



**ADDIS ABABA UNIVERSITY**

**ADDIS ABABA INSTITUTE OF TECHNOLOGY**

**SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING**

**Design, manufacturing and testing of pyrolysis system  
for biochar Production from Water Hyacinth (“Emboch”)**

A thesis submitted to Addis Ababa University Institute of Technology School of  
Mechanical and Industrial Engineering in partial fulfilment of the requirements  
for the Degree of Masters of Science in Thermal Engineering

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**Advisor: Dr. Ing. Wondwossen Bogale**

Addis Ababa, Ethiopia

June 2020

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## Declaration

I, the undersigned, declare that this thesis entitled “Design, manufacturing and testing of pyrolysis system for biochar Production from Water Hyacinth (“Emboch”)” is my original work under School of Mechanical and Industrial Engineering, AAiT, and has not been submitted by any other person for an award of a degree in this or any other University, and that all resources of materials used for this thesis have been duly acknowledged and a list of references is given.

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## Lists of acronym, symbols, units and abbreviations

$\rho$	Density
$C_p$	Specific heat of water hyacinth biomass
$m_{in}$	Mass input
$m_{out}$	Mass output
$\Delta m_{CV}$	Change of mass in control volume
$m_{WH}$	Mass of water hyacinth
$m_g$	Mass of gas
$m_{BC}$	Mass biochar
$m_{air}$	Mass of air
$m_{wood}$	Mass of wood
$m_{BM}$	Mass of biomass
Nu	Nusselt number
k	heat conduction of reactor material
$L_{react}$	Length of the reactor
$h_c$	Convection heat transfer coefficient
$A_s$	Heat transfer surface area
$T_s$	Temperature of the surface
$T_\infty$	Temperature of the water hyacinth biomass sufficiently far from the surface
$v_b$	Speed of belt
$\mu$	Coefficient of friction between the belt and the pulley
$T_1$	Tensions in the tight side of belt
$T_2$	Tensions in slack side of the belt
$\theta$	Angle of lap of the belt.
$\theta_1$	Angle of contact on smaller pulley

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$\theta_2$	Angle of contact on larger pulley
W	watt
kg	kilogram
MJ	mega joule
°C	degree Celsius
$r_1$	Radius of smaller pulley
$r_2$	Radius of smaller pulley
$r_i$	Inner Radius of reactor
$r_o$	Outer Radius of reactor
g	Acceleration due to gravity
$M_{max}$	Maximum bending moment
$L_s$	Length of shaft
$\beta$	Angle of groove
$Re$	Reynolds number
$R_{Tot}$	Overall thermal resistance
$E_{gen}$	Energy generate
$\dot{Q}_{loss}$	Overall heat loss rate
$\dot{Q}_{py}$	Pyrolysis energy rate
$Q_{gain}$	Energy gain by reactor
$\dot{Q}_{saved}$	Heat rate saved
$H_{wh}$	Water hyacinth enthalpy
HHV	high heating value
LHV	low heating value
WHB	water hyacinth biochar
WHM	water hyacinth biomass

## **Acknowledgement**

First and foremost, I would like to thank my advisor Dr.Ing Wondwossen Bogale, for giving me the opportunity to conduct this research work under his supervision. His excellent guidance, follow-up and advice throughout all phases of my research activities motivated me in my efforts. Under his guidance, I have gained a great deal of technical knowledge as well as the completion of this work became true.

I also express my deep appreciation to individuals and organization that helped me through my work, to Addis Ababa University Chemistry Department and Geological Survey of Ethiopia for their crucial help during laboratory test on biomass and biochar of water hyacinth characterization

My special thanks are extended to all Addis Ababa Institute of Technology Workshop workers for their technical support.

Finally, special thanks to all my friends who have supported and encouraged me.

## Abstract

Aquatic biodiversity of Lake Tana, that is the largest lake in Ethiopia, is at extreme risk due to the aggressive water hyacinth, locally named as Emboch. It causes a health risk on animal in the lake and decline the economic activities of the lake. Because of this problem huge amount of water hyacinth has been removed from the water surface and thrown to the landfill without considering for other uses. Finding innovative technology to produce biochar from water hyacinth is very crucial to save the lake. The main objective of this paper is to design, manufacture and test pyrolysis system to produce biochar from water hyacinth.

The overall methods used for this research is described as follows. Water hyacinth biomass collected and prepared; three dimensions of screw reactor is modelled by solid work 2018 software and continuous screw reactor has been manufactured and tested to produce biochar from water hyacinth. The biochar produced from water hyacinth feedstock. The experiment was conducted using the pyrolysis temperature reached 500°C screw reactor. Characterization of water hyacinth biomass and its biochar has been done by proximate and ultimate analysis. Also the energy content has been measured by bomb calorimeter.

Based on experimental result, the conversion efficiency of biochar produced from stem and leaves is 68 % and 65.71 % respectively. The energy yield of leaves and stems of biochar are 70.05 % and 72.35 % respectively and approximately 656 kg of biochar can be generate daily. Optimum temperature has a significant effect on the produced biochar. From the result of test were pyrolysis temperature is increased the biochar yield is decreased.

Based on the result, the volatile matter of produced biochar from water hyacinth decreases by 40.87% and the moisture content of the produced biochar from water hyacinth decreases by 37.94% with respective to the feedstock while fixed carbon of produced biochar from water hyacinth increases by 59.381% with respective to the water hyacinth biomass. The measured lower heating values of the produced biochar is 15.39MJ/kg while the lower heating values of water hyacinth biomass is 14.425MJ/kg. Based on the experiment results, biochar produced from water hyacinth higher energy content than the water hyacinth feedstock. This, producing biochar from water hyacinth have a significant benefit by solving aquatic biodiversity problem, reducing environmental impacts of water hyacinth, used for charcoal or soil improvement.

Keywords

Biochar, water hyacinth, Emboch, moisture content, pyrolysis, continuous screw reactor

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## Chapter One

### 1. Introduction

#### 1.1. Background

Water hyacinth (*Eichhornia crassipes*), locally known as 'Enboch', is an invasive aquatic weed plant with broad, thick, glossy, ovate leaves and breeds very quickly [1]. The weed adversely affects the environment, such as river blockages, biodiversity loss and fish endangerment due to depletion of the amount of dissolved oxygen in the water [2]. It can bring highly ecological danger for bodies of water, lakes, irrigation structures, etc. Besides, the presence of Water hyacinth on water surfaces increases the evapotranspiration rate and it serves as a channel for greenhouse gas emissions from water bodies [3]. Water hyacinth floats in water due to presence of large air cavities in the parenchyma tissue called Aerenchym. Thus, it covers a large area of water surface, reduce underwater light intensity and hinder air exchange at the water-air interface, thus negatively affecting water ecosystem [4].

Lake Tana is one of Africa's most unique aquatic ecosystems and the source of 50 % of Ethiopia's freshwater. Since June 2015, Lake Tana designated as a World Heritage site by UNESCO for its unique ecological biosphere reserve. The weed is introduced to the lake in 2011 and now covers about 40 thousand hectares and Water hyacinth in Lake Tana is destroying the fishery industry, destroying maize, cereal crops , making cattle sick and creating serious environmental imbalance [5].

Since Water hyacinth is extremely difficult to eradicate once established, most management efforts is to minimize economic costs and ecological change [6]. Developed countries like the United States with such large scale weed infestation mainly use environmentally-friendly chemicals [7]. The control method depends on extent of water hyacinth infestation, regional climate, and proximity to human and wildlife [8]. Hand removal, Mechanical shredding and Biological control are widely used to remove Water hyacinth [9]. In Lake Tana, modern water hyacinth harvester (Aquatic Weed Harvester) introduced in 2018 [10] and before the introduction of the machine, removal of the weed of Lake Tana was carried out manually by the community by engaging farmers living in the Kebeles surrounding the Lake [11]. Even though there are several initiatives including harvester run by Amaga Private Limited Company, the report by charitable organization for Integrated Tana Basin development on Evaluation of Water Hyacinth Harvester in Lake Tana concluded that there is still a lot of issues to be solved to permantly remove Water Hyacinthn problem in Lake Tana. However, finding

effective solution for water hyacinth control are environmentally friend, economical, efficiently is a very difficult task in lake and river. This is due to the fact that huge amount of water hyacinth removed from the water surface to throw on the landfill. It cannot be used directly as fertilizer and has no known direct food value to wildlife. Therefore, water hyacinth waste on land will generate large amounts of organic matter. This will pose serious environmental hazard.

Biochar is defined as carbon-rich product obtained when biomass is heated in a closed container with little or no available air through a process called pyrolysis [12]. One of the priority issues while producing Biochar from Water Hyacinth using pyrolysis is to improve the conversion efficiency of the system, used for sustainable waste management and used for so long since it mitigate climate change [13]. There are different method to produce biochar including pyrolysis, gasification, hydrothermal and carbonation [14]. From those method, pyrolysis is the most adopted method to produce biochar from water hyacinth biomass. Pyrolysis, a thermal conversion process, is indisputably one of the most promising technologies for production of solid residue (biochar), liquid product (bio-oil) and gaseous mixture (syngas) [15].

In this paper, a detailed analysis has been done to improve the efficiency of the Biochar conversion system. The pyrolysis unit has been design, manufactured and tested. Water hyacinth is continuously fed from feed hopper into cyclone by help of screw conveyor through inner reactor. The sample water hyacinth input to inner reactor is heated indirectly by heat transfer from combustion chamber to inner reactor to produce biochar. Proximate and Ultimate analysis and heating value of the water hyacinth (leaf and stem) and produced Biochar both from the leaf and the stem has been determined by standard procedure in laboratories. Sensitivity analysis to see the effect of temperature on Biochar Production and effect of insulation has been done in detail. Thus, the water hyacinth has been converted into an opportunity, besides reduced water hyacinth waste on water surface and reduce environmental impact.

## **1.2. Problem statement**

Lake Tana is affected by the growth of water hyacinth is the main problem in Ethiopia, because 50% of the country's fresh water is Lake Tana. The water hyacinth is now estimated cover 50000 hectares of the lake. Also it causes a health risk on the people and decline the economic activities of the lake. Because of this problem huge amount of water hyacinth removed from the water surface and throw to the landfill without considering for other uses. It has no known

direct food value to wildlife and it cannot be used directly as fertilizer. Generally, it generates large amounts of organic matter which posed serious environmental hazard. However finding effective solution for water hyacinth control are economical, efficient and environmentally friendly is a very difficult task.

Therefore, in this research the efficient and cost effective technology to produce biochar from water hyacinth for solving ecological and economic problems facing the Lake Tana ecosystem will be proposed. The biochar will be used for various purposes like cooking and soil amendment purpose. Thus, the water hyacinth is will be converted into an opportunity.



Figure 1-1.Lake Tana Effected by Water Hyacinth (“Emboch”)

### **1.3. Objective**

#### **1.3.1. Main objective**

The main objective of this research is to design, manufacture and test of pyrolysis system for biochar production from water hyacinth (“Emboch”)

#### **1.3.2. Specific objective**

- i. To design, manufacture and test using water hyacinth biomass
- ii. To analyses the mass and energy balance of the pyrolysis system
- iii. To characterize the properties of water hyacinth leaf and stem and its biochar
- iv. To study Effects of Temperature, moisture, and Insulation on biochar production

#### **1.4. Scope of study**

The main objective of the research is to design, manufacture and test of pyrolysis system using Water Hyacinth (“Emboch”). Analyze the energy utilization of the pyrolysis system and characterize the properties of water hyacinth leaf and stem and its biochar. However environmental impact assessment and densification of produced biochar were not included in this research.

#### **1.5. Limitation of Study**

Fresh water hyacinth is collected from Lake Tana in Amhara regional state approximately 563km long distance from Addis Ababa, Ethiopia, due to this long distance the water hyacinth transportation cost was high and the dried time of water hyacinth was taken long days because of moisture content of this water hyacinth was high. Also characterize water hyacinth and biochar is take long time due to experimental setup is not available in university.

#### **1.6. Thesis Organization**

This study deals with design, manufacture and test of pyrolysis system using water hyacinth (“Emboch”). It has eight chapter which starts with chapter one describing the introduction of research work followed by the significance of study under background, problem statement, objectives and important pyrolysis process parameters. Chapter two discusses existing literatures on previous work on biochar production processes, Mode of operation and parameters effecting on biochar production. Chapter three presents methodology such as method and materials used for biochar production. Chapter four tells pyrolysis reactor experimental setup including design, modelling and manufacturing screw reactor for continuous biochar production. Chapter five study experimental analysis under preparation and characterization of water hyacinth and biochar. Under Chapter six presents analyses mass and energy balance in the screw reactor. Chapter seven discusses the results and discussions and chapter eight presents conclusion and recommendation of this research.

## Chapter Two

### 2. Literature Review

#### 2.1. Introduction

Biochar is defined as carbon-rich product obtained when biomass is heated in a closed container with little or no available air through a process called pyrolysis [16]. It has been used for sustainable waste management and used for so long since it mitigate climate change [13]. The Application of biochar has attracted increased attention because of the potential of this material in global warming mitigation, soil fertility improvement, pollution remediation and agricultural waste recycling [14].

#### 2.2. Literature review on topics

Bogale (2017) study shows that, to recover energy from flower waste by novel technology with the objective of producing biochar from flower waste by using pyrolysis process. He has produced 10 kg of biochar from 18 kg of flower waste with 55.5% conversion efficiency and approximately 310.8kg of biochar generated daily. Based on this result, the measured value of lower heating value is 26.54 MJ/kg and approximately 392.2kg of firewood is replaced daily. His conclusion show that by adopting this technology and producing biochar, energy is recovered from flower waste, the energy problems of the society is solved and environmental impact of the flower waste is reduced [9].

Cornette, et al, (2018) study showed that biochar were produced from water hyacinth at three pyrolysis temperature (300, 450 and 500°C) and their properties characterized. The general objective of this study is to assess the suitability of water hyacinth (*Eichornia crassipes*) biochar as a soil amendment. Laboratory experiments were conducted to investigate how the physicochemical properties of the biomass change due to thermal processing. Increasing the pyrolysis temperature transformed the biomass matrices into a lighter and porous structure causing a decrease in density. There is significant difference in the ash content, volatile matter and fixed carbon obtained from the pyrolysis temperatures ( $p \leq 0.05$ ).

Ash content and fixed carbon content increased while volatile matter decreased with pyrolysis temperature indicating a higher concentration of organic matter available for carbon sequestration at higher pyrolytic temperatures. Further, the presents of micro-nutrients and high pH makes biochar from these water hyacinth samples suitable as a liming agent and a soil amendment for vegetables, legumes and grains in open-field or shaded conditions. Also, the

biochar is recommended as a fertilization and soil improvement additive to aid the expansion of Guyana's agricultural production into its Hilly Sand and Clay region [17].

R. Ebhin Masto, et al (2013) studies shows that, the waste eichornia weed could be gainfully utilized as a soil quality amendment material by converting it to biochar. They indicated that stability of biochar carbon increased while biochar yield decreased with increase of pyrolysis temperature. The optimum condition for obtaining maximum stable carbon in water hyacinth is 300-350°C with 30-40 min residence time. Impact of the EBC on soil quality was studied using a red soil, from Dhanbad, India. Soil biochemical properties (dehydrogenase, fluorescein hydrolases, catalase, respiration, active microbial biomass) and maize seedling growth were used to investigate the effects of biochar addition to the soil. Maize seedling vigour index increased from 1.0 at control to 1.61 in 20 g/kg EBC treatment. Active microbial biomass carbon increased by 3.0 times, and soil respiration by 1.9 times due to biochar application. Their conclusion shows that the conversion of water hyacinth to biochar could be a sustainable option for gainful use of this weed [3].

Li Feng et al. (2016) studies shows that investigate the preparation and characterization of biochar from water hyacinth at 300°C to 700°C for cadmium (Cd) removal from aqueous solutions by adsorption processes. According to the results of the elemental and Fourier transform infrared spectroscopy analyses, the adsorption of Cd onto the biochar was dominated by oxygen-containing functional groups via esterification reactions. The X-ray diffraction results indicated that the mineral components contributed to absorbing Cd through precipitation or co-precipitation. The maximum adsorption capacities based on the Langmuir isotherm method 49.837,36899 and 25.826 mg/g and the adsorption processes of the biochar followed the pseudo-second order kinetics, with the equilibrium achieved around 5h. Their conclusion shows that, biochar generate from water hyacinth is a promising adsorbent which is convert environmental problem to a new cleaning technology [18].

Shahabaldin rezania et al (2016) studied show that investigated the fuel properties of bio-briquettes made from a combination of water hyacinth and empty fruit bunch fiber (palm oil mill residue). They mixed water hyacinth with empty fruit bunch fibers in a ratio of 25, 50, 75 90 and 100% by weight and cassava starch added as binder. Their experiment results showed that the addition of water hyacinth had a little effect on the physical and combustion properties of the briquettes and the moisture content, ash content and fixed carbon content were increased with the increase in water hyacinth amount 25 to 100% while the volatile matter content and calorific value decreased. Also their combustion test showed that the increase in water hyacinth

percentage in bio-briquette resulted in the decreased of O<sub>2</sub> and CO level, whereas, that of CO<sub>2</sub>, NO, NO<sub>2</sub> and SO<sub>2</sub> were increased. Generally they conclude that the water hyacinth to empty fruit bunch biomass bio-briquette could be a great potential as an alternative source to conventional coal to minimize the emission of greenhouse gases [19].

Lili et al (2016) studied characterization of the properties of biochar produce from bamboo shoot shell. Their result show that biochar production from the bamboo shoot shell was performed as a function of temperature range from 300 to 500°C under nitrogen flow and the nitrogen content and pH value in biochar produce from bamboo shoot shell were first increased and then decreased with increasing of pyrolysis temperature. Biochar derived at 400°C had the best properties in terms of contents of C, H, O, N, P and K [20].

Frederik Ronsse et al (2013) studied show that to produce biochar from various feedstock biomasses by fixed-bed slow pyrolysis under a range of process conditions. Process conditions varied were the highest treatment temperature and residence time. The produced biochar were characterized by proximate analysis, CHN-elemental analysis, pH in solution, bomb calorimetry for higher heating value. In proximate analysis, it was found that the fixed carbon content in the biochar samples strongly depended on the intensity of the thermal treatment such as higher temperatures and longer residence times in the pyrolysis process. Their conclusion showed that HHV of the produced chars was largely consistent for any given feedstock material beyond a moderate pyrolysis treatment. HHV of the biochar trended towards a consistent limit for each feedstock with increasing pyrolysis intensity and as chars with low fixed carbon content had a larger amount of volatile, more easily biodegradable, carbon compounds [21].

Michael et al (2016) they investigated the impact of biochar on the anaerobic digestion of citrus peel waste. Batch type process has been used. They well established that the addition of black carbon, including Biochar, to contaminated soil and sediments can reduce the mobility and bioavailability of potential toxic chemicals. They found shows that the presence of biochar had two effects: a reduction in the length of the lag phase and greater production of the methane relative to citrus peel waste only incubations. The microbial lag phases decreased with increase in citrus peel to Biochar ratios [22].

### **2.3. Biochar production processes (techniques)**

There are different kind of processes can be used to convert biomass into energy. These processes are physical, thermo-chemical and bio-chemical (Figure 2.1). The physical processes use densification technique including crushing, heat and pressure applications for conversion

biomass into biofuels. The biochemical processes use enzymes and micro-organisms to convert biomass into desirable energy products and the thermo-chemical processes use heat energy and chemical catalysts for decomposition of biomass into high value energy products. This processes included direct combustion, pyrolysis and gasification. In the direct combustion of biomass, the primary product is the thermal energy which may be used as the energy source for the production of electricity, or for the combined heat and power production plants. Pyrolysis process is used for production of bio-fuels, chemicals and charcoal with electricity and combined heat and power generation using turbines, engines and boilers. The biomass gasification process is used for production of bio-fuels such as gasoline and electricity. The liquefaction process may be used for direct conversion of biomass into crude oil for generation of heat and power [23].

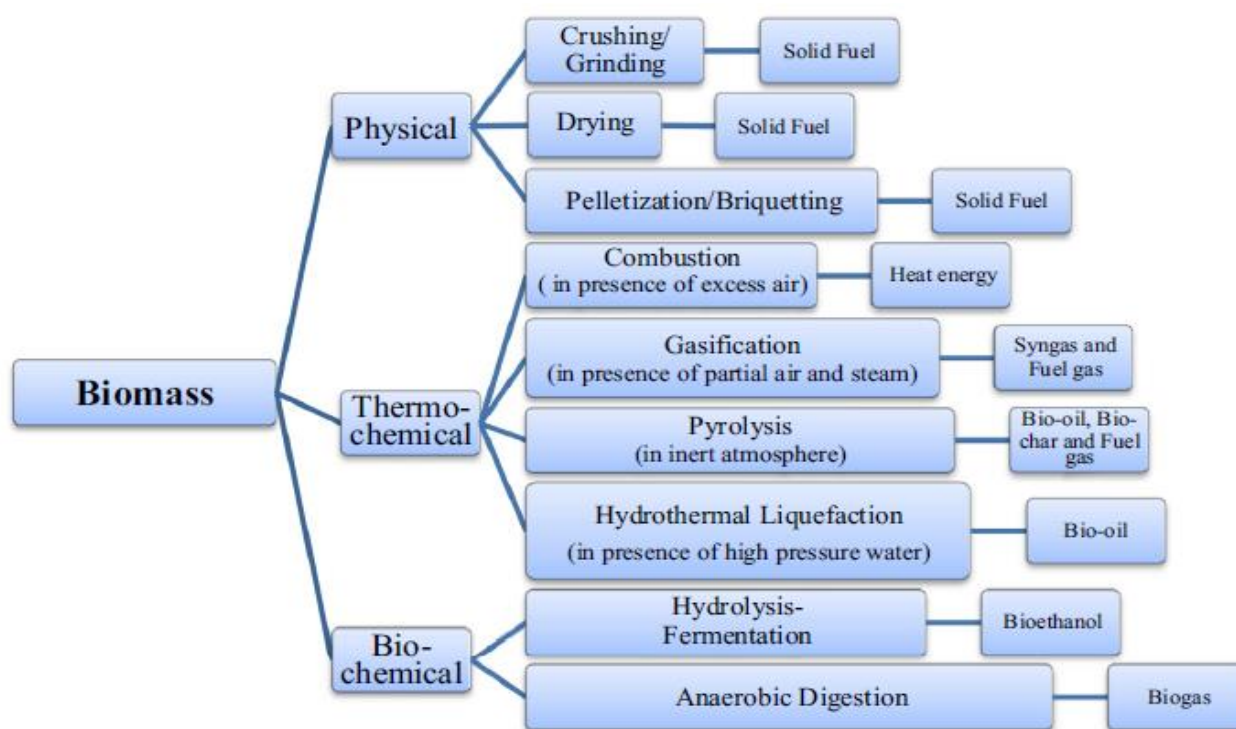


Figure 2-1. Flow Diagram for Biochar Production Process and the Biomass to Bioenergy Conversion Pathway [23]

Generally, major biomass conversion techniques can be divided into two groups namely biochemical conversion and thermochemical conversion. Biochemical conversion technology is less expensive and more environment friendly as compared to thermochemical conversion technique but the rate of hydrogen production and yield is quite low in bio-chemical conversion method. Because of this constraint, thermochemical conversion is more popular as compared to bio-chemical conversion [24].

