 Conclusion

From the experimental work carried out to investigate the effect of particle sizes on packed bed biomass combustion, In general the following conclusions can be drawn from the current study in terms of the fuel size effect:

- Ignition time is high with a bed of larger particles than with smaller particles at the same operating condition.
- Burning rate decreases with increase in fuel size particles.
- Larger fuel particles produced a higher burning temperature in the bed;
- Small particles presented a uniform flame propagation speed during most part of the combustion process while large particles showed a more transient feature where the burning rate changes for the most part of the combustion process;
- As the particle size increased, the biomass consumption rate decreased and the actual air/fuel equivalence ration increased, while the amount of excess air increased with increasing particle sizes.
- The effective excess air has to be recognized as one of the main design variables for the appliance to control both pollutant emission and performances, independently from the total air flow fed.
- The nominal excess air fed to the appliance during combustion must be controlled and possibly reduced with increasing particle size.

5.1 Future Work

Based on the experiments carried out for this study and the observations made from the results obtained, the following suggestions have been reached to further improve this future research into this study:

- For the experiments carried out, the wall of the fixed bed should be insulated. This is to reduce the heat lost to the surrounding which in turn affects the results.
- Also, the bed height should be increased to get the complete combustion of biomass due to this reactor bed height is not sufficient to complete combustion.
- Further study of this work can be carried out with changing inlet air flow rate. And with using the different type of biomass material.
- Also changing biomass type and biomass particle shape can be carried out this work.
- Further, the experiment should be carried out with non-uniform particle shapes and size.

References

1. Biswas A. Effect of chemical and physical properties on combustion of biomass particle [PhD Thesis]. Lule\a a tekniska universitet; 2015.
2. Parikka M. Global biomass fuel resources. Biomass and Bioenergy. 2004;27(6):613–20.
3. Input IEA, Ministerial CE. Tracking Clean Energy Progress 2013 Tracking Clean Energy Progress 2013. 2013;
4. Vakkilainen E, Kuparinen K, Heinimö J. Large Industrial Users of Energy Biomass. 2013;75.
5. Lanka SRI, Sector E, Plan D, Knowledge-based FORA. Ministry of power & Energy.
6. Mckendry P. Energy production from biomass (part 1): overview of biomass. 2002;83(July 2001):37–46.
7. Klason T. Modelling of Biomass Combustion in Furnaces. Ph.D. dissertation, Division of Fluid Mechanics, Department of Energy Science, Lund Institute of Technology, Media Tryck AB; 2006.
8. Plant B. Biomass Drying for an Integrated Bioenergy Plant. 2015;847–60.
9. Kumar A, Jones DD, Hanna MA. Thermochemical Biomass Gasification: A Review of the Current Status of the Technology. 2009;556–81.
10. Office RE, Information T, Ridge O. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a BIllion - Ton Annual Supply. 2005;
11. Ageneal. Energias renováveis [Internet]. 2006. Available from: http://www.ageneal.pt/content01.asp?BTreeID=00/01&treeID=00/01&newsID=8
12. Biomass Processing Technologies - Google Books.
13. Prabir Basu. Biomass gasification and pyrolysis. Vol. 5, Comprehensive Renewable Energy. 2012. 133-153 p.
14. McKendry P. Energy production from biomass (part 2): Conversion technologies. Bioresour Technol. 2002;83(1):47–54.

15. Vassilev S V., Baxter D, Andersen LK, Vassileva CG. An overview of the chemical composition of biomass. Fuel [Internet]. 2010;89(5):913–33. Available from: http://dx.doi.org/10.1016/j.fuel.2009.10.022

16. Wurzenberger JC, Wallner S, Raupenstrauch H, Graz A-, Khinast JG. Thermal Conversion of Biomass : Comprehensive Reactor and Particle Modeling. 2002;48(10).

17. Roddy DJ, Manson-Whitton C. Biomass gasification and pyrolysis. Vol. 5, Comprehensive Renewable Energy. 2012. 133-153 p.

18. I Tracking Clean Energy Progress 2013,IEA Input to the Clean Energy Ministerial. 2013.

19. Luo Z, Zhou J, Key S, Utilization CE. Handbook of Climate Change Mitigation. Chen W-Y, Seiner J, Suzuki T, Lackner M, editors. New York, NY: Springer US; 2012.

20. Gómez MA, Porteiro J, Patiño D, Míguez JL. CFD modelling of thermal conversion and packed bed compaction in biomass combustion. 2014;117:716–32.