### 2.3.1. Thermochemical conversion

In thermo-chemical conversion involves heat energy and chemical catalysts to produce energy from biomass. Production of thermal energy and synthesis of syngas into liquid transport fuels are examples of thermochemical conversion processes. The thermo-chemical decomposition of biomass can be carried out in number of ways such as Combustion, Gasification and Pyrolysis by varying the operating conditions such as residence time, heating rate and reactor configuration.

Table 2-1. Comparison of thermochemical techniques

Parameters	Combustion	Gasification	Pyrolysis
Temperature	800-1000	700-900	400-1200
Air Supply	Excess	Marginal	Nil
Pressure	0.1	0.1	0.1-0.5
Resource	Solid Biomass	Solid Biomass	Solid Biomass
Pretreatment	Not Required	Required	Required
Cost	Low	High	High
Harmful Emission	High	Low	Low
Products	Heat	Syngas, Bio-Oil and Char	Char, Bio-Oil and Syngas

#### 1. Combustion

Combustion is a process in which the chemical energy stored in the biomass is obtained in the form of heat by its direct burning in excess air. Combustion of biomass take place within high temperature recovering almost all the available chemical energy into thermal energy leaving noun converted energy in flue gas and very low unconverted energy in ash. It is feasible only if the moisture content in the biomass is less than 50%.

#### 2. Gasification

Gasification is a thermochemical partial oxidation process in which carbonaceous materials, such as biomass, coal and plastic are converted into gaseous fuel using gaseous medium like oxygen, air, carbon dioxide, and steam or gas mixture at high temperature. In a gasification process gaseous, liquid and solid formed because gasification aimed at producing gaseous products [15].

### 3. Pyrolysis

Pyrolysis is a thermochemical process in which biomass is thermally degraded in its chemical constituents under oxygen-free condition. Also it is a method of splitting a substance to new compounds by using heat in a low oxygen environment and one of the most effective and efficient process to gate energy in the form of solid, liquid and gaseous from biomass. It is the first stage of the thermal break down processes before the gasification stage and the full combustion stage. The common process in pyrolysis reactor are include slow and fast pyrolysis and the most successful approach for high yield biochar production is via slow pyrolysis. The condition, type and product type in pyrolysis as follow [25].

Table 2-2. Final products of biomass during pyrolysis and gasification process [25]

Pyrolysis Process	Condition	Bio-oil	Biochar	Syngas
Fast Pyrolysis	Moderate temperature (~500°C) Short vapor residence time (<2 s)	75%	12%	13%
Intermediate Pyrolysis	Low-moderate temperature Moderate hot vapor residence time	50%	25%	25%
Slow Pyrolysis	Low-moderate temperature Long residence time	30%	35%	35%
Gasification	High temperature (>800°C) Long vapor residence time	5%	10%	85%

#### 3.1 Fast pyrolysis

Fast pyrolysis is characterized by high heating rates and short vapor residence times. This generally requires a feedstock prepared as small particle sizes and a design that removes the vapors quickly from the presence of the hot solids. It is a used for the production of bio-oil as the oil product yield in fast pyrolysis dominates to the char and gaseous product yield. The main idea in fast pyrolysis is to take the biomass up to a temperature at which thermal cracking can take place as well as minimize the exposure time which favors the char formation. The high heating rate involved in the fast pyrolysis converts the input biomass to liquid product before it could react to form the undesired char [14]. There are different fast pyrolysis technologies used in this process including fluidized beds, rotating cone, ablative pyrolysis, circulating fluid bed and vacuum pyrolysis systems.

### 3.2. Slow pyrolysis

Slow pyrolysis is the conventional type of pyrolysis which is characterized by slow heating rate and long residence time. Slow pyrolysis favors the formation of char but liquid and gaseous products are also formed in a small quantity. In slow pyrolysis, lower heating rate and longer vapor residence time provides a suitable ambience and sufficient time for the secondary reactions to complete. Moreover, longer vapor residence time allows those vapors to be removed which are produced during the secondary reaction. To optimize the yield and quality of char, the following parameters are required:

- A reaction temperature in the region of 400-500°C for most biomasses
- A slow heating rate (1-50 °C/min) with large particle sizes typically <5cm and
- A long vapor residence time: 5-30 minutes biochar contact time to promote secondary reactions.

This ultimately results in the formation of solid carbonaceous biochar and any reactor that utilizes particles larger than 2mm in diameter is considered a slow pyrolysis reactor. Modified slow pyrolysis process is shown as follows [26].

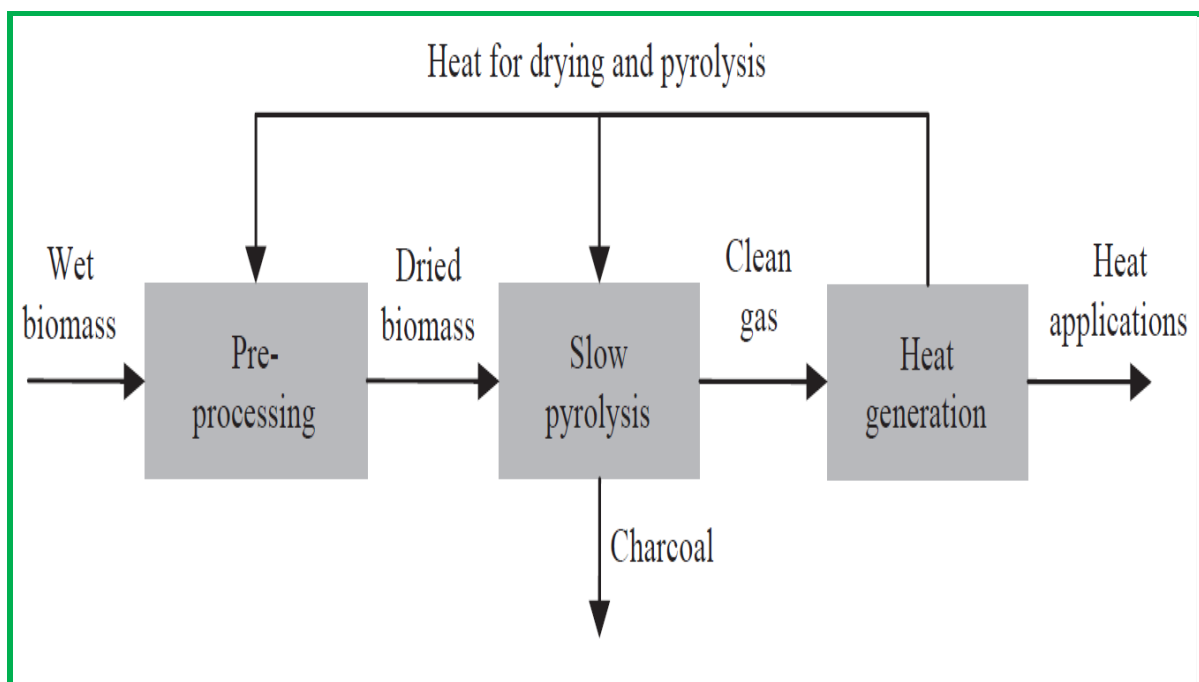


Figure 2-2. Process flow chart of slow pyrolysis

### 2.4. Mode of operation

Based on the mode of operation, pyrolysis reactors can be classified as batch, semi-batch and continuous

### 2.4.1. Batch operation

Batch-type kilns are the technology that was developed centuries ago to produce one of the first charcoal fuels. The production methods with different variations have mostly been used up until the present. The introduction of pyrolysis gas recirculation in the pyrolysis chamber, thus supplying the heat that is necessary for the pyrolysis process without using a part.

### 2.4.2. Semi continuous operation

The semi-batch operated system is portable and makes better use of hot ovens. Heat containing vapors are recycled between batch reactors. Some of these systems allow recovery of liquid products, but most are typically used to produce Biochar.

### 2.4.3. Continuous operation

Continuous operation reactors are designed to run nearly continuously with occasional down time for maintenance. Most continuous operation reactors are justified only if the flow rate is high. A typical continuous unit for the production of Biochar has a capacity over 2.75ton/hr. They are often more economical for large-scale production.

## 2.5. Literature on processes and parameters effecting biochar production

Table 2-3. Operation condition of different of pyrolysis process [24]

Condition	Slow	Fast	Flash	Intermediate	Vacuum	Hydro
Temperature (°C)	400-500	850-1250	900-1200	500-650	300-600	350-600
Heating Rate (°C/s)	0.1-1	10-200	>1000	1-10	0.1-1	10-300
Residence Time(s)	300-550	0.5-10	<1	0.5-20	0.001-1	>15
Pressure(Mpa)	0.1	0.1	0.1	0.1	0.01-0.02	5-20
Particle Size(mm)	5-50	<1	<0.5	1-5	–	–

Gao Ningbo et al (2011) Studied show that the continuous pyrolysis of pin sawdust was carried out in a screw reactor to investigate products, energy distribution and energy profit rate under the influence different pyrolysis temperature and solid residence time. CO was the dominating composition at pyrolysis temperature between 600 and 900°C with solid residence time ranging from 3 to 7 min. They concluded that biochar have lower volatile content and higher fixed carbon content when compared with the raw material. The maximum calorific value of biochar was attained at 600 °C with 7min, which indicated that longer solid residence time benefits

higher heat value bio-char production and the maximum yield of gas was obtained at 54.5% and maximum energy profit rate reach 6.49% at a temperature of 900 °C with solid residence time of 6 min and the activation energy of biochar is 461.10kJ/mol and 108.45kJ/mol in the range of 290 °C to 314°C and 314 to 518°C respectively [27].

Muhammad et al (2016) shows that to optimize the conditions to produce a biochar with unique properties and increase the potential to absorb contaminants and sequester C. the pyrolysis of *Achnatherum splendens* L conducted at 300, 500 and 700°C for a 2 hour residence time in a fixed-bed pyrolysis system under a pure nitrogen atmosphere and heating values were determined by bomb calorimetry. Their conclusion show that biochar yield from pyrolysis *Achnatherum splendens* L decreased and syngas yield increased as pyrolysis temperature was increased and the maximum bio-oil yield was obtained at 500°C [28].

Tao et al (2016) studied, lignocellulosic biomass pyrolysis to review the number of parameters affect the biomass pyrolysis process, yields and properties of products such as the biomass type, biomass pretreatment, reaction atmosphere, temperature, heating rate and vapor residence time. Based on the heating rate and residence time, biomass pyrolysis can be divided into three main categories slow (conversational), fast and flash pyrolysis mainly aiming at maximizing either the bio-oil or biochar yield. Biomass pyrolysis generally follows three step mechanism comprising of dehydration, primary and secondary reactions. Their conclusion show that heating rate and temperature are the two most process conditions. Higher heating rates promote production of higher liquid yield, while lower heating rates are applied for enhanced biochar yields and The optimum temperature for maximized liquid and solid product yields in the range of 400-550°C [29].

Yining sun et al (2014) studied that the effects of feedstock type, production method and pyrolysis temperature on biochar and hydro-char properties. Their result of studied show that increases of pyrolysis temperature during biochar production led to the decrease of production rate and increased of its carbon content and thermal stability and hydro-char had a lower pH and carbon content than that from regular pyrolysis and hydro-char made at lower temperatures had higher production rate. Also the production method strongly effect on biochar properties. Their concussion indicated that biochar with different properties could be developed by changing productions conditions to better satisfy their environmental applications [30].

Nurhidayah et al (2012) investigated the impact of temperature and heating rate on the yield and properties of biochar derived from cassava wastes in slow pyrolysis process. Their

conclusion show that the increment of temperature and heating rate of slow pyrolysis for cassava wastes had raised, the fixed carbon content of biochar but decreased the biochar yield and more biochar was produced at lower temperature and lower heating rate. Temperature gave more influence on the biochar as compared to the heating rate parameter. The fixed carbon content in the derived biochar from cassava was much higher compared to their raw feedstock. Biochar produced from Cassava waste is suitable for carbon sequestration [31].

Dusan Klinar (2016) showed that to develop theoretical back ground of the general mass and heat balance of typical slow pyrolysis process as a basis for techno-economic assessment (TEA) performing and develop is more users' friendly TEA model with the objective are: theoretical background of the general mass and heat balance model, calculate typical case of wood chips biomass use, compare results with published data and assess reliability and develop a model of mass and heat balance adapted for full support of TEA. His study result showed that, the model calculation of typical case enable modification of the mass and heat balance that supports views and needs of investors in the preparation of a techno-economic assessment of the technology [32].

Jie Zhang et al (2015) showed that, the effects of pyrolysis temperature and heating time on the yield and physicochemical and morphological properties of biochar obtained from straw and lignosulfonate were investigated. Their result shows that as pyrolysis temperature increased pH, ash content, carbon stability and total content of carbon also increased while biochar yield, volatile matter, total content of hydrogen, oxygen, nitrogen and sulfur decreased. The type of feedstock also affected yield, elemental composition and chemical structure of biochar [33].

All above previous researchers produce the biochar from different feedstock waste for the cooking. Most of them characterized only the waste before pyrolysis and increasing the yield of biochar based on pyrolysis temperature and process condition. This research is focused on design, manufacture and biochar production from leaves and stems of water hyacinth in this continuous screw reactor, to characterize leaves and stems of water hyacinth before and after pyrolysis and analysis the preparation method, structure of biochar, the efficiency and mechanism of reactor for increasing the quality of biochar. Also the effect of insulation, moisture content of raw material on biochar production and energy analysis on screw reactor included in this paper.

## Chapter Three

### 3. Methodology and Materials

The methods to be followed and materials needed in thesis is discussed as follows.

#### 3.1. Methodology

The method used to produce biochar from water hyacinth is discussed as follows:

##### 3.1.1. Collection and Preparation of Water Hyacinth

First the water hyacinth biomass sample is collected from Lake Tana by man power. The Sample collected is reduced to appropriate size by pole then dried by sunlight.

##### 3.1.2. Characterization of Water Hyacinth Biomass and Biochar Samples

Characterization of samples were important in order to identify its suitability to undergo the thermochemical conversion process. The proximate and ultimate analysis, calorific value and pure density of the water hyacinth biomass and biochar samples determined by standard procedure in laboratories.

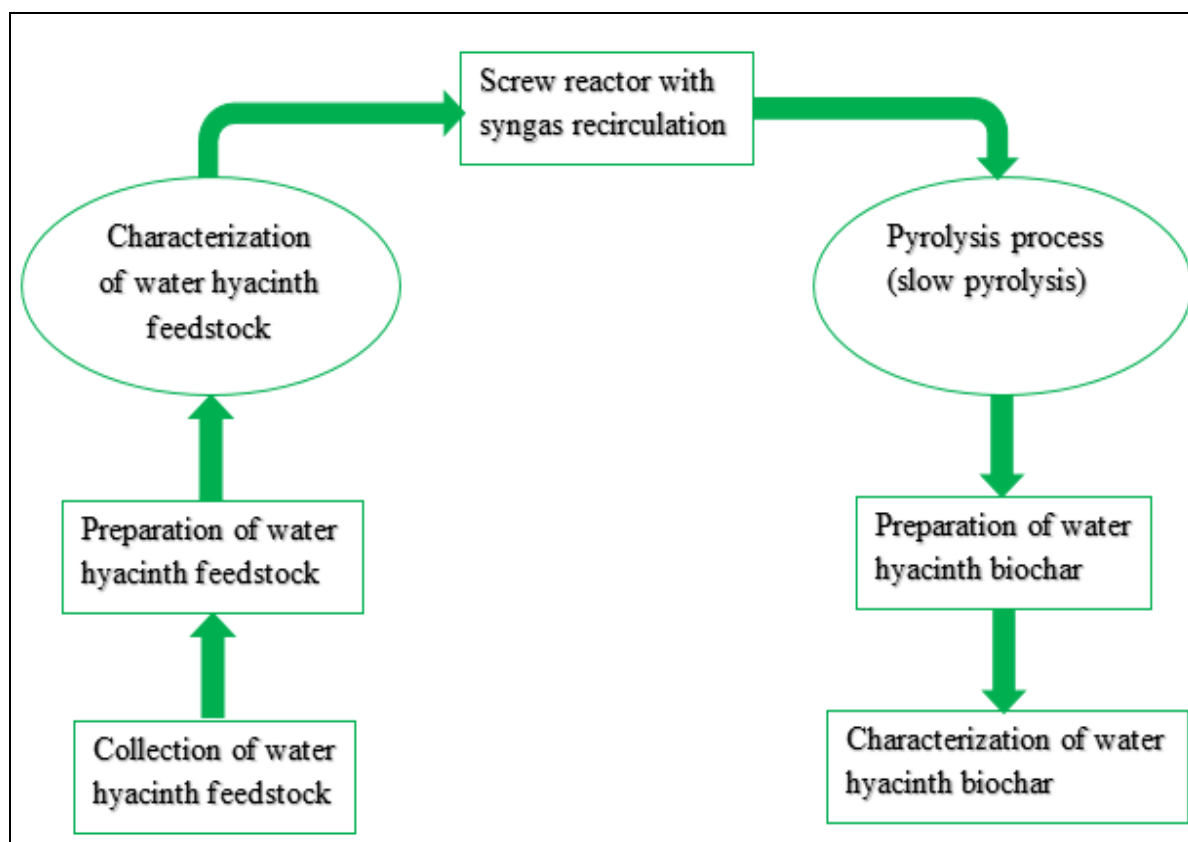


Figure 3-1. General Methodology of Biochar Production from water hyacinth

### 3.1.4. 3D Modelling and Manufacturing Pyrolysis Experimental Setup

Biochar production from water hyacinth biomass continuously was conducted using continuous screw reactor. The reactor system consists of hopper, screw conveyor, outer and inner reactors, a motor, pulleys, gear box, V-belt, frames with wheel, a cyclone and a return pipe. The 3D of this reactor is modelled using solid work software and manufactured.

### 3.1.5. Mass and Energy Balance Calculation

The mass balance is calculated by measured mass of water hyacinth input and mass of biochar output. Also the energy balance is calculated by measuring the temperature distribution on reactor.

## 3.2. Materials

The materials needed for biochar production from water hyacinth is discussed as follows.

### a. Raw Material

The raw material used for biochar is water hyacinth (Emboch)



Figure 3-2 Water Hyacinth biomass

### b. Instrument needed

1. Moisture analyzer to measure moisture of water hyacinth biomass and its biochar
2. Infrared thermometer used to measure temperature of reactor
3. Bomb calorimeter used to measure heating values

c. Equipment needed for production biochar from water hyacinth biomass include the following:

- a. Pre-processing equipment such as grinding and drying.
- b. Pyrolysis reactor setup which consist such as

- Feed hopper: to feed water hyacinth biomass to screw conveyor.
  - Screw conveyor: to convey and mix the water hyacinth biomass.
  - Cyclone: to separate the gases and biochar of water hyacinth.
  - Combustion chamber
  - Inner and outer reactor
- c. Motor and blower

## Chapter Four

### 4. Pyrolysis reactor Experimental setup

#### 4.1. Selection of reactor for biochar production from water hyacinth

The main objective of the pyrolysis reactor experimental setup was to convert water hyacinth into biochar by heat which is supplied to pyrolysis reactor. The main part of a pyrolysis plant is the reactor. The most common type of pyrolysis reactor are modern reactor and traditional reactor. Modern reactor includes fluidized bed reactor, ablative reactor, rotating cone reactor, and screw reactor and traditional reactor included earth mound kiln and earth pit kiln. In this research modern reactor is selected for biochar production.

##### 4.1.1. Types of designed modern reactors

There are different types of reactor design by world researchers for change agricultural wastes to useful energy. Based on type of pyrolysis process such as slow and fast pyrolysis, the different types of designed reactors referred from literatures are the following:

1. Continuous Screw Reactor: In these reactor biomass particles is heated by the hot surface of reactor which gain heat from combustion chamber, conveyed and mixed biomass from inlet to outlet and efficient to produce bio-oil, biochar and syngas.
2. Fluidized Bed Reactor: These reactors are more effective with gasification reactions because there is effective heat and mass transfer.
3. Ablative Reactor: in these reactor biomass particles are moved by high speed on a hot surface of reactor. Ablation of any char forming at a particle's surface maintains a high rate of heat transfer from reactor.
4. Rotating Cone Reactor: Pre-heated hot material such as sand and biomass particles are introduced into a rotating cone. Because of the rotation of the cone, the mixture of heat and biomass is transported across the cone surface by centrifugal force.
5. Fixed beds reactor: they are poor in heat transfer to the biomass because the bed of reactor is heated in one side and there is no uniform mixing inside the reactor. These reactor have been used for the traditional production of charcoal.

Based on review of many literature continuous screw reactor is best from above list designed reactors, continuous screw reactor is selected for this experimental analysis because it is slow, indirect heated biomass and efficient for produce biochar from water hyacinth biomass.

## 4.2. Design of Continuous Screw Reactor with Its Components

The main objective of the continuous screw reactor in this experiment was to convert water hyacinth biomass into water hyacinth biochar by heat which is supplied to pyrolysis reactor. The continuous screw reactor was designed with its components for biochar production previously. But some parts of that reactor such as frame, screw feeder and after burner are not properly work, because of this problem the reactor is not functional for biochar production from water hyacinth so that this reactor was modified. This modified reactor is movable, reduce heat loss and increased the capacity of biochar production daily. The continuous screw reactor used for this research is made up from outer reactor, inner reactor, screw conveyor, combustion chamber, feeder hopper, return pipe, wheel and Cyclone Separator. The main body of those reactor is horizontal pipe length 1.3m with an inner diameter 164mm and 3mm thick, made from mild steel with thermal properties such as  $43\text{W/kg}^\circ\text{C}$  is thermal conductivity,  $7801\text{kg/m}^3$  is density and  $473\text{ J/kg}^\circ\text{C}$  is specific heat. Inside the main pipe, an assembled screw goes along all pipe length and an electric engine with 3kW power is connected to gear box by the main shaft. The screw conveyor rotate by the motion transfer from output shaft into screw shaft by belt. The rotation of screw carries the water hyacinth biomass sample from inlet reactor towards the heating (reaction) zone or the outer reactor of diameter 305mm and 1.1m until the products collection point on the other end of the reactor.

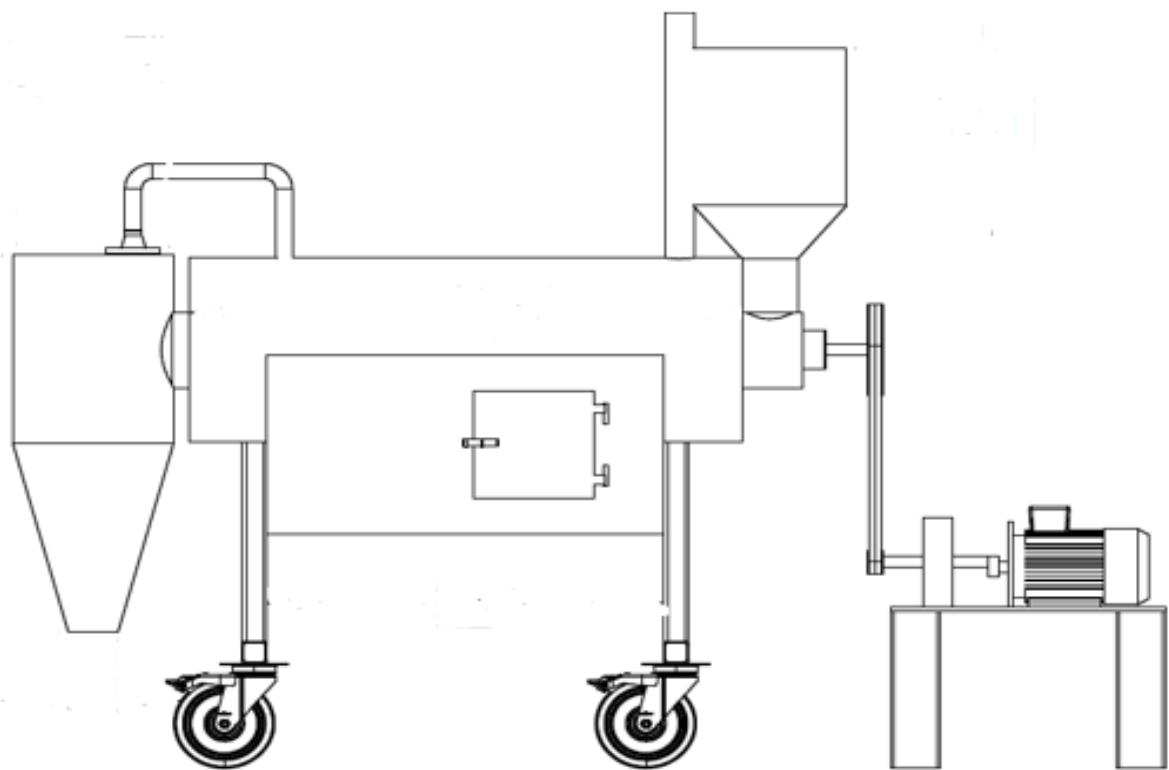


Figure 4-1. Schematic diagram of screw reactor

### 4.2.1. Design of shaft

A shaft is rotating machine member, circular cross section which is used to transmit power or motion from one to other place. In this reactor motion consists bending moment and torque. Bending moment calculated due to reaction between shaft and bearing and torque calculated due to power transmission to the shaft. There are three shafts used for power or motion transmission from motor to the reactor as the following:

1. Shaft with screw is used to convey water hyacinth biomass.
2. Main shaft is used to transmit torque from motor to the gear box.
3. Output shaft (pulley mini) is used to transmit torque from gear box to belt.

Shaft with screw is supported by bearings in the rigid machine housing and the power is transfer from one shaft to other shaft by pulleys mounted on it and connected by belt. In this designed continuous screw reactor; a shaft was support by two bearings placed 1.588m apart and a pulley is mounted at a distance of 130mm to the right of right hand bearing.

#### 4.2.1.1. Selection of Shaft Material

The material selected for the shafts should have high strength, good machinability, high wear resistance and good heat treatment. The shaft is made from alloy steel material which have high strength because of smaller diameter and high weight distribution on it. There are three stresses induced in the shaft. Those are:

- Shear stressed due to the transmission of torque
- Bending stresses due to forces acting pulley and due to the weight of screw with it.

The shaft with allowance for keyways used in continuous reactor for biochar production from water hyacinth continuously. According to American society of mechanical engineers code for the design of transmission shaft, the maximum permissible working stresses and shear stresses takes as 84MPa and 42 MPa respectively.

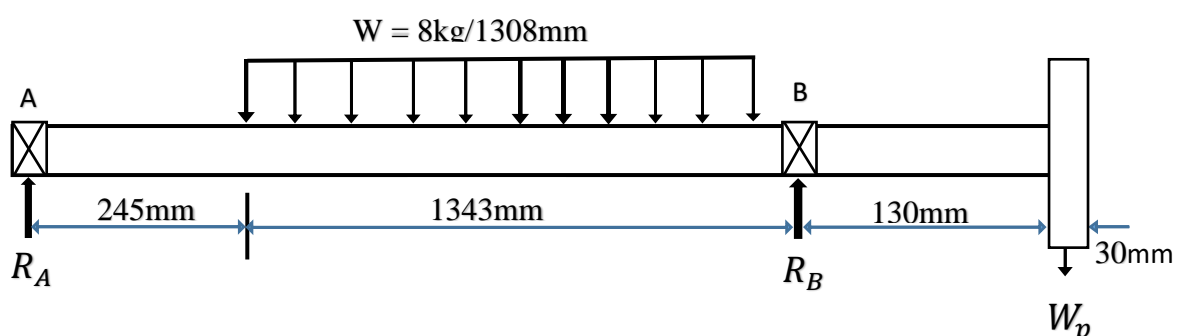


Figure 4-2. Free body diagram on shaft with screw

#### 4.2.1.2. Shaft Design Specification

1. Shaft material is alloy steel
2. Power is constant = 3kW i.e. from motor selection
3. Allowable shear stress of shaft material 42 MPa
4. Approximate mass of flight = 6kg and Mass of larger pulley = 3kg

The torque transmission by the shaft due to power

$$T_s = \frac{60P}{2\pi N} \dots \dots \dots 4.1$$

The torque transmitted by the belt to pulley from driven shaft

$$T_p = (T_1 - T_2)R_p \dots \dots \dots 4.2$$

Where  $T_1$  and  $T_2$  are tensions in the tight side and slack side of the belt respectively and  $R_p$  is radius of the pulley. The torque of screw shaft and the pulley are equal.

The maximum bending moment of the acting on the shaft

$$M_{max} = FxL_s \dots \dots \dots 4.3$$

According to maximum shear stress theory, equivalent twisting moment of solid shaft given

$$T_e = \sqrt{M^2 + T^2} = \frac{\pi}{16} \tau \times d^3 \dots \dots \dots 4.4$$

The total vertical load acting on screw shaft by pulley assume the mass of pulley 3kg

$$W_p = T_1 + T_2 + m_p g \dots \dots \dots 4.5$$

From equilibrium equation of force acting on the shaft

$$\sum F_y = 0 = R_A - W_{sk} + R_B - W_p = 0 \dots \dots \dots 4.6$$

#### 4.2.2. Screw Conveyor

Screw conveyor was a mechanism that used to rotate helical screw to transport the material into the process. This screw conveyor consists of a shaft and helical blade which enclose the shaft. The shaft is coupled to driving and supported by bearing in the inner reactor at both ends. In this research the function of solid shaft screw conveyor is to convey horizontally the water hyacinth biomass from feed hopper to cyclone separator through the heated zone where the slow pyrolysis reaction occurs in the reactor by 11.6rpm rotational speed. It is made from Tempered Stainless steel screw conveyors are flights can be welded continuously to ideal for used where extreme temperatures are a problem. Stainless steel conveyor screws and parts are

manufactured to the same specifications as are standard mild steel. The flights can be welded continuously to both sides of the solid shaft and the weld may then meet specifications. The important dimensions such as screw diameter, clearance between screw and tube, pitch of screw, shaft diameter, thickness of screw flight and length of shaft are 160mm, 2mm, 100mm, 25mm, 3mm and 1.748m respectively.

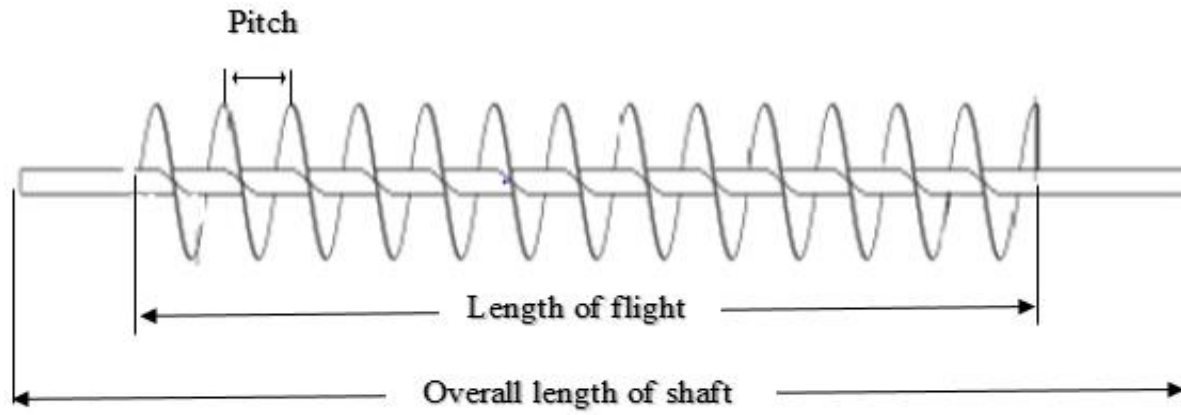


Figure 4-3. Schematic diagram of screw conveyor

#### 4.2.3. Design of Pulley

The pulleys are used to transmit power from one shaft to another by means of flat belts or ropes. Since the velocity ratio is the inverse ratio of the diameters of driving and driven pulleys, therefore the pulley diameters should be carefully selected in order to have desired velocity ratio. The pulleys may be made of cast iron, cast steel or pressed steel and aluminum. For the continuous biochar production pulleys material is aluminum. The dimension of standard V-grooved pulley is selected from which we find that for D type belt. In general the dimension of larger pulley  $D = 240\text{mm}$  and  $W = 30\text{mm}$ .

#### 4.2.4. Cyclone Separator

Cyclone separator used to remove biochar from a gas stream without the use of other force such as filters. It consists of an upper cylindrical part and a lower conical part. The mixture of solid biochar and gas flow enters the cyclone separator by screw conveyor. The gas stream enters tangentially at the upper cylindrical part and solid biochar travel downward into the conical part.

#### 4.2.5. Combustion Chamber

Combustion chamber is rectangular made of stainless steel having length of 790mm, height 400mm and 500mm width with 3mm thickness. When the temperature of reactor reaches

pyrolysis temperature the water hyacinth dry biomass are feed into screw reactor continuously. The pyrolysis temperature was externally heated by heat generated from combustion at a heating rate of 50 °C /min to the desired temperature.

#### 4.2.6. Selection of Bearing

Rotating shafts with screw required to be supported at suitable places. The mechanical device which can take up the load and support the shaft called bearing. The bearing is so named because the surface of support is subjected to a bearing load. A bearing is machine elements which support another moving machine element (known as journal). It permits a relative motion between the contact surfaces of the members, while carrying the load. In the bearings, the relative motion between the two mating surfaces causes friction and generates heat. Any substance placed between the two surfaces which reduces friction, wear and takes away heat, known as lubricant. In order to reduce frictional resistance and wear in some cases to carry away the heat generated, a layer fluid (known as lubricant) may be provided. The lubricant used to separate the journal and bearing is usually a mineral oil refined from petroleum, but vegetable oils, silicon oils, greases etc. are may be used. Based on the direction of load bearing may be broadly classified in to two categories:

- a. Radial bearings; radial bearings carry external load perpendicular to the axis of rotation of the shaft. Journal bearings and some types of ball and roller and roller bearings belong to this category.
- b. Thrust bearings; in these bearings, the load acts along the axis of rotation, e.g. hydrostatic bearings and antifriction thrust bearings.

Based on the nature of contact bearings are also classified according to the nature of relative motion between members.

- a. Sliding contact bearings; Bearings with sliding friction between the members are called sliding bearings, e.g. journal bearings and hydrostatic bearings.
- b. Rolling contact bearings; Bearings with rolling contact friction between the members are known as rolling contact bearings; e.g. ball, roller and taper roller bearings. These bearings have either point contact or line contact.

The selection of bearing for a particular application is based on several characteristics relating to mechanical, environmental and economic requirements. The following considerations are of parameters importance in the selection of bearings for this continuous screw reactor.

**Load:** the rolling element bearing are superior to slider bearings because they can carry high unidirectional and cyclic loads whereas the load carrying capacity of slider bearings depends on the speed of journal.

**Speed:** Both sliding and rolling element bearings have a practical limit to the peripheral velocity, fixed by different criteria. In sliding bearings, the speed limitation is on account of the rise in temperature of lubricating oil caused by high speed shearing action. In the rolling element bearings, the limit speed is a function of the product of shaft diameter (mm) and speed in rpm.

**Misalignment:** A slider bearing can tolerate misalignment better than what the rolling element bearing can because the later has rigid structure and close tolerances.

**Frictional loss:** Rolling element bearings have low starting friction but journal bearings attain lower coefficient of friction only when sufficient pressure is built up.

**Space:** Journal bearings occupy less space in radial direction whereas rolling element bearings require less space in axial direction.

#### **4.2.6.1. Bearing Material**

A bearing however, carefully and properly designed, may fail either due to deflection, temperature distortion, and surface roughness or due to faulty selection of the bearing material. Therefore, a proper selection of bearing material is very important. Since the rolling elements and the races are subjected to high local stresses of varying magnitude with each revolution of the bearing, therefore material of the rolling element i.e. steel should be of high quality. The balls are generally made of high carbon chromium steel. The material of both the balls and races are heat treated to give extra hardness and toughness.

#### **4.2.6.2. Life of Bearing**

The life of an individual ball (or roller) bearing may be defined as the number of revolutions (hours at the some given constant speed) which the bearing runs before the first evidence of fatigue develops in the material of one of the rings or any of the rolling elements. The rating life of a group of apparently identical ball or roller bearings is defined as the number of revolutions (or hours at some given constant speed) that 90 percent of a group of bearings will complete or exceed before the first evidence of fatigue develops (i.e. only 10 percent of a group bearings fail due to fatigue). The term minimum life is also used to denote the rating life. We may say that the average life of a bearing is 5 times the rating life (or minimum life). It may be

noted that the longest life of a single bearing is seldom longer than the 4 times the average life and the maximum life of a single bearing is about 30 to 50 times the minimum life [34].

For continuous Biochar production reactor single row deep groove ball bearing selected based on radial load and known shaft with screw diameter ( $d=25\text{mm}$ ) which is equal to bore diameter (25mm) of bearing. Generally based on 25mm bore diameter selected single row deep groove ball bearing with 52mm outside diameter and 15mm width from Table 4.1.

Table 4-1. Basic Capacities and principal dimension for selection radial ball Bearings [35]

Bearing dimensions in mm			Basic Capacities of bearing in KN			
Bore diameter	Outside diameter	Width	Single row deep groove ball bearing		Single row angular contact ball bearings	
			Static	Dynamic	Static	Dynamic
10	30	9	2.24	5.07	—	—
12	32	10	3.1	6.89	—	—
15	35	11	3.55	6.1	3.75	6.3
17	40	12	4.4	7.5	4.75	7.8
20	47	14	6.65	10	6.65	10.4
25	52	15	7.1	11	7.8	11.6
30	62	16	10	15.3	11.2	16
35	72	17	13.7	20	15.3	21.2

### 4.3. Motor and Gear Box

#### 4.3.1. Selection of Motor

An electric motor is an electrical machine that converts electrical energy to mechanical energy. First detailed understanding the type of motors, mounting and enclosures duty helps for identifying appropriate type of motor and its applications. The criteria for motor selection includes; operating conditions, driven equipment, electrical specifications, mounting requirements, enclosure and bearing parameters. For continuous biochar production from water hyacinth the motor specification is 50/60rpm, 220V and 3kw purchased i.e. from industrial guide book of motor selection. Thus motor is drive the gear box by the shaft transmit torsion

from motor to gear box. From previous design and review literatures at the maximum rotational speed of the screw conveyor; the produced product intended to be obtained becomes less or no product and slow pyrolysis process operates at low rotational speed to produced biochar. In order to reduce the rotational speed by used speed reduction driving unit like gear box and pulleys in this research (significant loss of energy).

#### **4.3.2. Gear Box**

The gear box used for reduce the rotational speed in this system is designed previously. This gear box is made from spur gear. Spur gears are used to transmit rotary motion between parallel shafts. They are cylindrical, and the teeth are straight and parallel to the axis of rotation. Thus they are not subjected to axial thrust due to tooth load. The pinion is the smaller of two meeting gears; the larger is called the gear. At the time of engagement of the two gears, the contact exceeds across the entire width on a line parallel to the axis of rotation. Based on previously design this gear box is reduce the speed of motor from 1450rpm to 58rpm by factor of 96%. The gear has large diameter fixed on the output shaft, so that the rotational speed of output shaft from gear box is equal to 58rpm. At the rotational speed of the shaft or gear is increasing the torque of that shaft or gear is decrease. The torque transmitted from motor into the screw shaft was increased based on the rotational speed of gear and pulleys.

#### **4.4. Selection of Belt drive**

The v-belt is mostly used where a great amount of power is to be transmitted from pulley mounted on shaft of gear box to the pulley mounted on shaft of reactor. Because of the two pulleys are very near to each other, easily installed and removed, high velocity ratio may be obtained and drive is positive, the v-belt type has been selected for this reactor. The selection of a belt drive depends on the various important factors are the following;

1. Center distance between the shafts
2. Power to be transmitted
3. Speed of the driving and driven shafts
4. Speed reduction ratio
5. Service conditions and space available

Generally the rubber belt material has been selected for power transmission because it is strong, flexible and durable and it must have high coefficient friction. When the pulleys have different angle of contact, then refer from design of pulley which have smaller the values of angle of contact when coefficient of friction between the belt and the pulley ( $\mu = 0.3$ ) and angle of

groove ( $\beta = 45^\circ$ ) of two pulley are the same. Since the angle of smaller pulley is small, therefore the design was based on smaller pulley. Based on the strength and length of belt the rotational speed was reduced from 58rpm to 11.6rpm. So that the rotational speed of larger pulley and the screw conveyor was calculated in appendixes C1 is 11.6rpm.

**4.4.1. Design Specification for V-belt derive**

The speed ratio of the v-belt calculated as follows:

$$\frac{N_1}{N_2} = \frac{D_2}{D_1} \dots\dots\dots 4.7$$

$$\sin \alpha = \frac{r_2 - r_1}{x} = \frac{D_2 - D_1}{2x} \dots\dots\dots 4.8$$

So the angle of contact on driving and driven pulley with the v-belt are  $\theta_1 = 180^\circ - 2\alpha$  and  $\theta_2 = 180^\circ + 2\alpha$  respectively.