21. Thunman H, Leckner B. Influence of size and density of fuel on combustion in a packed bed. Proc Combust Inst [Internet]. 2005;30(2):2939–46. Available from: http://dx.doi.org/10.1016/j.proci.2004.07.010

22. Duffy N. Investigation of Biomass Combustion in Grate Furnaces using CFD. 020301_CombustionBiomass. 2012;(December).

23. Engineering P. CFD Simulation of the Thermal Conversion of Solid Biomass in Packed Bed Furnaces by Ramin Mehrabian Bardar. 2013;(November).

24. ENERGY_EMPOWERED_NATION_2015_2025.pdf.

25. Azlina W, Abdul W, Ghani K, Mohd A, Bachmann RT, Taufiq-yap YH, et al. Biochar production from waste rubber-wood-sawdust and its potential use in C sequestration : Chemical and physical characterization. Ind Crop Prod [Internet]. 2013;44:18–24. Available from: http://dx.doi.org/10.1016/j.indcrop.2012.10.017

Appendix

Mass loss readings

Time	25×25×25	38×38×38	50×50×50	63×63×63
0	3.905	4.005	3.79	3.6
2	3.825	3.985	3.77	3.6
4	3.715	3.95	3.74	3.6
6	3.56	3.815	3.72	3.58
8	3.25	3.63	3.68	3.56
10	2.775	3.305	3.51	3.5
12	2.32	2.95	3.28	3.4
14	1.905	2.505	2.88	3.3
16	1.54	2.045	2.5	3
18	1.155	1.52	2.05	2.8
20	0.87	1.175	1.62	2.55
22	0.64	0.94	1.3	2.22
24	0.54	0.775	1.13	1.98
26	0.53	0.64	0.99	1.78
28	0.52	0.57	0.81	1.64
30	0.5	0.525	0.72	1.54
32	0.47	0.455	0.63	1.46
34	0.445	0.445	0.55	1.36
36	0.415	0.415	0.52	1.26
38	0.38	0.4	0.51	1.16
40	0.38	0.4	0.49	1.08
42		0.4	0.48	1.02
44			0.48	0.96
46			0.47	0.92
48			0.46	0.9
50			0.455	0.88
52			0.455	0.86
54			0.44	0.82
56				0.78
58				0.78
60				0.76
62				0.74
64				0.74
66				0.72
68				0.72
70				0.7

Biomass bed Shrinkage readings

Time	25×25×25	38×38×38	50×50×50	63×63×63
0	22.5	20	20	22.5
2	22.5	20	20	22.5
4	22.2	20	20	22.5
6	22	17.8	20	22.5
8	20.1	15	19.2	22.5
10	16.9	15	19.2	22.5
12	10.4	14.5	18.5	22.5
14	9	14.5	18.5	22.3
16	6.5	10.5	18.1	21
18	5.5	9.8	17.6	19.7
20	5	8	16.9	19
22	2	7.5	15.4	17.7
24	1.5	7.5	9.3	16
26	1.2	6.5	8	14.7
28	1.2	4	7.7	13
30	0.4	3.5	7.5	12.3
32	0.4	3.5	7.3	9.3
34	0.4	3.5	7.3	9
36	0.4	1.9	6.5	6.2
38	0.4	0.8	6	3.5
40	0.4	0.8	3.9	3.5
42		0.8	3	3
44			2.7	2.5
46			2.7	2.5
48			2.5	2.5
50			0.9	2.2
52			0.9	1.5
54			0.5	0.7
56				0.6
58				0.6
60				0.6
62				0.6
64				0.5
66				0.5
68				0.5
70				0.5

Flue gas Temperature.

	25×25×25	38×38×38	50×50×50	63×63×63
0	25	27	27	27.5
2	266	147.5	100	45
4	459	335	256	71
6	635	402.5	378	246.5
8	636	531.5	464	401.5
10	640	637	615	535
12	643	682.5	672	615.5
14	578	627	655	654.5
16	526	569.5	708	671.5
18	494	519	663	681
20	464	494.5	646	685.5
22	422	405	627	701
24	379	364.5	583	712.5
26	342	335.5	531	714
28	300	301	499	676.5
30	270	279.5	453	648.5
32	243	261.5	377	630
34	217	248.5	330	588
36	186	234	288	554.5
38	163	218.5	265	520
40	131	206	253	486
42		186	244	459.5
44			230	437
46			218	378.5
48			205	378
50			198	368.5
52			182	349
54			165	333
56				307
58				277
60				259
62				242.5
64				226.5
66				210.5
68				201
70				189