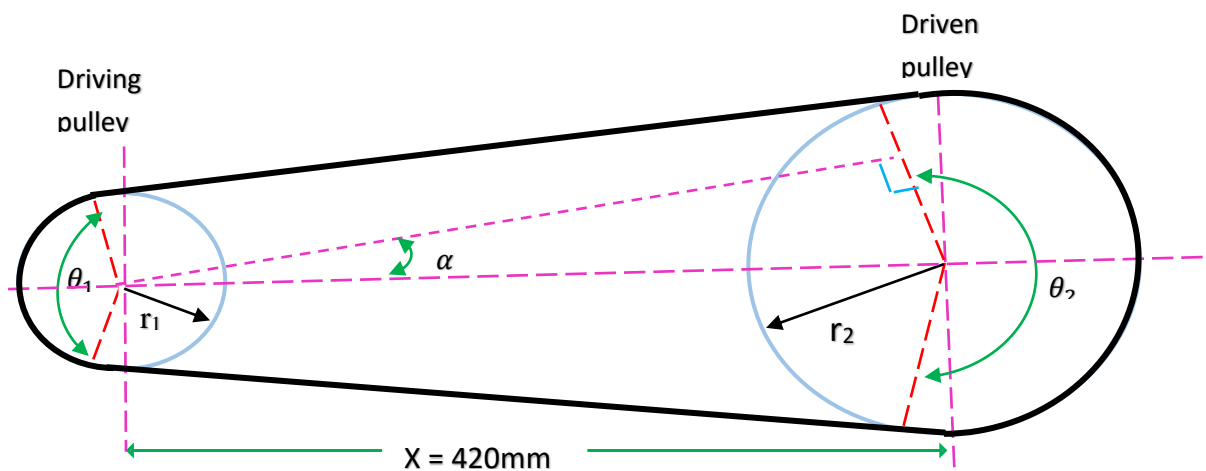


Figure 4-4. V-belt with pulleys

$$\sin \alpha = \frac{102 - 25}{420} = \frac{204 - 50}{2 \times 420} = 0.183$$

$$\alpha = 10.56^\circ$$

Now the angle of contact on smaller pulley

$$\theta_1 = 180^\circ - 2 \times 10.56 = 156.88^\circ$$

$$\theta_1 = 156.88^\circ \times \frac{\pi}{180^\circ} = 2.738rad$$

Angle of contact of larger pulley

$$\theta_2 = 180^\circ + 2 \times 10.56 = 201.12^\circ$$

$$\theta_2 = 201.12^\circ \times \frac{\pi}{180^\circ} = 3.51rad$$

According to Hannah and Stephens (1970), the power transmitted by belt is given by

$$P = (T_1 - T_2)v_b \dots \dots \dots 4.9$$

$$v_b = \frac{\pi DN_1}{60} \dots \dots \dots 4.10$$

$$2.3 \log\left(\frac{T_1}{T_2}\right) = \mu \theta \operatorname{cosec} \beta \dots \dots \dots 4.11$$

For smaller pulley

$$2.3 \log\left(\frac{T_1}{T_2}\right) = 0.3 \times 2.738 \times \operatorname{cosec} 45^\circ = 1.16$$

$$\log\left(\frac{T_1}{T_2}\right) = 0.5$$

$$\frac{T_1}{T_2} = 3.2 \text{ Then } T_1 = 3.2T_2$$

#### 4.5. Selection of Wheel

There are many types of wheels based on their capacities and specifications. Based on the load of screw reactor rotating swivel wheels with brake, roller bearing, covered by Zink plated, black rubber and 250kg maximum load capacity is selected from the swivel Europe type industrial 8" rubber caster wheels specification. This types of swivel caster wheel allows for movement in all direction. The wheels fixed on the frame and carries all parts of screw reactor. In this experiment the screw reactor moves by four wheels and its lock when it to start pyrolysis.



Figure 4-5. Swivel black rubber caster wheel

## 4.6. Modelled and manufactured prototype of the continuous screw reactor

Screw reactor used for pyrolysis water hyacinth was modelled and manufactured based on determined dimension and standard material selection.

### 4.6.1. Modelled Continuous Screw Reactor

Continuous screw reactor is modelling with its components by SolidWorks 2018. The 3D, overall dimension, name of main components and section view of continuous screw reactor are shown in figures 4.5 and 4.6.

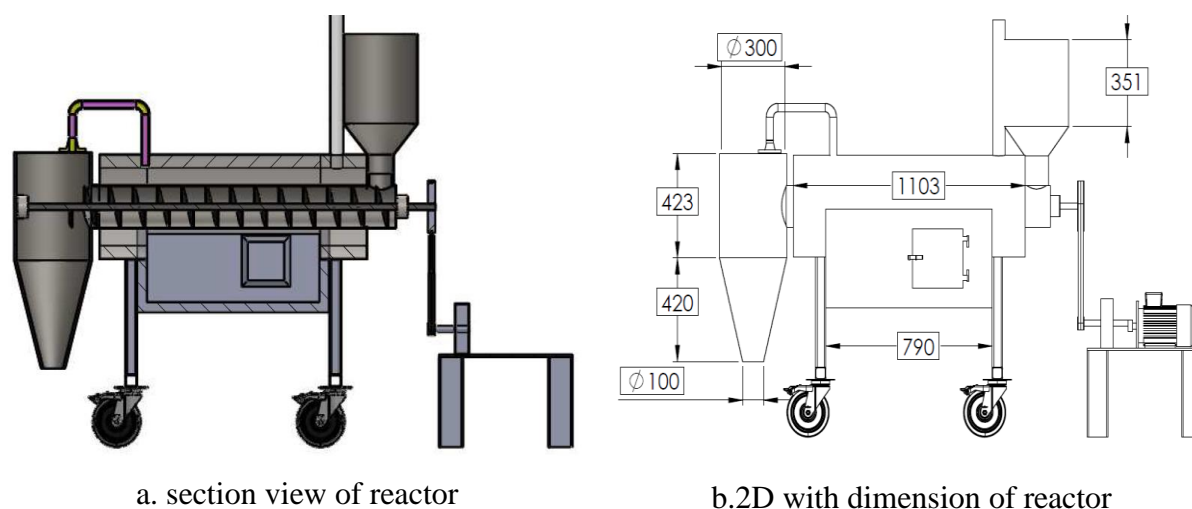


Figure 4-6. Section view and overall dimension of continuous screw reactor

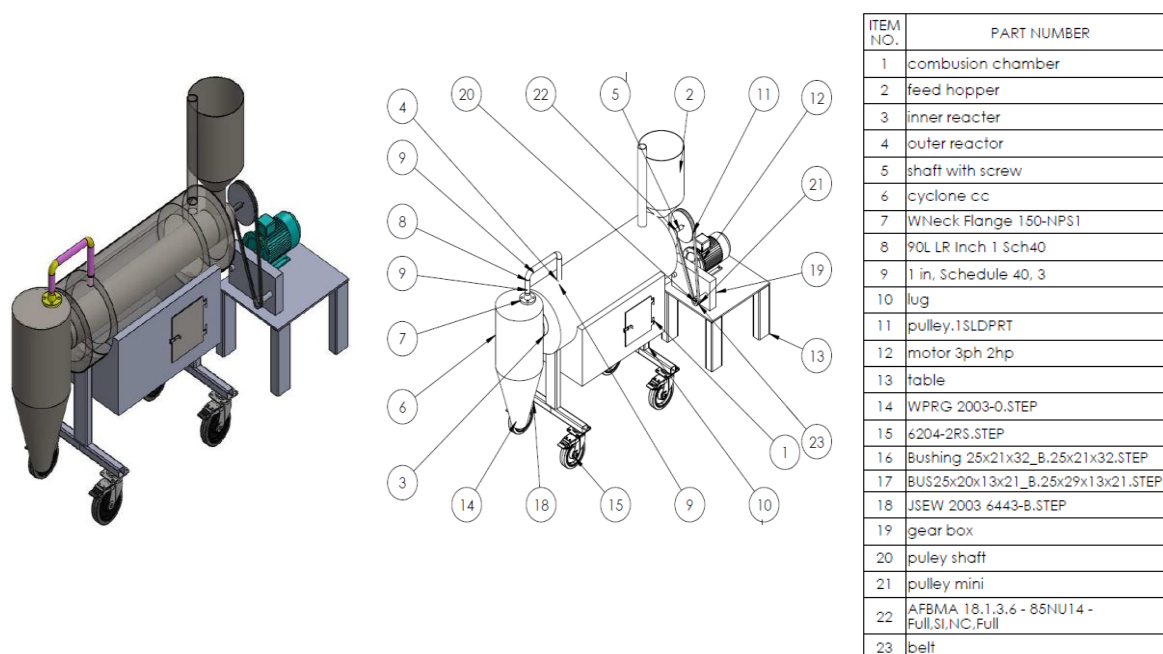


Figure 4-7. 3D modelled and components of continuous screw reactor

#### 4.6.2. Manufactured Prototype Continuous Screw Reactor

The materials selected for manufacture the continuous reactor, dimension of all components of reactor, 2D and 3D modelled continuous reactor submitted into AAiT work shop. Based on specification of submitted continuous reactor manufactured by lap technicians. The prototype with paint color shown on (figure 4.8).



Figure 4-8. Continuous screw reactor prototype

#### 4.7. Compare Current with Previous Continuous Screw Reactor

Reactor used for this experiment consists inner reactor, outer reactor with ash insulation, feed hopper, cyclone separator, combustion chamber and screw conveyor. Previous reactor (designed by Geremew Nuguse) consists not work, extra components such as screw feeder and afterburner. Previous screw reactor type biochar production takes longer time when compared with this continuous biochar production because feeding screw not function. . From the experimental result, the production capacity of continuous biochar production is about 656kg/day from water hyacinth while the previous type biochar production about is 470kg/day from flower waste.



a) current reactor

b) previous reactor

Figure 4-9. Continuous screw reactor prototype

## Chapter Five

### 5. Analyze Mass and Energy Balance in the screw reactor

#### 5.1. Mass balance calculation in the reactor

The net mass transfer to or from a control volume during a time interval ( $\Delta t$ ) is equal to the net change in the total mass within the control volume during time interval ( $\Delta t$ ) can be expressed by conservation of mass principle as [36].

$$m_{in} - m_{out} = \Delta m_{CV} \dots \dots \dots 5.1$$

During a steady-flow process, the total amount of mass contained within a control volume does not change with time. Then the conservation of mass principle for a general steady-flow system requires that the total amount of mass entering equal the total amount of mass leaving a control volume can be expressed in rate form as [37]

$$\frac{d}{dt} \int_{CV} \rho dV = \sum \dot{m}_{in} - \sum \dot{m}_{out} = 0. \dots \dots \dots 5.2$$

Based on the conservation of mass principle, the Mass balance in the screw reactor which is contains the one inlet and two outlet was performed by weighting the water hyacinth feedstocks input and the biochar outputs. Also determine the mass of the syngas output by difference of feedstocks mass and biochar mass.

$$m_{WH} = m_g + m_{BC} \dots \dots \dots 5.3$$

Mass balance in combustion chamber

$$m_{BM} + m_{air} = m_{ash} + m_{gas} \dots \dots \dots 5.4$$

$$m_g = \dot{v} \cdot \rho \cdot t \dots \dots \dots 5.5$$

$$m_{air} = \alpha \cdot \varepsilon \cdot \frac{\pi d^2}{4} \sqrt{2 \cdot \rho \cdot \Delta p} \dots \dots \dots 5.6$$

#### 5.2. Heat transfer and Energy balance calculation in the screw reactor

##### 5.2.1. Energy supplied to the system

The energy used for this experiment is generated in the combustion chamber from dry wood. Dry wood selected for this experiment based on its advantages. The completely dry wood contains HHV 18.5MJ/kg selected. Feed 10.77kg of completely dry wood to the combustion chamber.

$$E_{gen} = m_{wood} \times HHV \dots \dots \dots 5.7$$

$$E_{gen} = 10.77kg \times 18.5MJ/kg = 199.245MJ$$

Energy used in the reactor for pyrolysis determined from the difference of pre –weighed dry wood and the wood remaining in combustion chamber at the end of test.

Table 5-1 Types of combustion fuel with higher heating values

No	Types of fuel	Higher heating values(MJ/kg)
1	Air dried wood	16.2
2	Completely dry wood	18.5
3	Charcoal	29.6
4	Petroleum	42

### 5.2.2. Heat transfer analysis in screw reactor

Heat is the form of energy that can be transferred from one systems to another system because of a temperature difference. The heat transferred always from the higher temperature system to lower temperature one and the heat transfer stops when the two systems are reach the same temperature [36].

In this experiment; First the wood biomass was enters to the combustion chamber and start combustion. In combustion chamber, the store chemical energy of the dry wood change into thermal energy by combustion process. The inner and outer reactors are heated by hot combustion gases distribution on wall surface of reactor by convection method and the heat transfer through the wall of reactor by conduction method. The heat continuously transferred from outer surface to inner surface of the inner reactor until the two surface are reaches the same temperature (pyrolysis temperature). The rate of heat in inner reactor increase by equal rate of heat gain from hot combustion gas. During the pyrolysis, the gases flow is parallel. The hot gases produced by pyrolysis biomass change the parallel flow to contour flow by enter to the combustion gases. The amount of heat return to the outer reactor equal to the amount of energy produce by blower for starting heat in combustion chamber.

### 5.2.3. Heating Method of the system of reactor

In screw reactor, the heat is continuously transferred from combustion chamber (higher temperature) to the screw conveyer (lower temperature) and to surround by conduction, convection and radiation method until reaches pyrolysis temperature. General heat transferred in screw reactor expressed as:

- Force heat convection from hot combustion gas to surface of inner reactor

The hot gas in combustion chamber is forced from combustion chamber into inner reactor by blower continuously until the temperature reach pyrolysis temperature.

- Conduction through wall of inner reactor
- Free convection from surface of inner reactor to gas in the reactor
- Force convection from hot combustion gas to surface of outer reactor
- Conduction through wall of outer reactor
- Conduction through wall of chamber

### 5.3. Governing equation of heat transfer for the system

Cylindrical system often experience temperature gradients in the radial direction only and may therefore be treated as one dimensional. The cylindrical system is analyzed by means of standard method which begins with the appropriate form of Fourier's law [38].

#### 5.3.1. Conduction heat transfer through the circular cylinder wall

First the heat is transfer from hot combustion gases to the surface of the inner reactor by transient heat conduction process. During a differential time interval  $dt$ , the temperature of the inner reactor rises by differential amount temperature  $dT$ . An energy balance of the solid for the time interval  $dt$  can be expressed as

Heat transfer into the reactor during  $dt$  = the increase in the energy of the reactor during  $dt$

$$q_{r,tot} = hA_s(T_\infty - T)dt = mC_p dT \dots \dots \dots 5.8$$

Noting that  $m = \rho V$  and  $dT = d(T_\infty - T)$  since  $T_\infty$  is constant

Boundary conditions  $t = 0, T = T_i$  and at any  $t, T = T(t)$

$$\dot{Q} = hA_s \Delta T_{ln} t = -\rho V C_p (T(t) - T_i) \dots \dots \dots 5.9$$

For one dimension steady state heat conduction with no heat generation in hollow cylinder, the heat equation can be expressed by Fourier's law of heat conduction [39].

$$\frac{1}{r} \frac{d}{dr} \left( kr \frac{dT}{dr} \right) = 0 \dots \dots \dots 5.10$$

The conduction heat transfer rate at which energy conducted through any cylinder wall and the temperature distribution associated with radial conduction through the cylindrical wall also expressed by Fourier's law is written as:

$$q_r = -kA \frac{dT}{dr} = -k(2\pi rL) \frac{dT}{dr} \dots\dots\dots 5.11$$

$$T(r) = \frac{T_{s,1} - T_{s,2}}{\ln \frac{r_1}{r_2}} \ln \frac{r}{r_2} + T_{s,2} \dots\dots\dots 5.12$$

Where area ( $A = 2\pi rL$ ) is perpendicular to the direction of heat transfer; Note that area of the surface depends on radius and thus it varies in the direction of heat transfer.

If the boundary conditions  $r = r_1$  where  $T(r_1) = T_{s,1}$  and  $r = r_2$  where  $T(r_2) = T_{s,2}$ , the Fourier's law equation is become as following by both side integrate.

$$\int_{r=r_1}^{r_2} q_r \frac{dr}{A} = - \int_{T=T_{s,1}}^{T_{s,2}} k dT \dots\dots\dots 5.13$$

$$q_r = -2\pi kL \frac{T_{s,2} - T_{s,1}}{\ln \frac{r_2}{r_1}} \dots\dots\dots 5.14$$

From equation 6.13 result, the thermal resistance of cylindrical wall against heat conduction is

$$R_{cond} = \frac{\ln \frac{r_2}{r_1}}{2\pi kL} \dots\dots\dots 5.15$$

**5.3.2. Convection heat transfer to and from the reactor surface**

The rate of convection heat transfer is observed to be proportional to the temperature difference and is conveniently expressed by newton's law of cooling as [40]

$$q_{conv} = hA_s(T_s - T_\infty) \dots\dots\dots 5.16$$

From equation 6.15 result, the thermal resistance of cylindrical wall against heat convection is

$$R_{conv} = \frac{1}{hA_s} \dots\dots\dots 5.17$$

**5.3.3. Reactor Heat gain from hot combustion gases during pyrolysis**

Heat is transferred from the hot combustion gases to the inner reactor and outer reactor by conduction and convection method until the temperature of screw conveyor in reactor reached pyrolysis temperature. Convection heat gains can be occur to outer surface of inner reactor and gas in the inner reactor. First the hot combustion gases externally steady flow over the outer surface of inner reactor by heat convective. To increase the rate of heat transfer from combustion chamber to the reactor by force convection means bellow. Convection heat

transfer coefficient  $h_c$  is calculated with the Nu is Nusselt number,  $k$  is heat conduction of reactor material and  $L_{react}$  is the length of the reactor expressed as [40]

$$Nu = \frac{h_c \times L_{react}}{k} \dots \dots \dots 5.18$$

The outer surface of inner reactor is gain heat from hot combustion gas, if the temperature of hot combustion gas is greater than the temperature of the outer surface of the inner reactor. Assume the amount of heat transfer into the inner reactor by convection equal to the amount of heat gain by inner reactor until the end of the transient process. From design of reactors, inner reactor with  $r_i = 82mm$   $r_o = 85mm$  and its length  $L = 1.30m$  has been determined and made from mild steel with thermal properties such as  $43W/kg.K$  is thermal conductivity,  $7801kg/m^3$  is density and  $473 J/ kg.K$  is specific heat.

At the temperature of the reactor changes from initial temperature  $25^\circ C$  to the temperature of hot combustion gas  $500^\circ C$  at the end of the transient process, the amount of heat gain by inner reactor were calculated with the equation 5.9 is

$$Q = 7801 \frac{kg}{m^3} \times 2.046 \times 10^{-3} m^3 \times 473 \frac{J}{kg.K} (773K - 298K) = 3586kJ$$

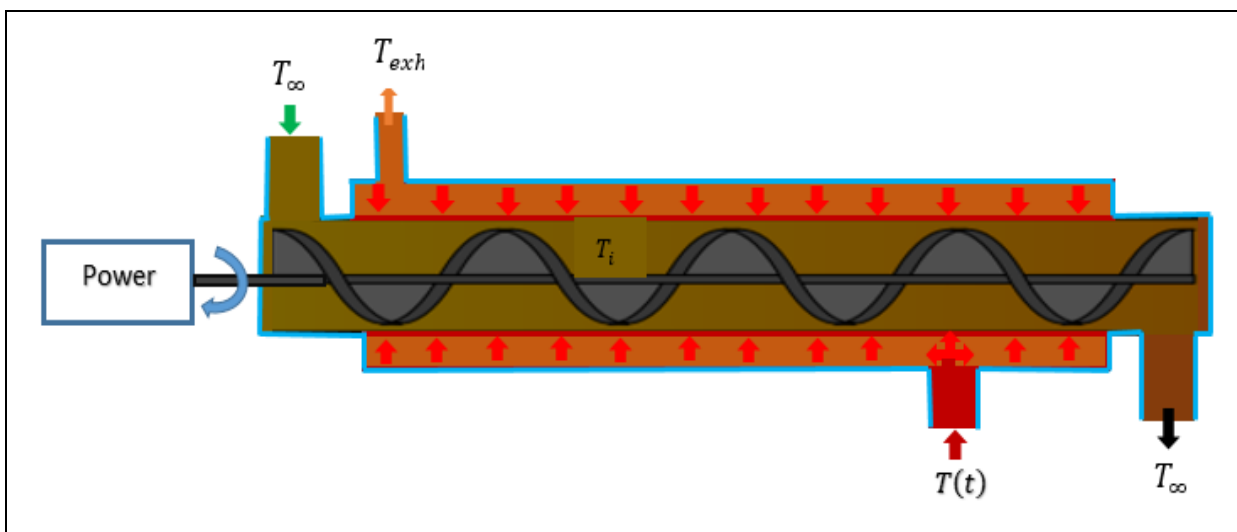


Figure 5-1. Heat gain by inner reactor during pyrolysis

**5.3.4. Insulations**

In this experiment my plan is to reduce the heat loss from the surface of reactor by best insulation. The surface of screw reactor insulated by wood ash and glass wool. When the two insulation are compared, wood ash insulation is best because it has considerable weight, excellent durability and it is very cheap to get may be free. Hence, it was adopted. For the purpose of this research wood ash was used. The addition of wood ash insulation on a surface

of reactor reduces the amount of heat loss from the reactor. So that the energy supplied to the reactor save in the reactor to produce biochar from water hyacinth continuously. If the thickness of insulation increases the heat loss decreases.

The advantage of the insulation in this experimental analysis:

- to reduce heat loss from reactor to surrounding
- to maintain temperature conditions in the slow pyrolysis process
- to maintain the effective operation of chemical reaction
- to assist in maintaining a product at constant temperature

Table 5-2 types of insulation with its thermal conductivity

Type	Temperature range (°C)	Thermal conductivity (W/m°C)
Wood ash	500-1000	0.02
Fiberglass board	20-450	33-52
Glass wool	645	0.089

### 5.3.5. Heat loss from the combustion chamber and outer surface of reactor

Heat is loss from the outer reactor and combustion chamber to surround by conduction, convection and radiation mechanism. Convection and radiation heat loss are occurs from top surface of reactor, side of reactor and wall of combustion chamber and also heat is loss from inner surface of reactor to the outer surface of reactor due to conduction. This process define by first law of thermodynamics since the amount of heat lost from screw reactor surface is equal to the amount of heat gain by the surrounding air. The outer reactor with  $r_i = 299mm$   $r_o = 152.5mm$  and its length  $L = 1.1m$  has been determined and made from stainless steel with thermal properties such as  $21.5W/kg.K$  is thermal conductivity,  $7900kg/m^3$  is density and  $500J/kg.K$  is specific heat and insulated by wood ash with  $0.02 W/m.K$  thermal conductivity.

#### 5.3.5.1. Heat loss from outer reactor before ash insulation is installed

Radiation can be a major form of heat loss. In this system, assume radiation losses negligible from the outer reactor surfaces i.e. on the whole sides of the reactor and combustion chamber. Convection heat losses can occur from the top of the reactor, the sides of the reactor, on the surface of the reactor and the wall of the reactor. Losses due to convection can be determined by variety of methods. Calculating the convective heat transfer coefficient using standardized method (Welty, 1978) is one where the heat transfer coefficient,  $hc$  is a function of the Nusselt

number. But on the surface of reactor insulated by ash which drop the outer surface temperature to a values close to the ambient temperature and one over four area of the outer surface connected with combustion chamber; so that heat loss is negligible. For determination of the Rayleigh number and the Nusselt number depends on the surface temperature which is measured by IR thermometer. The average temperature of the outer surface of reactor with insulation, without insulation and ambient temperature are 100°C , 450°C and 25°C respectively. The rate of radiation heat transfer between a surface of emissivity  $\epsilon$  and area  $A_s$  at temperature  $T_{os}$  and the surround temperature can be expressed as

$$\dot{Q}_{rad} = \epsilon\sigma A_s(T_{os}^4 - T_{sur}^4) \dots \dots \dots 5.19$$

The convection heat transfer between a surface area  $A_s$  at temperature  $T_{os}$  and the ambient temperature can be expressed as

$$Q_{conv} = h_{cov}A_s(T_{os} - T_{\infty}) \dots \dots \dots 5.20$$

The surface exposed to a surrounding air involves radiation and convection simultaneously and the total heat transfer at a surface is determined by adding convection and radiation components because convection and radiation are parallel with each other. The air flow on surface is free flow so that the surrounding and ambient temperature approximately equal. When  $T_{sur} \approx T_{\infty}$  the combined heat transfer coefficient expressed as

$$h_{com} = h_{cov} + h_{rad} \dots \dots \dots 5.21$$

The overall heat transfer rate to the surrounding from the reactor may be expressed as

$$q_{loss} = \frac{T_{py} - T_{\infty}}{R_{Tot}} = UA_o(T_{py} - T_{\infty}) \dots \dots \dots 5.22$$

$$R_{Tot} = \frac{\ln \frac{r_{co}}{r_{ci}}}{2\pi k_{cyl}L} + \frac{\ln \frac{r_{i1o}}{r_{ci}}}{2\pi k_{ins1}L} + \frac{\ln \frac{r_o}{r_{i1o}}}{2\pi k_{ins2}L} + \frac{1}{2\pi r_o L h_{cov}} \dots \dots \dots 5.23$$

$$U = \frac{1}{\frac{r_o}{k_{cyl}} \ln \frac{r_{co}}{r_{ci}} + \frac{r_o}{k_{ins1}} \ln \frac{r_{i1o}}{r_{ci}} + \frac{r_o}{k_{ins2}} \ln \frac{r_o}{r_{i1o}} + \frac{1}{h_{cov}}} \dots \dots \dots 5.24$$

The total heat loss from outer reactor at the constant inner surface temperature is 500°C and the ambient temperature of air is 25°C calculate in equation 5.22. Assume steady operation condition outer surface, the critical Reynolds number is  $5 \times 10^5$ , the radiation effects on the surface are negligible, the local atmospheric pressure is 1 atm and air flow velocity is 7m/s.

From heat transfer book the properties of air at 1atm and 25°C are:

$$k = 0.02551 \frac{W}{m \cdot ^\circ C}; Pr = 0.7296 \text{ and } \nu = 1.562 \times 10^{-5} m^2/s$$

Analysis: the Reynolds number is

$$Re = \frac{V_\infty \times L}{\nu} = \frac{7m/s \times 1.1m}{1.562 \times 10^{-5} m^2/s} = 492957.7465$$

The Reynolds number is less than critical Reynolds number. Therefore, the outer flow is laminar. Using the proper relation for nusselt number, heat transfer coefficient is determined with the following equation.

$$Nu = \frac{h_c \times L_{react}}{k} = 0.664Re^{0.5}Pr^{1/3} = 0.664 \times 492957.75^{0.5} \times 0.7296^{1/3} = 419.58$$

$$h_{cov} = \frac{Nu \times k}{L} = \frac{419.58 \times 0.02551 \frac{W}{m \cdot ^\circ C}}{1.1m} = 9.73 \frac{W}{m^2 \cdot ^\circ C}$$

From equation 6.22, the overall thermal resistance of the outer reactor without ash insulation is become:

$$R_{Tot} = \frac{4}{3} \left[ \frac{\ln \frac{0.1525}{0.1495}}{2\pi \times 21.5 \times 1.1} + \frac{1}{2\pi \times 0.1525 \times 1.1 \times 9.73} \right] = 0.1432^\circ C/W$$

The rate of heat loss from outer reactor before ash insulation is installed becomes

$$\dot{Q}_{loss} = \frac{500^\circ C - 25^\circ C}{0.1432^\circ C/W} = 3.317kW$$

From equation 6.22, the overall thermal resistance of the outer reactor with ash insulation is

$$R_{Tot} = \frac{4}{3} \left[ \frac{\ln \frac{0.1525}{0.1495}}{2\pi \times 21.5 \times 1.1} + \frac{\ln \frac{0.2025}{0.1525}}{2\pi \times 0.02 \times 1.1} + \frac{\ln \frac{0.2055}{0.2025}}{2\pi \times 21.5 \times 1.1} + \frac{1}{2\pi \times 0.2055 \times 1.1 \times 9.73} \right]$$

$$R_{Tot} = 2.831^\circ C/W$$

The rate of heat loss from outer reactor after ash insulation is installed becomes

$$\dot{Q}_{loss} = \frac{T_{py} - T_\infty}{R_{Tot}} = UA(T_{py} - T_\infty) = \frac{500^\circ C - 25^\circ C}{2.831^\circ C/W} = 167.79W$$

The heat rate save by ash insulation is the difference heat rate before and after the screw reactor is insulated by ash insulation.

$$\dot{Q}_{saved} = 3.317W - 0.16779W = 3.14921kW$$

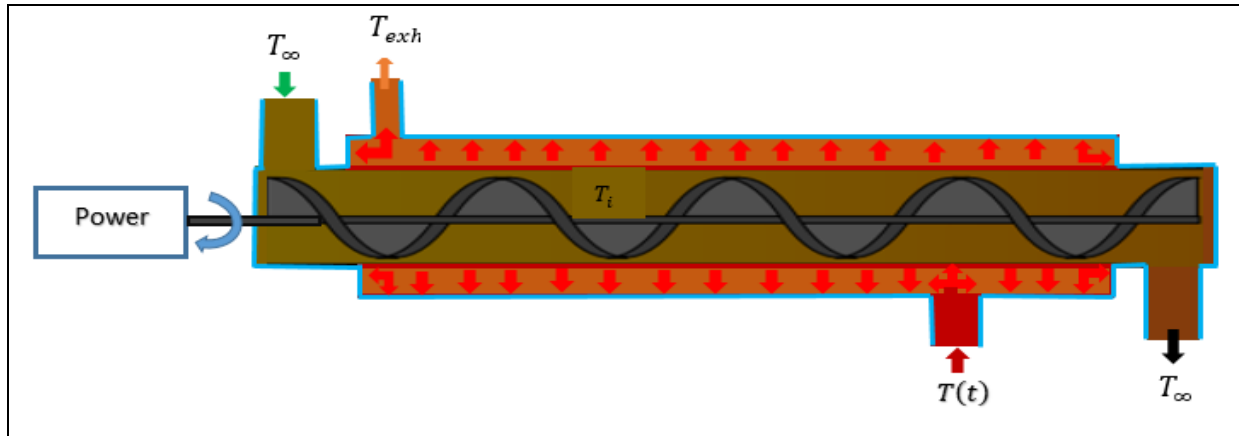


Figure 5-2. Heat transfer through outer reactor to surround

**5.3.5.2. Heat Loss from Combustion Chamber**

The heat loss from combustion chamber in all sides by conduction and convection. Combustion chamber is rectangular 790mm length, 500mm width and 400mm height with 56mm thickness which made from stainless steel with thermal properties such as 21.5W/kg.K is thermal conductivity, 7900kg/m<sup>3</sup> is density and 500J/ kg.K is specific heat and insulated by wood ash with 0.02 W/m.K thermal conductivity. The temperature in the combustion chamber is 600°C and the surrounding temperature is 25°C. The rate of heat transfer to the surrounding is

$$q_{loss} = \frac{T_{com} - T_{\infty}}{R_{Tot}} \dots \dots \dots 5.25$$

$$R_{side1} = \frac{0.006}{21.5 \times 0.316} + \frac{0.05}{0.02 \times 0.316} + \frac{1}{11.485 \times 0.316} = 8.19$$

$$Re = \frac{V_{\infty} \times L}{\nu} = \frac{7m/s \times 0.79m}{1.562 \times 10^{-5} m^2/s} = 354033.29$$

$$Nu = \frac{h_c \times L_{react}}{k} = 0.664 \times 354033.29^{0.5} \times 0.7296^{\frac{1}{3}} = 355.67$$

$$h = \frac{355.67 \times 0.02551}{0.79} = 11.485 \frac{W}{m^2 \cdot ^\circ C}$$

$$R_{side2} = \frac{0.006}{21.5 \times 0.2} + \frac{0.05}{0.02 \times 0.2} + \frac{1}{14.44 \times 0.2} = 12.85$$

$$Re = \frac{V_{\infty} \times L}{\nu} = \frac{7m/s \times 0.5m}{1.562 \times 10^{-5} m^2/s} = 224071.7$$

$$Nu = \frac{h_c \times L_{react}}{k} = 0.664 \times 224071.7^{0.5} \times 0.7296^{\frac{1}{3}} = 283$$

$$h = \frac{283 \times 0.02551}{0.5} = 14.44 \frac{W}{m^2 \cdot ^\circ C}$$

The total thermal resistance of combustion chamber before ash insulation is instilled

$$R_{tot} = 2 \times \left( \frac{0.006}{21.5 \times 0.316} + \frac{1}{11.485 \times 0.316} + \frac{0.006}{21.5 \times 0.2} + \frac{1}{14.44 \times 0.2} \right) = 0.624^\circ C/W$$

$$\dot{Q}_{loss} = \frac{600 - 25}{0.624} = 921.47W$$

The total thermal resistance of combustion chamber after ash insulation is instilled

$$R_{tot} = 2 \times 12.85 + 2 \times 8.19 = 42.08^\circ C/W$$

$$\dot{Q}_{loss} = \frac{600-25}{42.08} = 13.66W$$

The heat rate save by ash insulation in the combustion chamber

$$\dot{Q}_{saved} = 924.47 - 13.66 = 907.81W$$

The general heat rate saved from combustion chamber and outer reactor

$$\dot{Q}_{saved} = 907.81W + 3149.21W = 4.05702kW$$

The operation time of this screw reactor is eight hour per day; so the energy loss from the outer surface of reactor and combustion chamber without ash insulation per day become

$$Q = 95.5296MJ + 26.538336MJ = 122.067936MJ$$

The energy loss from the outer surface of reactor and combustion chamber with ash insulation per day become

$$Q = 4.832352MJ + 0.393408MJ = 5.22576MJ$$

The general heat saved from combustion chamber and outer surface of screw reactor become

$$Q = 122.067936MJ - 5.22576MJ = 116.842176MJ$$

Wood ash insulation is best insulation for this system because it saved 116.842176MJ heat where compared heat loss per day from screw reactor without and with ash insulation.

### 5.3.6. The Heat Transfer into Water Hyacinth Biomass

In the inner reactor, there is no heat loss and registered heat gain by the reactor. From newton's law of cooling, the rate of heat transfer to the water hyacinth flowing in inner reactor, if the surface temperature is constant can be expressed as

$$\dot{Q}_{py} = hA_s\Delta T_{ln} = \dot{m}C_p(T_e - T_i) \dots \dots \dots 5.26$$

That is, the increasing in the energy of water hyacinth by an increases mean temperature is equal to the heat transferred to the mass of water hyacinth from surface of reactor by convection. Where  $T_i$  and  $T_e$  are the mean temperature at inlet and exit of the reactor respectively, and  $\dot{Q}_{py}$  is the rate of heat transfer into the mass of water hyacinth biomass. Assume the outer surface of inner reactor is adiabatic after the temperature reaches the pyrolysis temperature and the surface temperature is constant. The rate of heat loss from inner reactor surface equal to heat gain by water hyacinth which it is converted to biochar. Considering the heating of a water hyacinth biomass in a reactor of constant cross section area whose inner surface is maintained at a constant temperature of  $T_s$ . It known that the mean temperature of water hyacinth increases in the flow direction as a result of heat transfer. There are two sample used in this experiment, so the mass flow rate is determined based on the mass input into the reactor in time. In this experiment water hyacinth biomass feed by screw conveyor from inlet to outlet of screw reactor take one minute and the mass flow rate of water hyacinth (leaf and stem) is 1.89kg/min

Simpson and TenWolde (1999) reported that the heat capacity of dry biomass is approximately related to temperature by the following equation.

$$C_{pBM} = 0.1031 \frac{kJ}{kgK} + 0.003867T_m \frac{kJ}{kgK^2} \dots \dots \dots 5.27$$

$$C_{pBC} = 0.1031 \frac{kJ}{kgK} + 0.003867T_e \frac{kJ}{kgK^2} \dots \dots \dots 5.28$$

At a Boundary conditions is  $x = 0, T_i = 25^\circ\text{C}$  and  $x = 1.3m, T_e = 490^\circ\text{C}$

$$\text{Where } \Delta T_{ln} = \frac{(T_i - T_e)}{\ln[(T_s - T_e)/(T_s - T_i)]} = \frac{(25 - 490)}{\ln[(500 - 490)/(500 - 25)]} = 120.44^\circ\text{C}$$

Generally the mass flow rate of those two samples of water hyacinth biomass are different based on their density, so take the average of mass flow rate of those two is 1.89kg/min for energy analysis in screw reactor. The rate of heat transfer into the water hyacinth at average specific heat of water hyacinth biomass is  $C_p = 2.15 \frac{kJ}{kg.K}$

From equation 6.26 the heat rate transfer into water hyacinth biomass in one minute

$$\dot{Q}_{py} = 1.89 \frac{kg}{min} \times 2.15 \frac{kJ}{kg.K} \times (763 - 298) = 1889.5275 \text{ kJ/min}$$

### 5.3.7. Energy Balance Calculation in the screw Reactor

The energy balance for any system undergoing any process is expressed as  $E_{in} - E_{out} = E_{system}$  which states that the amount of energy consumed by biomass during a process is equal to the difference between the amount of energy entering and the amount of energy leaving a reactor by mass [40].

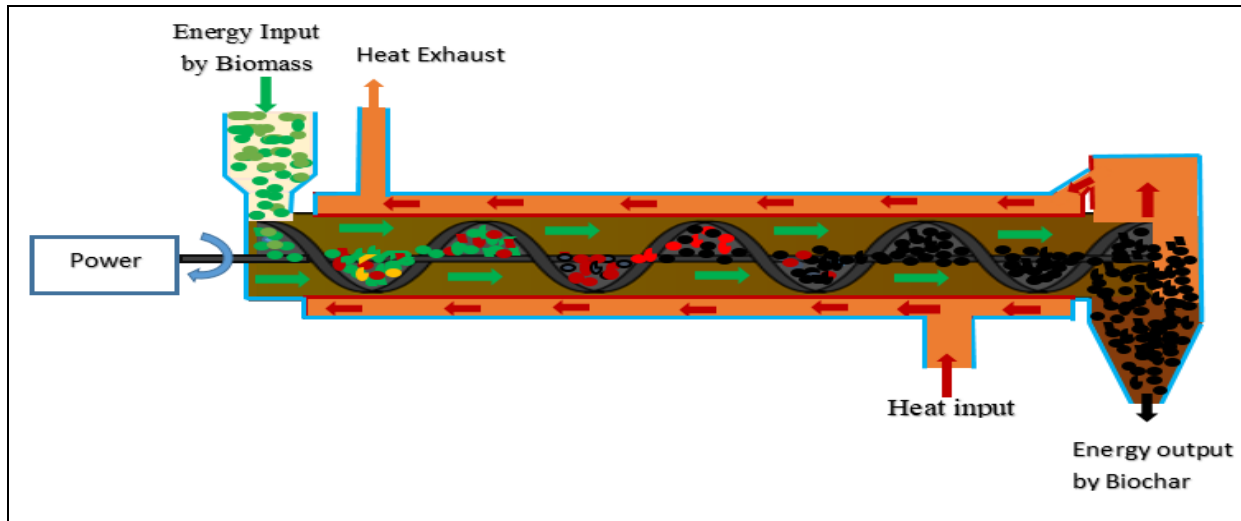


Figure 5-3. Energy balance in screw reactor

The energy available in the pyrolysis process are: input, output, loss and consumption energy by reactor and water hyacinth biomass. Energy input to the pyrolysis system was calculated based on the biomass energy and heat energy supplied to the reactor. Energy output was the total energy from biochar and pyrolysis gas. The energy loss and gain during each test was the sum of the energy required for pyrolysis heating plus energy required for system transmission and it was registered. So that, the energy consumed by water hyacinth biomass ( $Q_{py}$ ) was the energy calculated based on enthalpy entering into reactor and leaving from reactor. In this experiment the energy flows for pyrolytic reactor are illustrated in the Figure 5.3 can be transferred by heat and mass only. First inflow represented by  $H_{wh}$  enthalpy (energy) produced from the water hyacinth biomass flowing into the reactor. The second inflow  $Q_{in}$  is the heat transfer from combustion chamber into the reactor by hot combustion gases. The energy outflow are the enthalpy ( $H_{out}$ ) produced from mass exiting inner reactor and heat loss ( $Q_{loss}$ ) from the reactor. The heat feedback to outer reactor by return pipe and heat loss by output hot gas from cyclone is calculated from energy supply to combustion chamber and energy used for pyrolysis. During this pyrolysis process, the system was brought and assumed to steady state with respect to the bed temperature of the reactor. All parameters remained constant at their initial values except for the mass flow rate of the water hyacinth biomass which was adjusted

until a constant bed temperature near 500°C was achieved in specified residence time approximately 15min.

The energy flows associated with the mass of water hyacinth biomass into the reactor were calculated on the basis of a specific heat value associated with the temperature of the water hyacinth biomass and surface temperature of the reactor. The mass flow rate of water hyacinth biomass is precisely determined from mass input in time keeping at start and end of pyrolysis. The temperature at inlet and exit of the reactor were monitored with IR thermometer are 25°C and 490°C respectively.

When concluded the energy balance in the screw reactor for this experiment at 192.78kg of water hyacinth biomass pyrolysis in 102min. from this energy balance; first 199.245MJ energy supply into combustion chamber. The heat gain by inner reactor registered before start pyrolysis is 3.586003MJ and the total heat loss from the surface reactor and combustion chamber calculated is became 1.110474MJ and the energy consumption by water hyacinth biomass calculated from change of enthalpy is 192.732MJ.

The overall energy balance in the screw reactor with ash insulation is

$$H_{out} + Q_{loss} + Q_{gain} + Q_{out} = H_{input} + Q_{input} \dots \dots \dots 5.29.$$

$$Q_{out} = Q_{input} - Q_{loss} - Q_{gain} - Q_{py} \dots \dots \dots 5.30.$$

The energy output with hot gas is separated into energy feedback and energy loss with hot gas is calculated blow.

$$Q_{out} = 199.245\text{MJ} - 1.110474\text{MJ} - 3.586003\text{MJ} - 192.732\text{MJ} = 1.81892\text{MJ}$$

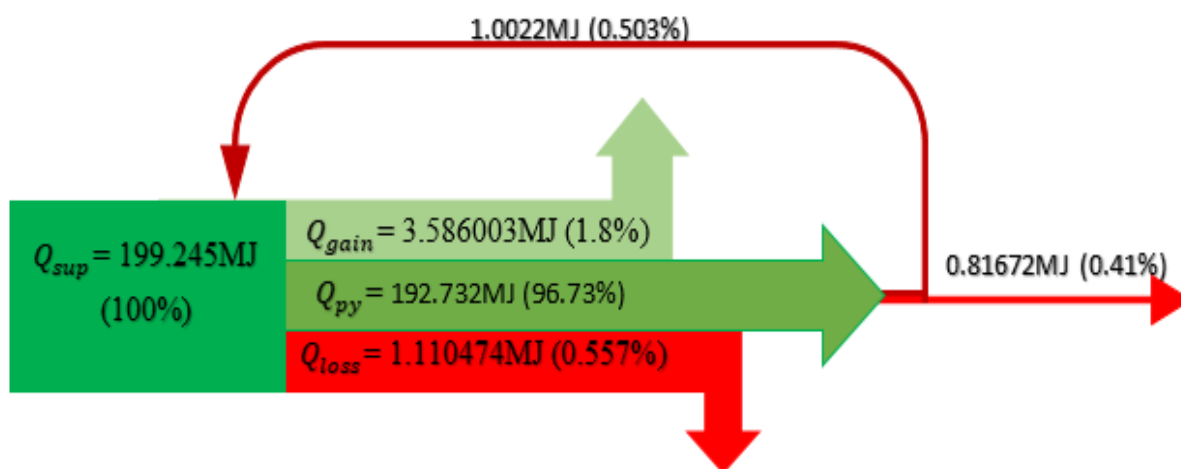


Figure 5-4. Sankey diagram of energy balance in continuous screw reactor

## Chapter Six

### 6. Experimental analysis

The general objective of this experiment is biochar production from water hyacinth continuously.