Solid surface temperature

	25×25×25	38×38×38	50×50×50	63×63×63
0	29	29	26	26
2	105	117.5	103.5	47.5
4	158.5	226.5	241.5	121.5
6	262	408	330	158
8	445	517.5	412	171.5
10	552.5	573	576	260
12	644.5	613	626	361.5
14	663.5	692.5	683.5	410
16	646	653	698.5	453
18	611.5	552.5	683	516.5
20	573.5	507.5	612.5	592
22	511	453.5	570.5	624.5
24	472	427.5	550.5	687.5
26	411.5	383.5	477	699.5
28	367.5	339.5	401.5	654
30	328.5	313.5	345	636.5
32	299	291	317	624
34	249	271	293.5	623.5
36	220.5	254	285	616
38	175.5	235	269	603.5
40	134	216	251.5	567
42		201.5	232.5	521
44			215	491.5
46			209	474.5
48			204	450
50			198	420.5
52			187	403
54			162	378.5
56				346.5
58				307
60				274.5
62				250
64				250.5
66				246.5
68				243
70				228

Grate temperature

	25×25×25	38×38×38	50×50×50	63×63×63
0	27	27	25	25.5
2	31	32	45	54.5
4	36.5	39	83	98
6	58	123	120	139.5
8	155	410.5	397	256
10	205	384	450	471.5
12	269.5	449	536	603
14	358.5	580.5	553	653.5
16	457	638.5	589	746
18	499.5	651	612	788.5
20	510	676	639	831
22	608	691	678	769
24	641.5	662.5	738	748.5
26	630	619.5	732	708
28	598	576.5	691	745.5
30	525.5	505	658	795.5
32	508	460.5	656	669
34	479	410	628	679
36	477.5	366.5	597	699
38	449	328.5	568	700
40	404.5	290.5	525	695.5
42		276	489	677.5
44			343	629.5
46			321.5	616.5
48			312.5	591
50			308	572
52			298	506
54			285.5	480
56				466
58				428.5
60				391
62				376.5
64				367.5
66				357.5
68				359.5
70				333

Temperature varies for particle 25mm×25mm×25mm

	FG	SGS	G
0	25	29	27
2	266	105	31
4	459	158.5	36.5
6	635	262	58
8	636	445	155
10	640	552.5	205
12	643	644.5	269.5
14	578	663.5	358.5
16	526	646	457
18	494	611.5	610
20	464	573.5	700
22	422	511	685
24	379	472	610
26	342	411.5	544
28	300	367.5	488
30	270	328.5	452
32	243	299	414
34	217	249	359
36	186	220.5	308
38	163	175.5	261
40	131	134	227

Temperature varies for particle 38mm×38mm×38mm

	FG	SGS	G
0	27	29	27
2	147.5	117.5	32
4	335	226.5	39
6	402.5	408	123
8	531.5	517.5	410.5
10	637	573	384
12	682.5	613	449
14	627	692.5	580.5
16	569.5	653	638.5
18	519	552.5	651
20	494.5	507.5	676
22	405	453.5	691
24	364.5	427.5	662.5
26	335.5	383.5	619.5
28	301	339.5	576.5
30	279.5	313.5	505
32	261.5	291	460.5
34	248.5	271	410
36	234	254	366.5
38	218.5	235	328.5
40	206	216	290.5
42	186	201.5	276

Temperature varies for particle 50mm×50mm×50mm

	FG	SGS	FG2
0	27	26	25
2	100	103.5	45
4	256	241.5	83
6	378	330	120
8	464	412	397
10	615	576	450
12	672	626	536
14	655	683.5	553
16	708	698.5	589
18	663	683	612
20	646	612.5	639
22	627	570.5	678
24	583	550.5	738
26	531	477	732
28	499	401.5	691
30	453	345	658
32	377	317	656
34	330	293.5	628
36	288	285	597
38	265	269	568
40	253	251.5	525
42	244	232.5	489
44	230	215	343
46	218	209	321.5
48	205	204	312.5
50	198	198	308
52	182	187	298
54	165	162	285.5

Temperature varies for particle 63mm×63mm×63mm

	FG	SGS	G
0	27.5	26	25.5
2	45	47.5	54.5
4	71	121.5	98
6	246.5	158	139.5
8	401.5	171.5	256
10	535	260	471.5
12	615.5	361.5	603
14	654.5	410	653.5
16	671.5	453	746
18	681	516.5	788.5
20	685.5	592	831
22	701	624.5	769
24	712.5	687.5	748.5
26	714	699.5	708
28	676.5	654	745.5
30	648.5	636.5	795.5
32	630	624	669
34	588	623.5	679
36	554.5	616	699
38	520	603.5	700
40	486	567	695.5
42	459.5	521	677.5
44	437	491.5	629.5
46	378.5	474.5	616.5
48	378	450	591
50	368.5	420.5	572
52	349	403	506
54	333	378.5	480
56	307	346.5	466
58	277	307	428.5
60	259	274.5	391
62	242.5	250	376.5
64	226.5	250.5	367.5
66	210.5	246.5	357.5
68	201	243	359.5
70	189	228	333