#### 6.1. Preparation and characterization of water hyacinth biomass

The experimental procedures for biochar production from water hyacinth biomass by continuous screw reactor as the follows:

##### 6.1.1. Preparation of leaves and stems of Water Hyacinth Biomass Sample

First, Fresh Water hyacinth is manually collected from Lake Tana in Amara region (12.00° N 37.25° E). The leaves and stems of collected water hyacinth sample are separated and Cut, the separated sample into small pieces of approximate 5-25mm by pole (Gejera). Then cut water hyacinth samples washed with water to remove any dust materials and stored in the polyethylene bags to taken in Addis Ababa institution of Technology compound by transportation. To remove moisture content from leaves and stems samples were sun-dried in 15days and 18days respectively. Then crushed the dried samples biomass into appropriate size by jaw crusher machine and kept in a polyethylene bag until used for pyrolysis.



Figure 6-1. General Preparation of Water Hyacinth Biomass Sample

##### 6.1.2. Characterization of leaves and stems of Water Hyacinth Biomass

Characterization of water hyacinth biomass sample was important in order to identify its suitability to undergo the thermochemical conversion process. The proximate and ultimate analysis tests by used “ASTM D3177-2” standard, calorific value and pure density of the water hyacinth biomass (leaf and stem) samples shows in Table 6.1.

### **6.1.2.1. Lower Heating Values of leaves and stems of water hyacinth**

A dried water hyacinth biomass sample is weighted and placed in a digital bomb calorimeter for calorific value or heating value determination. Then the digital bomb calorimeter is sealed and the water hyacinth sample is ignited electrically. The complete combustion of this biomass releases heat. So that by using a digital sensor, of the water bath surrounding the bomb calorimeter measured the change of temperature of biomass. The heat of combustion can be calculated from the resulting rise in temperature. The lower heating values of stems and leaves of water hyacinth biomass 3569.96cal/gm and 3320.55cal/gm respectively.

### **6.1.2.2. Proximate Analysis of Leaves and Stems of Water Hyacinth**

The proximate analysis of leaves and stems of water hyacinth biomass samples such as moisture content, ash content, volatile matter and fixed carbon content were determined by standard procedures.

The moisture content of stems and leaves sample of biomass were determined by first weighting 1g of each of wet sample biomass then placed in an oven to dry at 105°C for one hour and weighted 0.9354g and 0.9444g of a dried sample respectively. The moisture content was a weight loss that occurs when each sample are dried in oven at 105°C for one hour. The volatile matter content (VMC) were determined by weighted 1g oven dried of each sample then placed in furnace at a temperature of 950°C for 6 minutes and weighted 0.3021g and 0.3765g after cooling in a desiccator respectively. The volatile matter was a weight loss that produced when oven dried of each sample burned in furnace at a temperature of 950°C for 6 minutes. The ash content (AC) were determined by heated weighting 1g oven dried samples biomass in ash furnace at a temperature of 950°C for 4hrs and weighed 0.1075g and 0.1881g after cooling. The ash content of each sample was the mass weighted after a temperature of 950°C for 4hrs in ash furnace. The Fixed carbon (FC) weight content of stems and leaves of water hyacinth biomass sample were determined by subtracted the sum of moisture content weight, volatile matter weight and ash content weight from the weighted wet sample biomass.

$$\text{fixed carbon\%} = 100\% - (\text{ash\%} + \text{volatile matter\%} + \text{moisture\%})$$

### **6.1.2.3. Ultimate analysis of leaves and stems of water hyacinth biomass**

The ultimate analysis provides that the overall percentage of N, C, H, S and O presented in the stems and leaves of water hyacinth samples. Ultimate analysis was done to directly determine the carbon, hydrogen, nitrogen and Sulphur contents of the leaves and stems of water hyacinth

biomass samples by using EA 1112 Flash CHNS/O analyzer model which Carrier gas flow rate of 120 ml/min, reference flow rate 100 ml/min, oxygen flow rate 250 ml/min; furnace temperature of 900 °C and oven temperature of 75 °C. Six (6) calibration points for every component. Sample was run **in triplicate** and the average values are to be taken in Table 6.1. The oxygen percentage was computed by subtracted the sum of carbon (C), hydrogen(H), Nitrogen(N) and Sulphur(S) from 100% of each of biomass samples .

$$O\% = 100\% - (C + H + N + S)\%$$

Table 6-1. Proximate and ultimate analysis, caloric value and pure density of water hyacinth (leaf and stem) biomass samples

Characterization of leaves and stems of Water Hyacinth Biomass				
Types of sample		Water Hyacinth Leaves (wt %)	Water Hyacinth Stems (wt %)	Average (wt%)
Proximate Analysis	Moisture Content	5.56	6.46	6.01
	Ash Content	18.81	10.75	14.78
	Volatile Content	62.35	69.79	66.07
	Fixed Carbon	13.28	13	13.14
	Total	100	100	100
Heating value	Lower heating value	3320.55cal/gm	3569.96cal/gm	3445.255
Density	Pure density	0.93	0.87	0.9
Ultimate analysis	C	37.704	42.166	39.935
	H	4.2785	4.508	4.39325
	O	45.115	33.1555	39.13525
	N	12.5385	19.947	16.24275
	S	0.364	0.2235	0.29375
	Total	100	100	100

## **6.2. Experimental setup for biochar production from water hyacinth**

In this experiment continuous slow pyrolysis of water hyacinth biomass such as leaves and stems were conducted in screw reactor shown in Figure 4.7. It is made from stainless steel with an inner diameter 164mm and length 1.3m, an outer reactor with insulation of inner diameter 299mm, outer diameter 411mm and length 1.1m and screw conveyor of 160mm diameter with shaft of 25mm diameter and 1.748m length. This reactor is with all components for:

1. Continuous conveying component such as screw conveyor and feeder hopper
2. Discharging component such as cyclone and chimney
3. Heating systems components such as combustion chamber
4. Moving component such as wheels
5. Reduction speed components are pulleys, belt and gear box
6. Power produced component is motor

## **6.3. Preparation and characterization of Water Hyacinth biochar**

### **6.3.1. Preparation of biochar from leaves and stems of water hyacinth**

The continuous biochar preparation using slow pyrolysis experiments of water hyacinth with and without ash insulation are tested. The pyrolysis temperature of this experiment comes from combustion chamber and it is controlled by heat return with hot gas and blower. The heat flow from combustion chamber into inner reactor until the temperature of the surface is constant. At the surface temperature of reactor is constant; weighted and start input water hyacinth biomass into reactor continuously. The parameters that influence the biochar produced including heating rate, residence time, and pyrolysis temperature, type of biomass and particle size of water hyacinth biomass refer from literature review.

The procedures of preparation biochar from water hyacinth follows as

1. First combustion chamber and reactor were cleaned and dried before starting the test.
2. Facilitate the material such as: watch for time keep, IR thermometer for measure temperature and scale for weighting water hyacinth biomass and biochar
3. Feed 10.77kg dry wood into combustion chamber to generate energy used for pyrolysis.
4. The temperature in screw reactor before start up heating measured is 25°C.
5. Startup heating dry wood in combustion chamber and connect electrical blower specification is 220V, 3000/3600rpm and 3inch size to it for control heat transfer to reactor.



Figure 6-2. Blower

6. Measured the increment of temperature by 5min interval until the temperature is steady state
7. Record the temperature on the length of reactor noted as A, B and C for all tests until the temperature reached pyrolysis temperature 500°C.
8. The temperature of water hyacinth biomass input measured by IR thermometer is 25°C.



Figure 6-3. IR thermometer

9. The measured pyrolysis temperature distributions on the inner reactor before feed water hyacinth sample is 500°C in 15min and 30 min when the reactor with and without ash insulation respectively.

10. Feed 3.5kg each of leaves and stems of water hyacinth biomass into feeder hopper at time and it finished this mass in 2 minute.
11. Finally weighted 2.38kg and 2.3kg produced of biochar from 3.5kg leaves and stems water hyacinth biomass respectively.

#### Test one

During start pyrolysis measured the inner and outer surface temperature of the reactor without insulation and with flue gas after burner and combustion chamber until the temperature steady state. Take three point on the inner and outer reactor such as center (B), right end(C) and left end (A) of reactor. The pyrolysis temperature in the reactor stable (500°C) in 30min residence time by increasing 16°C/*min* and the average of outer surface temperature of reactor (450°C).

Table 6-2. Temperature distribution on inner and outer surface reactor without insulation

Time interval (min)	Temperature in reactor (°C)				Surface temperature of reactor(°C)			
	Left	Center	Right	Average	Left	Center	Right	Average
0	25	25	25	25	25	25	25	25
5	100	110	105	105	90	99	94.5	94.5
10	175	195	185	185	155	173	164	164
15	250	280	265	265	220	247	233.5	233.5
20	325	365	345	345	285	321	303	303
25	400	450	425	425	350	395	372.5	372.5
30	500	500	500	500	450	450	450	450
35	500	500	500	500	450	450	450	450

#### Test two

During start pyrolysis measured the inner and outer surface temperature of the reactor with ash insulation, flue gas return pipe and combustion chamber until the temperature steady state. Take three point on the inner and outer reactor such as center (B), right end(C) and left end (A) of reactor.

The pyrolysis temperature in the reactor stable ( $500^{\circ}\text{C}$ ) in 15min residence time by increasing  $40^{\circ}\text{C}/\text{min}$  and the average of outer surface temperature of reactor ( $100^{\circ}\text{C}$ ).

Table 6-3. Temperature distribution on inner and outer surface of reactor with ash insulation

Time interval (min)	Temperature in reactor ( $^{\circ}\text{C}$ )				Surface temperature of reactor( $^{\circ}\text{C}$ )			
	Left	Center	Right	Average	Left	Center	right	Average
0	25	25	25	25	25	25	25	25
5	220	230	225	225	44	46	45	45
10	415	435	425	425	83	87	85	85
15	500	500	500	500	90	100	95	95

The pyrolysis temperature in the reactor stable ( $500^{\circ}\text{C}$ ) in 15min residence time and the average of outer surface temperature of reactor ( $100^{\circ}\text{C}$ ) with ash insulation where The pyrolysis temperature in the reactor stable ( $500^{\circ}\text{C}$ ) in 30min residence time and the average of outer surface temperature of reactor ( $450^{\circ}\text{C}$ ) without ash insulation. Heat loss from reactor without insulation higher than the reactor with ash insulation.



Figure 6-4. Reactor with and without ash insulation

### 6.3.2. Characterization of leaves and stems of water hyacinth biochar

Characterization of water hyacinth biochar sample was important in order to identify its suitability to undergo the thermochemical conversion process. The proximate and ultimate

analysis tests by used “ASTM D3177-2” standard, calorific value and pure density of the water hyacinth (leaf and stem) biochar samples shows in Table 6.4.

### **6.3.2.1. Lower Heating Values of water hyacinth biochar**

The leaves and stems of water hyacinth biochar samples are weighted and placed in a digital bomb calorimeter for calorific value or heating value determination. Then the digital bomb calorimeter is sealed and the water hyacinth biochar sample is ignited electrically. The complete combustion of this biomass releases heat. So that by using a digital sensor, of the water bath surrounding the bomb calorimeter measured the change of temperature of biochar. The heat of combustion can be calculated from the resulting rise in temperature. The lower heating values of stems and leaves of water hyacinth biochar 3931.53cal/gm and 3420.44cal/gm respectively.

### **6.3.2.2. Proximate Analysis of Leave and Stem of Water Hyacinth biochar**

The proximate analysis of leaf and stem of water hyacinth biochar sample such as moisture content, ash content, volatile matter and fixed carbon content were determined by standard procedures. The moisture content of stems and leaves sample of biochar were determined by first weighting 1g of each of sample biochar then placed in an oven to dry at 105°C for one hour and weighted 0.9351g and 0.9903g of a dried sample biochar respectively. The moisture content was a weight loss that occurs when each sample are dried in oven at 105°C for one hour. The volatile matter content (VMC) were determined by weighted 1g oven dried of each sample then placed in furnace at a temperature of 950°C for 6 minutes and weighted 0.4981g and 0.7108g after cooling in a desiccator respectively. The volatile matter was a weight loss that produced when oven dried of each sample burned in furnace at a temperature of 950°C for 6 minutes. The ash content (AC) were determined by heated of weighting 1g oven dried samples biomass in ash furnace at a temperature of 950°C for 4hrs and weighed 0.2157g and 0.4278g after cooling. The ash content of each sample was the mass weighted after a temperature of 950°C for 4hrs in ash furnace. The Fixed carbon (FC) weight content of stems and leaves of water hyacinth biochar sample were determined by subtracted the sum of moisture content weight, volatile matter weight and ash content weight from the weighted sample of biochar.  $\text{fixed carbon\%} = 100\% - (\text{ash\%} + \text{volatile matter\%} + \text{moisture\%})$

### **6.3.2.3. Ultimate analysis of leaves and stems of water hyacinth biochar**

The ultimate analysis provides that the overall percentage of N, C, H, S and O presented in the water hyacinth biochar sample. Ultimate analysis was done to directly determine the carbon,

hydrogen, nitrogen and Sulphur contents of the leaves and stems of water hyacinth biochar samples by using EA 1112 Flash CHNS/O analyzer model which Carrier gas flow rate of 120 ml/min, reference flow rate 100 ml/min, oxygen flow rate 250 ml/min; furnace temperature of 900 °C and oven temperature of 75 °C. Four (4) calibration points for every component. Samples were run in duplicate and the average values are reported in Table 6.4. The oxygen percentage was computed by subtracted the sum of carbon (C), hydrogen(H), nitrogen(N) and Sulphur(S) from 100% of each of biochar samples.

$$O\% = 100\% - (C + H + N + S)\%$$

Table 6-4. Proximate and ultimate analysis, caloric value and pure density of water hyacinth (leaf and stem) biochar samples

Characterization of leaves and stems of Water Hyacinth Biochar				
Types of sample		Water Hyacinth Leaves (wt %)	Water Hyacinth Stems (wt %)	Average (wt%)
Proximate Analysis	Moisture Content	0.97	6.49	6.01
	Ash Content	42.78	21.57	32.175
	Volatile Content	28.92	50.19	39.555
	Fixed Carbon	27.33	21.75	24.54
	Total	100	100	100
Heating value	Lower heating value	3420.44	3931.53	3675.985
Density	Pure density	0.71	0.88	0.795
Ultimate analysis	C	35.5155	44.47	39.99275
	H	2.5415	3.468	3.00475
	O	50.948	51.3625	51.15525
	N	10.995	-	5.4975
	S	-	0.6995	0.34975
	Total	100	100	100

The result from experimental analysis from Table 6.1 and 6.4 compared proximate, ultimate and caloric values of water hyacinth (leaves and stems) biomass and biochar. The fixed carbon,

ash content and calorific value of water hyacinth biochar are higher than water hyacinth biomass when volatile matter of water hyacinth biomass higher than it biochar.

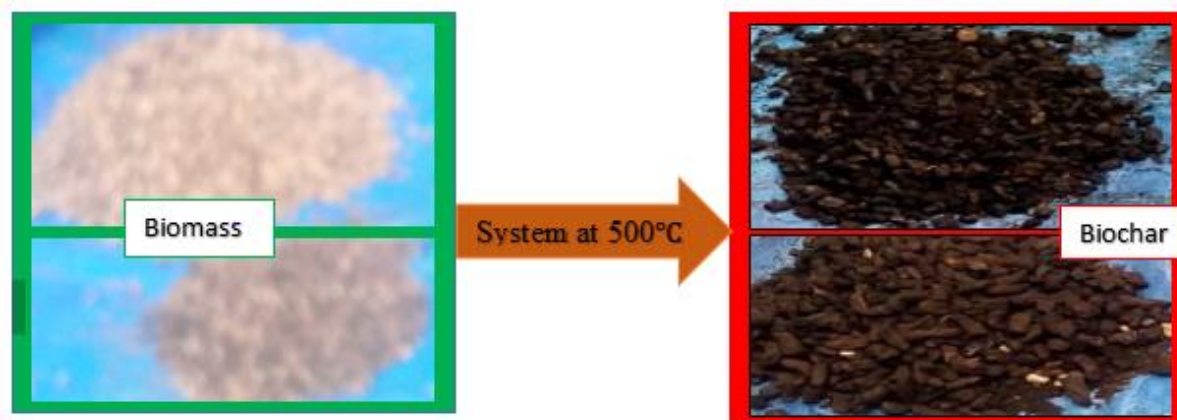


Figure 6-5 System to Produced Biochar from Water Hyacinth Biomass

#### 6.4. Total Cost of Screw Reactor Prototype and Characterization of Samples

Table 6-5. Total cost of material for machine and characterization of water hyacinth samples

No	Items	Description	Quantity	Unit Price	Total Cost
1	Screw With Shaft		1	1200	1200
2	Sheet Metal		3	1100	3300
	Bearing		2	130	260
3	Pulleys		2	600	1200
4	Belt		1	200	200
5	Wheels		4	150	600
6	Samples Preparation and Samples Characterization		4	2200	8800
7	Electric motor		1	2000	2000
8	Electric blower		1	500	500
	Total Cost				18060

## Chapter Seven

### 7. Result and Discussion

#### 7.1. Mass and Energy Yield of biochar

Mass yield of biochar is calculated based on the amount of water hyacinth biomass weighting input to reactor and the amount of weighting water hyacinth biochar produced after pyrolysis. Whereas the energy yields of the biochar was calculated based on the amounts of energy contain of the initial biomass and biochar after pyrolysis.

$$\text{biochar yield}(\%) = \frac{\text{mass of biochar}}{\text{mass water hyacinth biomass}} \times 100\%$$

$$\text{energy yield}(\%) = \frac{\text{mass biochar} \times LHV_{BC}}{\text{mass water hyacinth biomass} \times LHV_{BM}} \times 100\%$$

Based on experimental result, the conversion efficiency of biochar produced from stem and leaves is 68 % and 65.71 % respectively. The energy yield of leaves and stems of biochar are 70.05 % and 72.35 % respectively. The measured lower heating values of the produces leaves and stems biochar 14.32MJ/kg and 16.46MJ/kg while the lower heating values of water hyacinth biomass of leaves and stems are 13.9MJ/kg and 14.95MJ/kg respectively. This results show that biochar of stems water hyacinth higher energy yield and lower biochar yield than biochar of leaves. The water hyacinth for study has been collected by manpower from Lake Tana in Amara region is generated 964.7kg daily and from experiment result 656 kg of biochar produced by screw reactor can be generate daily. Optimum temperature has a significant effect on the produced biochar. From the result of test were pyrolysis temperature is increased biochar yield is decreased.

#### 7.2. Characterization of Biochar

##### 7.2.1. Proximate Analysis, Heating Value and Density Estimation

Proximate analyses of the Biochar produced from stem and leaves part of water hyacinth is determined experimentally as shown in Table 7.1. Heating value of 14.95 MJ/kg and 13.9 MJ/kg were obtained for Biochar produced from stem and leaves of water hyacinth. The volatile matter of the produced Biochar from stem of Water Hyacinth decreases by 28.14 % with respective to the feedstock. The volatile matter of the produced Biochar from leaves of Water Hyacinth decreases by 53.61% with respective to the feedstock. The average volatile matter of produced biochar from water hyacinth decreases by 40.87% with respective to the

feedstock. The result of Mierzwa-Hersztek M et al [41] and it is good to note that thermal conversion of organic materials by pyrolysis reduced the volatile matter content.

The fixed carbon of the produced Biochar from stem of Water Hyacinth increases by 67.31 % with respect to the feedstock. The same applies for the Biochar produced from leaves of water Hyacinth increases 51.41% with respect to the feedstock. The average fixed carbon of produced biochar from water hyacinth increases by 59.381% with respect to the water hyacinth biomass. This result is good to note that thermal conversion of organic materials by pyrolysis increases the fixed carbon content [42]. Based on the result, the biochar yield increases where, the fixed carbon content of Biochar produced from both feedstock (Leaves and stem of water Hyacinth) increases while volatile matter decreases.

The result also showed that, the moisture content of the produced Biochar from Water Hyacinth decreases by 37.94% with respect to the feedstock. This means the moisture content of water hyacinth biomass is higher than the moisture content of produced biochar. Due to the decrease in the moisture content of produced biochar, the ash content of this biochar increases. The lower heating value of produced Biochar in both cases is higher than the initial feedstock. This is due to the fact that, during the pyrolysis process, the volatile matter is released, the fixed carbon content is increased and the moisture content is decreased. This leads to an increase in the lower heating value of the biochar [43]. The results of pure density determined in the experiment show that the density of biochar produced from both water hyacinth biomass (leaf and stem) decreases with respect to their feedstock. When comparing the density of leaves and stems of water hyacinth biomass, leaves have a higher pure density than stems. This is due to the fact that, the biomass has a high density to produce a high product. So that the water hyacinth leaves biomass have a higher conversion efficiency than stems of water hyacinth biomass.

### **7.2.2. Ultimate Analysis**

Ultimate analyses of the Biochar produced from stem and leaves part of water hyacinth is determined experimentally as shown in Table 7.1. From the experiment results, the hydrogen in biochar produced from leaf decreases by 40.6% with respect to the leaf of water hyacinth biomass and the hydrogen in biochar produced from stems decreases by 23.07% with respect to the stem water hyacinth biomass. Based on the result of ultimate analysis, the carbon and oxygen in Biochar produced from both feedstock (Leaves and stem of water Hyacinth) increase while hydrogen decreases with respect to their initial feedstock. Generally, we compare the produced biochar with water hyacinth biomass based on ultimate

analysis result, the carbon in water hyacinth biochar increases by 0.15% with respect to water hyacinth biomass while hydrogen is decreased by 31.61%.

Generally from the results of characterization of biochar and biomass of water hyacinth, biochar produced from water hyacinth biomass has high value of carbon content and calorific value than its feedstock. Due to this fact that, biochar produced from pyrolysis of water hyacinth biomass was acceptable for use as a renewable solid fuel (charcoal) and production of carbonaceous materials.

Table 7-1. Proximate and Ultimate Analysis, Density and Calorific Value of Water Hyacinth Biomass (Leaves and Stems) and Produced Biochar

Characterization of leaves and stems of Water Hyacinth biomass and Biochar						
Proximate Analysis						
Content	Water Hyacinth biomass			Water Hyacinth biochar		
	Leaves	Stems	Average	Leaves	Stems	Average
Moisture Content	5.56	6.46	6.01	0.97	6.49	3.73
Ash Content	18.81	10.75	14.78	42.78	21.57	32.175
Volatile Content	62.35	69.79	66.07	28.92	50.19	39.555
Fixed Carbon	13.28	13	13.14	27.33	21.75	24.54
Total	100	100	100	100	100	100
LHV( Cal/gm)	3320.55	3569.96	3445.26	3420.44	3931.53	3675.985
Pure density	0.93	0.87	0.9	0.71	0.88	0.795
Ultimate analysis						
C	37.704	42.166	39.935	35.5155	44.47	39.99275
H	4.2785	4.508	4.39325	2.5415	3.468	3.00475
O	45.115	33.1555	39.1352	50.948	51.3625	51.15525
N	12.5385	19.947	16.2427	10.995	-	5.4975
S	0.364	0.2235	0.29375	-	0.6995	0.34975
Total	100	100	100	100	100	100

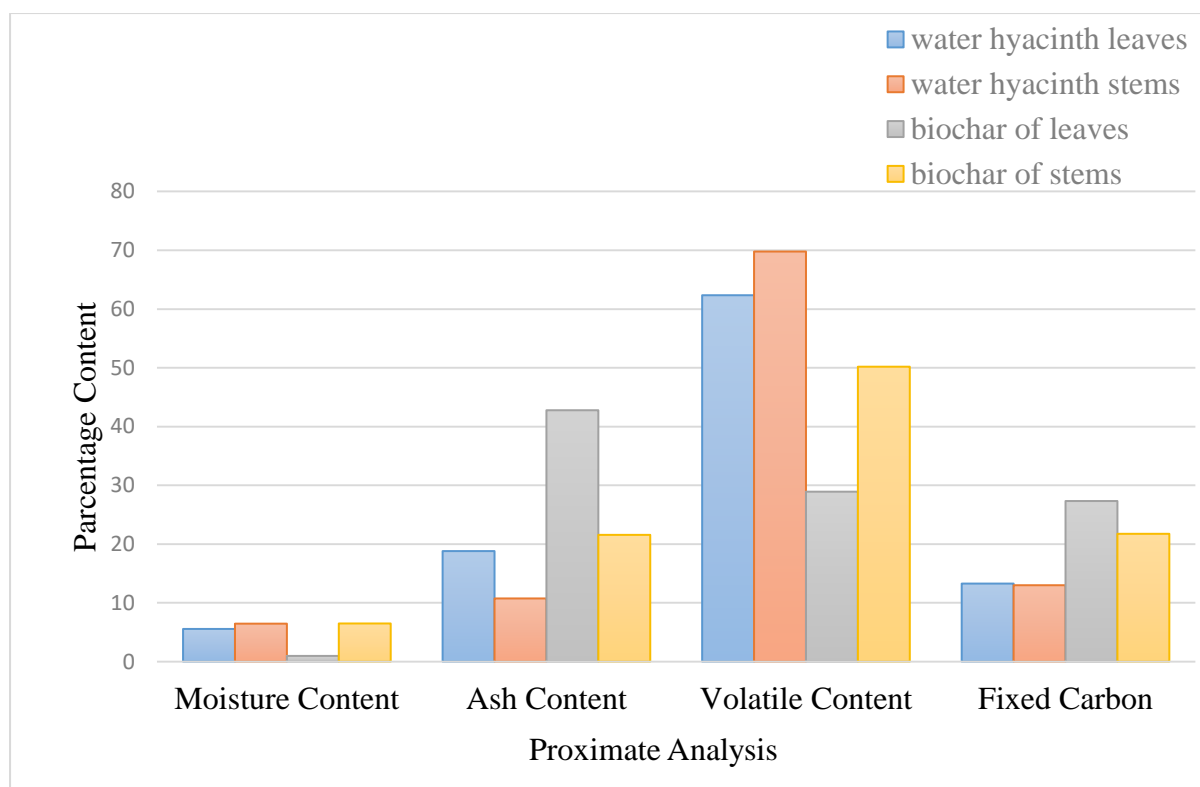


Figure 7-1. Compare the biochar of leaves and stems with their feedstock by proximate analysis

### 7.3. Effects of various Parameters on Biochar Production

#### 7.3.1. Effect of Temperature

Pyrolysis temperatures significantly influences biochar yield production from water hyacinth biomass. The results of biochar produced at 450, 500 and 600°C when input the 1kg of water hyacinth biomass shown in figure 7.1. At pyrolysis temperature increases from 450°C to 500°C the yield of biochar produced from leaves and stems decreased by 30% and 25% with respective to their feedstocks respectively . At pyrolysis temperature increases from 500°C to 600°C the yield of biochar produced from leaves and stems decreased by 30% and 45% with respective to their feedstocks respectively. Also results of experiment show that at increases pyrolysis temperature the size particle, oxygen and hydrogen presence in biochar produced decreases while carbon content increased. The degree of carbonization for biochar produced from water hyacinth was accelerated with increasingly pyrolysis temperature until 600°C.

The result Tao Kan et al [29] show at temperature higher than 600°C pyrolysis temperature the biochar products are converted into gas due to the dominant secondary cracking reactions. Based on this experiment result, 500°C suitable for biochar production from both leaf and stems water hyacinth biomass.

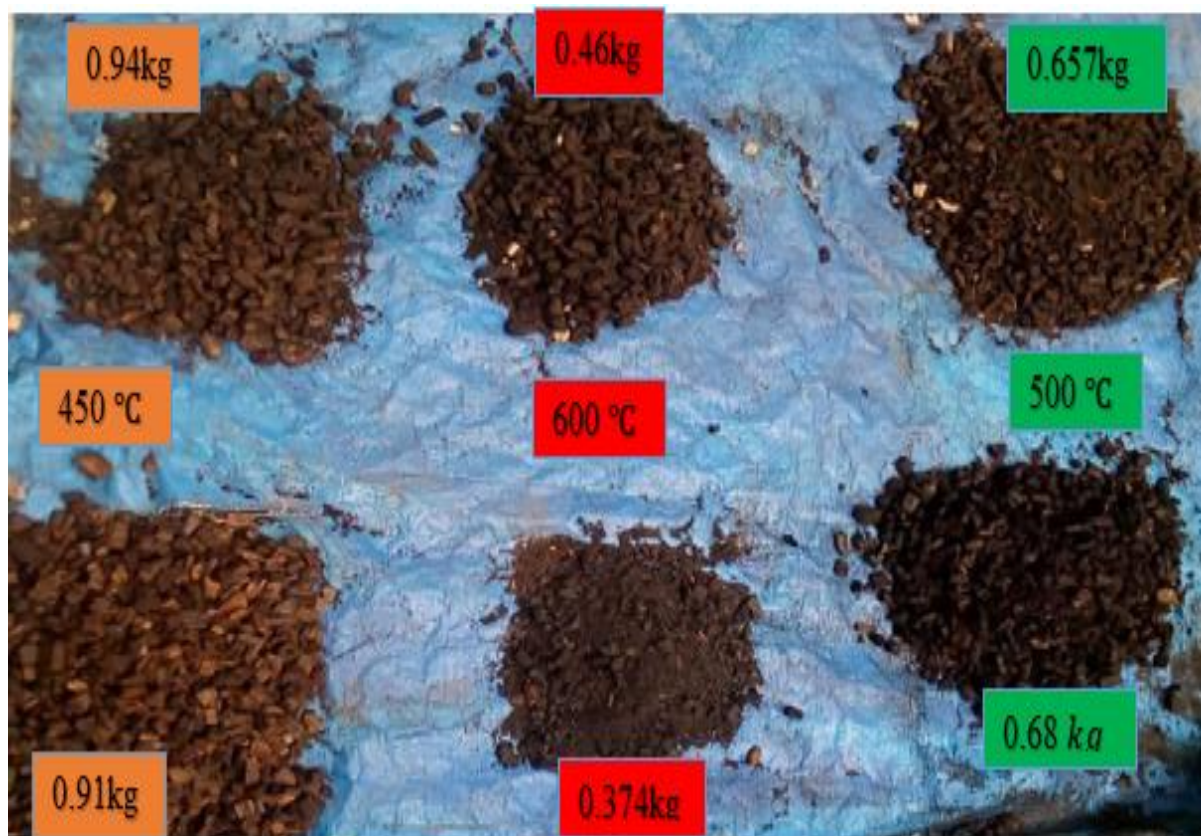


Figure 7-2. Effect of different pyrolysis temperature on biochar production

### 7.3.2. Effect of Insulation

In this experiment the surface of screw reactor is insulated by wood ash. The addition of wood ash insulation on a surface of reactor reduces the amount of heat loss from the screw reactor. So that the energy supplied to the reactor save in the reactor for produce biochar from water hyacinth continuously. If the thickness of insulation increases the heat loss decreases. The temperature distribution on manufactured prototype of screw reactor has been detected without and with ash insulation while the experiment was conducted making use of Infrared thermometer show in Table 5.2 and 5.3 respectively. Based on result of energy analysis, reactor with ash insulation is reduced heat loss by 95% and time consume for start pyrolysis reduced from 30min to 15min with respect to reactor without ash insulation.

Table 7-2. Compare heat loss and time consume by screw reactor without and with ash insulation

Type of reactor	$Q_{sup}$	$t_{spy}$	$Q_{loss}$	$m_{BC}$	$t_{epy}$
Reactor without insulation	199.245MJ	30min	22.633MJ	114.38kg	89min
Reactor with insulation	199.245MJ	15min	1.1105MJ	131.1kg	102min

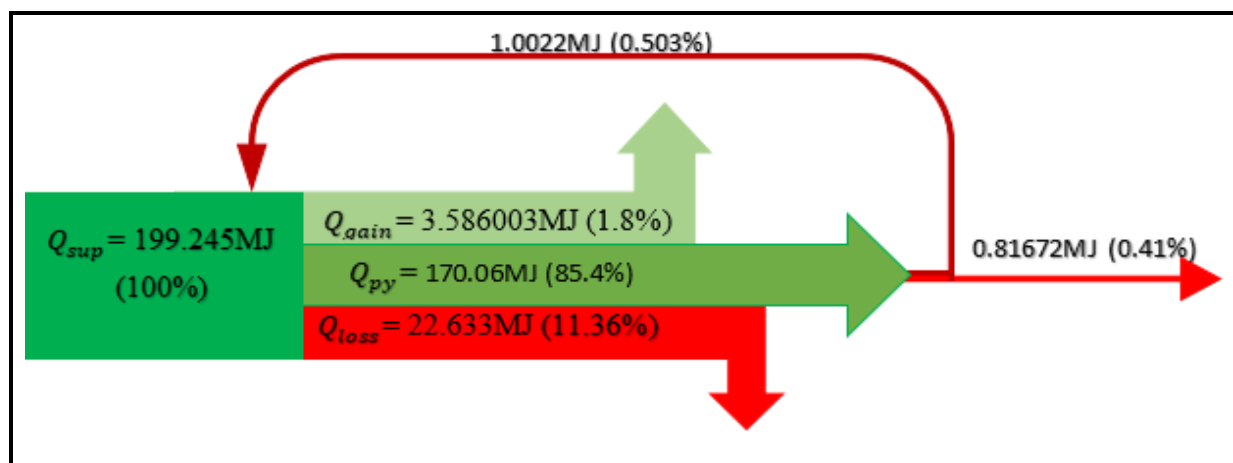


Figure 7-3. Sankey diagram of energy analysis in screw reactor without ash insulation

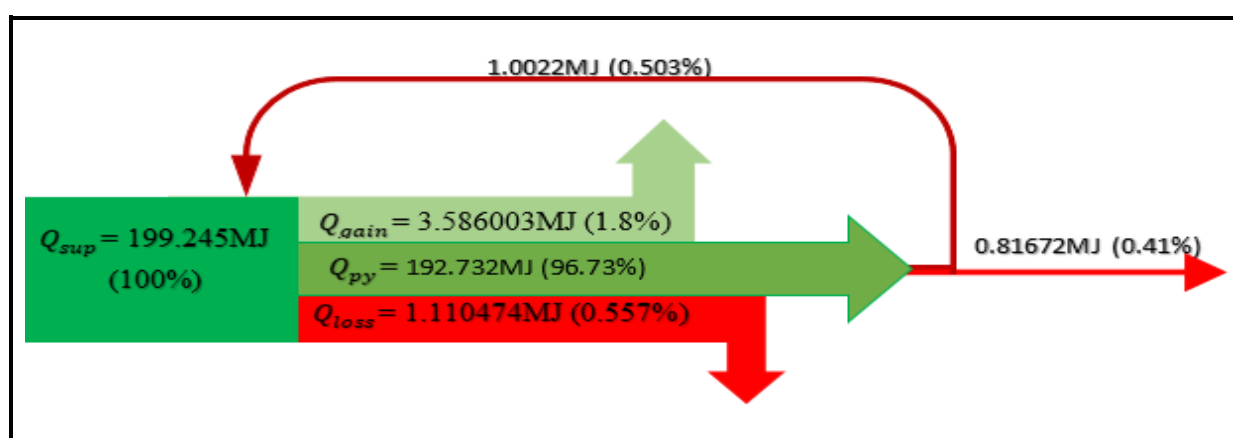


Figure 7-4. Sankey diagram of energy analysis in screw reactor with ash insulation

### 7.3.3. Effect of moisture

Moisture is the amount of water available in material; it is a critical component of biomass quality and a function quality control in biochar production. The moisture content in both leaves and stems of water hyacinth biomass can have different effects on the production of biochar and pyrolysis gas depending on the environment in the reactor. The collected water hyacinth biomass (leaf and stems) dried to remove the moisture content by sunlight. water hyacinth stems take 18 days for drying while water hyacinth leaf take 15 days, this means stems of water hyacinth higher moisture content than leaves of water hyacinth during pre-processing. From the result of proximate analysis, moisture content of stems higher than moisture content of water hyacinth leaves biomass which is shown in Table 7.1. The stems of water hyacinth to produce smaller biochar than leaves of water hyacinth due to higher moisture presence in stems. The experiment results concluded that water hyacinth biomass contain high moisture content influences the transformation effectiveness, decreased fixed carbon, increased volatile matter and decreased the calorific value of biochar

#### 7.4. Comparison continuous and batch reactor based on capacity and time

From the experimental result, the production capacity of continuous biochar production is about 656 kg/day from water hyacinth while the batch type biochar production about is 310.8kg/day from flower waste (Bogale, 2017). In Ethiopia, 50kg of wood charcoal can be sold approximately 240 birr. So, the income generated was calculated by keeping their selling price and amount to be sold the same; Continuous biochar production generates 3148.8 Ethiopian birr per day while batch biochar production generates 1491.84 Ethiopian birr per day. Also batch type biochar production takes longer time compared to continuous biochar production. Because feeding the raw materials and discharging the product was performed by using screw conveyor which is driven by a motor, where as in batch type production process, feed and product is discharged manually. The most benefits of continuous biochar production over batch is that it has no delay time for charging water hyacinth biomass and discharging the biochar. Therefore it has been found that continuous biochar production is more economical than batch type.



Figure 7-5. A. Continuous biochar production

B. Batch type Biochar production [12]

Continuous screw reactor saved energy than batch reactor because continuous reactor is insulated by ash insulation. The conversion efficiency of biochar produced from water hyacinth is 68 % while the conversion efficiency of biochar produced from flower waste is 55.5%. Based on this result water hyacinth is higher conversion than flower waste. Flower waste is collected from flower farm after collected flower so that for gate flower waste any time is very difficult while water hyacinth is unwanted waste available on water surface and gate any time easily. Biochar production from water hyacinth is economical other than biochar production from flower waste.

## Chapter Eight

### 8. Conclusion and Recommendation

#### 8.1. Conclusion

In this paper, biochar is produced from both leaves and stems of water hyacinth biomass, characterized and compared with water hyacinth biomass properties. Also a novel Pyrolysis technology to produce Biochar from water hyacinth has been done, 3D modelling, manufactured and tested. It is very important in producing biochar that is an attractive technology, easily moving from one place to another place and excellent for even production of yields. Water hyacinth biomass used for this experiment collected from Lake Tana. Based on experimental result, the efficiency of conversion is 68 % and 65.71 % for biochar produced from leaves and stems of water hyacinth respectively. The energy yield of leaves and stems of biochar are 70.05 % and 72.35 % respectively. Ultimate and proximate analysis of both water hyacinth and biochar determined were shown in Table 7.1. The measured lower heating values of the produced leaves and stem biochar is 14.32 MJ/kg and 16.46 MJ/kg respectively. From experiment result, biochar contains low volatile matter, low moisture content, high LHV and high fixed carbon content than its feedstock. Ash Insulation was used to maintain temperature condition in the slow pyrolysis process. Based on result of energy analysis, ash insulation used for screw reactor is reduced heat loss by 95% and time consumed for start pyrolysis reduced from 30min to 15min. based on daily operational hour of 8, the system produces 656.21 kg and 613.872 kg of Biochar from the leaves and stem of water hyacinth biomass respectively and 11.84MJ energy saved by ash insulation. In Ethiopia, 50 kg of wood charcoal can be sold approximately 200 Ethiopian Birr (An average value for 2019). Therefore, by selling 656.21kg of the produced charcoal, 2624.84 Ethiopian Birr can be obtained daily. In general water hyacinth biomass and biochar produced characterized, energy used for this pyrolysis is determined with effect of temperature. Due to adopting this continuous pyrolysis technology, water hyacinth problem can be converted into an opportunity. The income would be generated from the selling of the produced Biochar and finally the serious environmental impact of the water hyacinth is reduced.

## **8.2. Recommendation**

The study presented in this document obviously indicates that biochar can be produced from water hyacinth. The main source of hydropower in Ethiopia such as lake and river are at extreme risk due to the aggressive water hyacinth. Thus the government, non-governmental organizations and private sectors should make combined efforts to improve the extreme risk due to the aggressive water hyacinth in Ethiopia.

- This study recommends measurement of experimental setup determined and modelled to be taken and duplicate at similar potential.
- Motivate peoples to remove water hyacinth from lake and river.

## **8.3. Future Work**

- Manufacturing a compacting machine to increase density of biochar.
- Identify cooling mechanisms for Cooling produced biochar.

## 9. Reference

### Reference

- [1] Su J Bin, Zhang GW, Zhu WZ, et al, *Removal Of Pb(II) Using Bio-Char from Microwave Pyrolysis Carbonization of Water Hyacinth. DEStech Transactions on Environment, Energy and Earth Science (peee)*. DOI: 10.12783/dteees/peee2016/3829., no. ISBN: 978-1-60595-376-2, 2016.
- [2] Worku M and Sahile S , "Impact of Water Hyacinth, Eichhornia crassipes (Martius) (Pontederiaceae) in Lake Tana Ethiopia: A Review," *Aquaculture Research & Development* , vol. 09(01), no. DOI: 10.4172/2155-9546.1000520, p. 9–11, 2017.
- [3] R. Ebhin Masto, Sandeep Kumar, T.K. Rout, Pinaki Sarkar, Joshy George and L.C. Ram, "Biochar from water hyacinth (Eichornia crassipes) and its impact on soil biological activity," *Catena*, vol. 111, pp. 64-71, 2013.
- [4] Wang Z and Yan SH , " Direct and strong influence of water hyacinth on aquatic communities in natural waters," *Environmental Challenges, Management and Utilization*, no. DOI: 10.1201/9781315151809, pp. 44-65, 2017.
- [5] D. Terefe, "a Weed Grown Out of Control," <http://projects.infonile.org/index.html>, 2018.
- [6] Hill MP and Coetzee JA , "Integrated control of water hyacinth in Africa," *EPPO Bulletin* , vol. 38(3), no. DOI: 10.1111/j.1365-2338.2008.01263, pp. 452-457, 2008.
- [7] S. Kibret, "Ethiopian lake tana is losing the fight to water hyhcinyh, university of California,," *postdoctoral research*, September 4,2017.
- [8] P. S, " Threats, management and envisaged utilizations of aquatic weed Eichhornia crassipes: An overview," *Environmental Science and Biotechnology* , vol. 11(3), no. DOI: 10.1007/s11157-012-9289-4, p. 249–259, 2012.
- [9] W.-b. H, "Water Hyacinth (Eichhornia crassipes) Biology and Its Impacts on Ecosystem, Biodiversity, Economy and Human Well-being," *Natural Sciences Research* , vol. 8(6), no. DOI: 10.7176/jnsr/9-12-04, p. 94–100, 2019.
- [10] S. A, "News\_ The first modern water hyacinth harvester arrived at Lake," 2018.

- 
- [11] C. O. f. I. T. B. Development, " Evaluation of Water Hyacinth Harvester and WH Management of Lake Tana , Ethiopia," 2018.
- [12] W. Bogale, "Preparation of Charcoal Using Flower Waste," *Journal of Power and Energy Engineering*, vol. 5, no. <https://doi.org/10.4236/jpee.2017.52001>, pp. 1-10, 2017.
- [13] J. Lehmann, "Bio-Energy in the Black," *Frontiers in Ecology and the Environment*, vol. 5, no. <https://doi.org/10.1890/1540-9295>, pp. 81-387, 2007.
- [14] Dinesh Mohan, Ankur Sarswat, Yong Sik Ok and Charles U. Pittman Jr, "Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent—a critical review," *.Bioresource Technology*, vol. 160, pp. 191-202, 2014.
- [15] Jin Sun Cha, Sung Hoon Park, Sang-Chul Jung, Changkook Ryu and Jong-Ki Jeon , "Production and utilization of biochar: A review," *Journal of Industrial and Engineering Chemistry*, no. <http://dx.doi.org/10.1016/j.jiec.2016.06.002>, pp. 1-15, 2016.
- [16] Johannes Lehmann, John Gaunt and Marco Rondon, " Biochar Sequestration in Terrestrial," *Mitigation and Adaptation Strategies for Global Change*, vol. 11, p. 403–427, 2006.
- [17] Jonelle Cornette, Clairmont Clementson and David Fredericks, "Environmentally Sustainable Management of Water Hyacinth (*Eichhornia crassipes*) in Guyana," *International Journal of Agriculture and Forestry* , vol. 8(1), no. DOI: 10.5923/j.ijaf.20180801.02, pp. 4-9, 2018.
- [18] Feng Li, Kaixuan Shen, Xiaolin Long, Jiasheng Wen, Xiaojie Xie and Xiangyun Zeng, "Preparation and Characterization of Biochars from *Eichornia crassipes* for Cadmium Removal in Aqueous Solutions," *PLoS ONE*, vol. 11(2), no. e0148132. doi:10.1371/journal.pone.0148132, 2016.
- [19] Shahabaldin Rezanian, Mohd Fadhil Md Din, Siti Fatimah Kamaruddin, Shazwin Mat Taib, Lakhveer Singh, Ee Ling Yong and Farrah Aini Dahalan, "Evaluation of water hyacinth (*Eichhornia crassipes*) as a potential raw material source for briquette production," *Energy* , vol. 111, pp. 768-773, 2016.

- [20] Liyi Ye, Jingmiao Zhang, Jie Zhao, Zhiming Luo, Song Tu and Yingwu Yin, "Properties of biochar obtained from pyrolysis of bamboo shoot shell," *Journal of Analytical and Applied Pyrolysis*, vol. 114, p. 172–178, 2015.
- [21] Frederik Ronsse, Sven Van Hecke, Dane Dickinson and Wolter Prins, "Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions," *Bioenergy*, vol. 5, p. 104–115, 2013.
- [22] Michael O. Fagbohunge, Ben M.J. Herbert, Lois Hurst, Hong Li, Shams Q. Usmani and Kirk T, "Impact of biochar on the anaerobic digestion of citrus peel waste," *Bioresource Technology*, vol. 216, pp. 142-149, 2016.
- [23] Abhishek Sharma, Vishnu Pareek and Dongke Zhang, "Biomass pyrolysis—A review of modelling, process parameters," *Renewable and Sustainable Energy Reviews*, vol. 50, p. 1081–1096, 2015.
- [24] Manoj Tripathi, J.N.Sahu and P.Ganesan, "Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review," *Renewable and Sustainable Energy Review*, vol. 55, pp. 467-481, 2016.
- [25] Hussein Kisiki Nsamba, Sarah E. Hale, Gerard Cornelissen and Robert Thomas Bachmann, "Sustainable Technologies for Small-Scale," *Journal of Sustainable Bioenergy Systems*, vol. 5, no. <http://dx.doi.org/10.4236/jsbs.2015.51002>, pp. 10-31, 2015.
- [26] Jan Pieters and Frederik Ronsse, "Heat and mass transfer modelling of auger reactors," *Xiaogang Shi*, p. Ghent, 2015-2016.
- [27] Gao Ningbo, Liu Baoling, Li Aimin and Li Juanjuan. , "Continuous pyrolysis of pine sawdust at different pyrolysis temperatures and solid residence times," *Journal of Analytical and Applied Pyrolysis*, vol. 114, no. <http://dx.doi.org/10.1016/j.jaap.2015.05.011>, p. 155–162, 2015.
- [28] Muhammad Irfan, Qun Chen, Yan Yue, Renzhong Pang, Qimei Lin, Xiaorong Zhao and Hao Chen, "Co-production of biochar, bio-oil and syngas from halophyte grass (*Achnatherum splendens* L.) under three different pyrolysis temperatures," *Bioresource*


- Technology*, vol. 211, no. <http://dx.doi.org/10.1016/j.biortech.2016.03.077>, p. 457–463, 2016.
- [29] Tao Kan, Vladimir Strezov and TimJ.Evans, "Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters," *Renewable and Sustainable Energy Reviews*, vol. 57, p. 1126–1140, 2016.
- [30] Yining Sun a,b, Bin Gao b, Ying Yao, June Fang, Ming Zhang, Yanmei Zhou, Hao Chen and Liuyan Yang, "Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties," *Chemical Engineering Journal*, vol. 240, pp. 574-578, 2014.
- [31] Nurhidayah Mohamed Noor, Nurhayati Abdullah and Adilah Shariff, "Slow Pyrolysis of Cassava Wastes for Biochar Production and Characterization," *Iranica Journal of Energy & Environment*, vol. 3, pp. 60-65, 2012.
- [32] D. Klinar, "Universal model of slow pyrolysis technology producing biochar and heat from standard biomass needed for the techno-economic assessment," *Bioresourc Technology*, vol. 206, p. 112–120, 2016.
- [33] Jie Zhang, Jia Liu and Rongle Liu, "Effects of pyrolysis temperature and heating time on biochar obtained from the pyrolysis of straw and lignosulfonate," *Bioresourc Technology*, vol. 176, pp. 288-291, 2015.
- [34] R.S. KHURMI and J.K. GUPTA, machine design, india, 2005.
- [35] Shigley's, Design of Mechanical Elements, Spur and Helical Gears, Eighth Edition, North Carolina State University:: The McGraw–Hill Companies, 2008.
- [36] Thermodynamics: An Engineering Approach, 5th edition, by Yunus A. Çengel and Michael A. Boles.
- [37] Michael J. Moran and Howard N. Shapiro, Fundamentals of Engineering Thermodynamics, 5th Edition, The Ohio State University and Iowa State University of Science and Technology: John Wiley & Sons, Inc.
- [38] I. dewitt, Fundamentals of Heat and Mass Transfer 7th Edition Incropera dewitt, Donnelley (Jefferson City): Macmillan Company, 2011.

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- [39] Incropera/DeWitt, One-Dimensional Steady-State Conduction; Radial Systems:Cylinder," in Fundamentals of Heat and Mass Transfer six edition, Bergman, Lavine, pp 125-129.
- [40] Y. A. CENGEL, CONVECTION HEAT TRANSFER MECHANISM;HEAT TRANSFER, A Practical Approach SECOND EDITION PP 334-340.
- [41] Mierzwa-Hersztek M, Gondek K, Jewiarz M, et al, "Assessment of energy parameters of biomass and biochars, leachability of heavy metals and phytotoxicity of their ashes," *Material Cycles and Waste Management*, vol. 21, p. 786–800, 2019.
- [42] Brachi P, Miccio F, Miccio M, et al , "Torrefaction of Tomato Peel Residues in a Fluidized Bed of Inert Particles and a Fixed-Bed Reactor," *Energy and Fuels*, no. DOI: 10.1021/acs.energyfuels.6b00328, p. 4858–4868, 2016.
- [43] Holtmeyer ML, Li G, Kumfer BM, et al., " The Impact of Biomass Cofiring on Volatile Flame Length.," *American Chemical Society, Energy & Fuel*, vol. 27, no. DOI: 10.1021/ef4013505., p. 7762–7771, 2013.

## Appendixes

### A. Proximate Analysis

#### A1. Proximate analysis of leaf and stems of water hyacinth biomass lab test result

	<b>GEOLOGICAL SURVEY OF ETHIOPIA</b>	Doc.Number: GSE/F 5.10-2	Version No: 1
	<b>GEOCHEMICAL LABORATORY DIRECTORATE</b>		Page 1 of 1
Document Title:	Hydrocarbon Laboratory Analysis Report	Effective date:	May, 2017

Issue Date: - 28/03/2019

Customer Name: - **Tamiru Adugna**

Request No: - GLD/177/19

Report No: - GLD/TR/135/19

Sample type: - Water Hynaeith blumass

Sample Preparation : - 60 Mesh

Date Submitted: - 22/03/2019

Number of Sample: - Two (2)


Elements to be determined: (Moisture, Volatile matter, Fixed carbon and Ash), Calorie & pure density.


Method of analysis: Proximate Analysis, Adiabatic Calorie Metter and Gravimetric method


Collectors' Code	Moisture %	Volatile Matter %	Fixed carbon %	Ash %	Calorific Value Cal/gm.	Pure Density
Steam	6.46	69.79	12.99	10.75	3569.96	0.87
Leaf	5.56	62.35	13.28	18.81	3320.55	0.93

Note: - This result represent only for the sample submitted to the laboratory


Analysts: Haimanot Bayeh  
Shashe Haile

Approved By:   
Alemnesh Abate

Quality Control:   
Negash Worku



## A2. Proximate analysis of leaf and stems of water hyacinth biochar lab test result

	<b><u>GEOLOGICAL SURVEY OF ETHIOPIA</u></b>	Doc.Number: GSE/F 5.10-2	Version No: 1
	<b><u>GEOCHEMICAL LABORATORY DIRECTORATE</u></b>		Page 1 of 1
Document Title:	<b>Hydrocarbon Laboratory Analysis Report</b>	Effective date:	May, 2017


Issue Date: - 18/06/2019  
 Request No: - GLD/384/19  
 Report No: - GLD/TR/335/19  
 Sample Preparation : - 60 Mesh  
 Number of Sample: - Two (2)

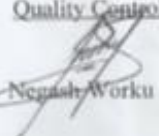
Customer Name: - Tamirat Adugna  
 Sample type: - water Hynacith biochar  
 Date Submitted: - 03/06/2019  
 Elements to be determined: (Moisture, Volatile matter, Fixed carbon and Ash), Calorie & Sulfur.  
 Method of analysis: Proximate Analysis, Adiabotic Calorie Metter and Gravimetric method


Collectors' Code	Moisture %	Volatile Matter %	Fixed carbon %	Ash %	Calorific Value Cal/gm.	Sulfur %	Pure Density
1-stem	6.49	50.19	21.75	21.57	3931.53	0.99	0.88
2-leaf	0.97	28.92	27.33	42.78	3420.44	0.17	0.71

Note: - This result represent only for the sample submitted to the laboratory..

Analysts:  
Haimanot Bayeh  
Shashe Haile

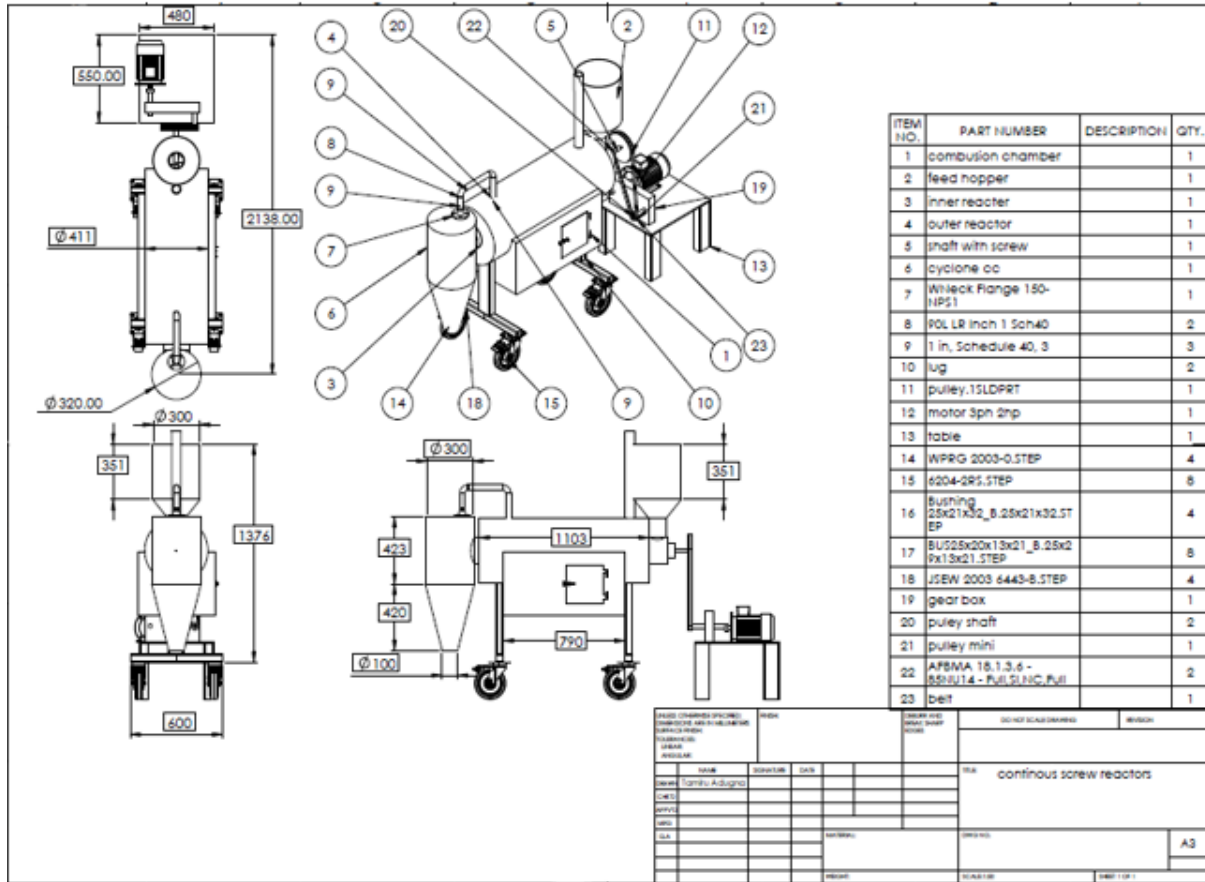
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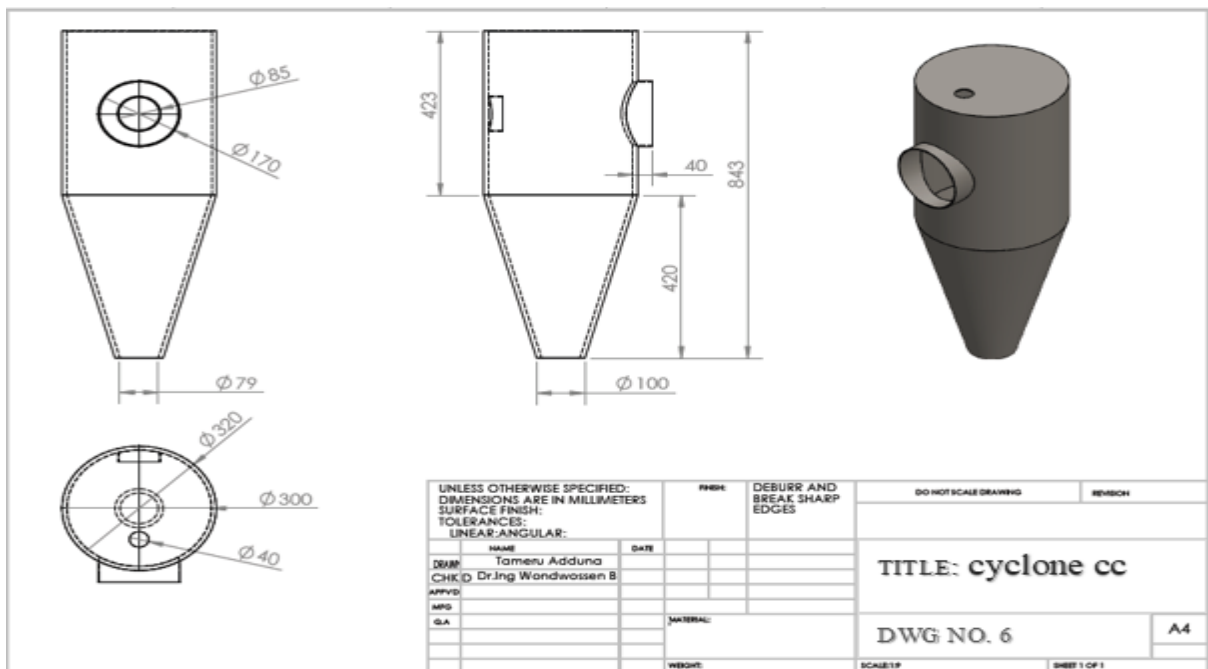


## B. Screw Reactor and Its Components With Dimensions

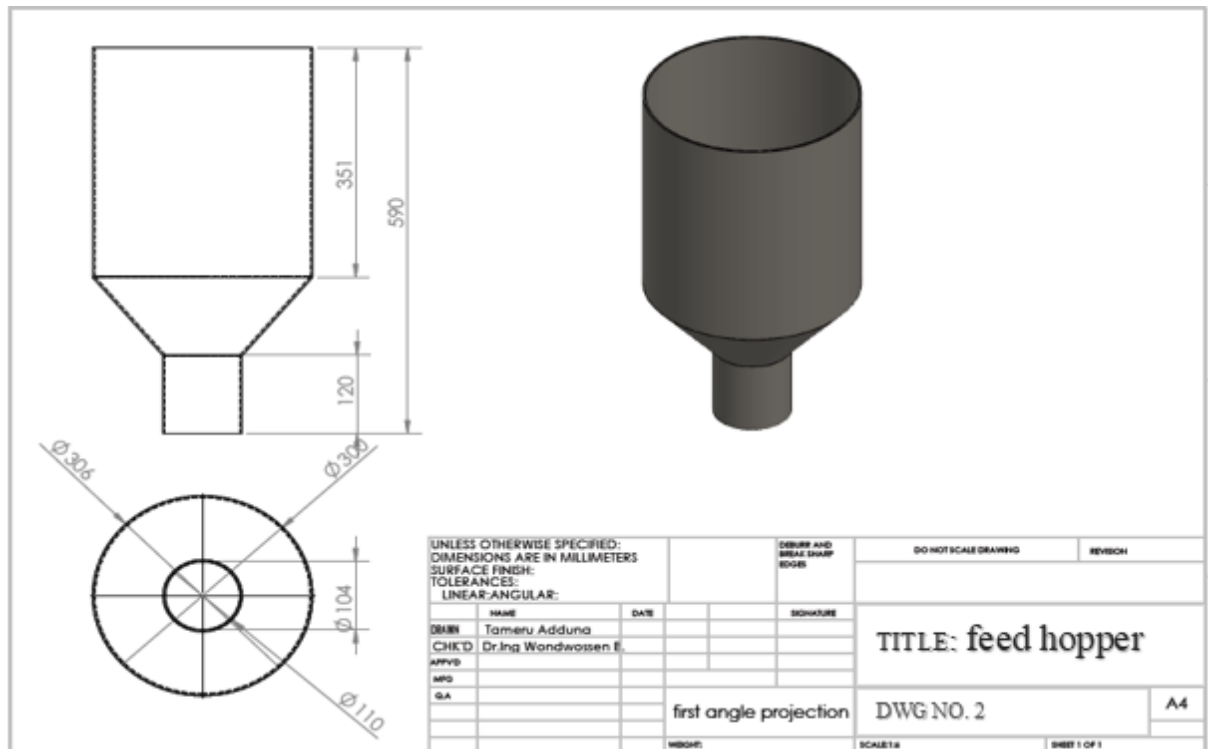
### a. Screw reactor



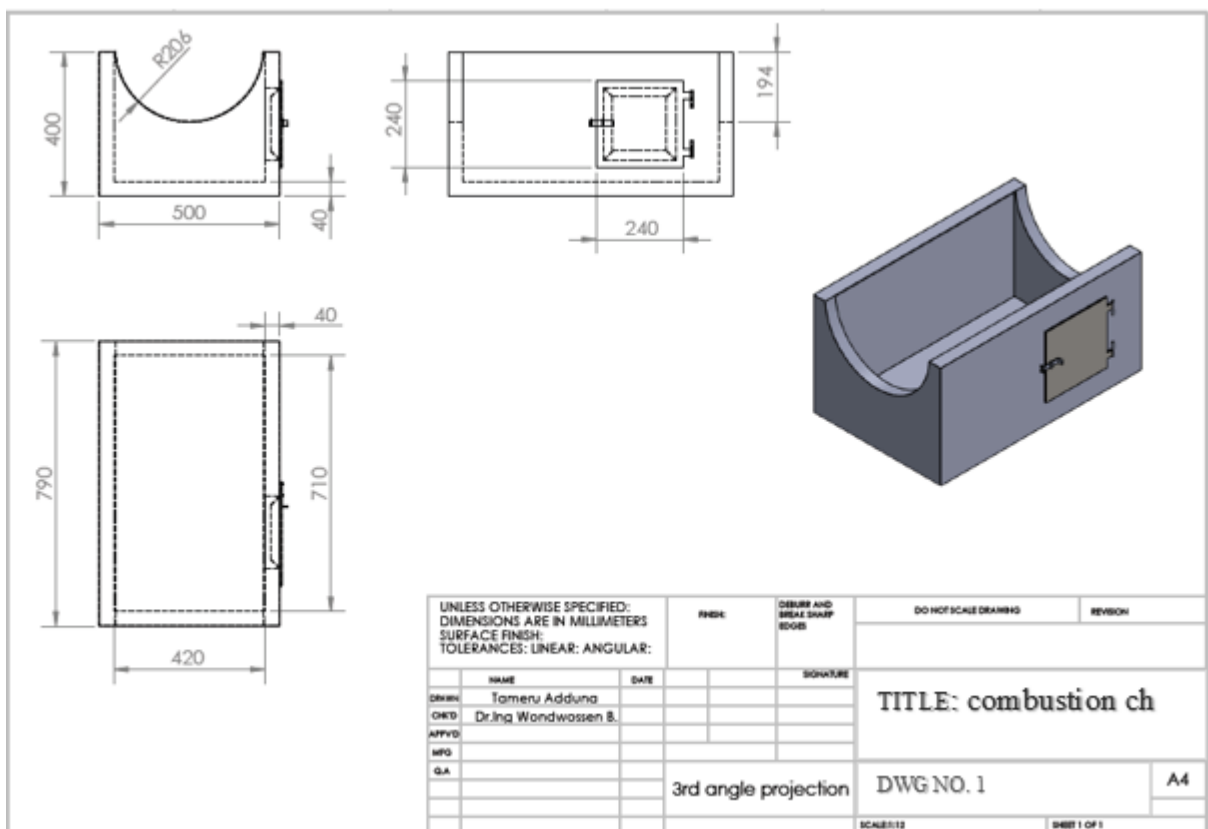
### b. Cyclone separator



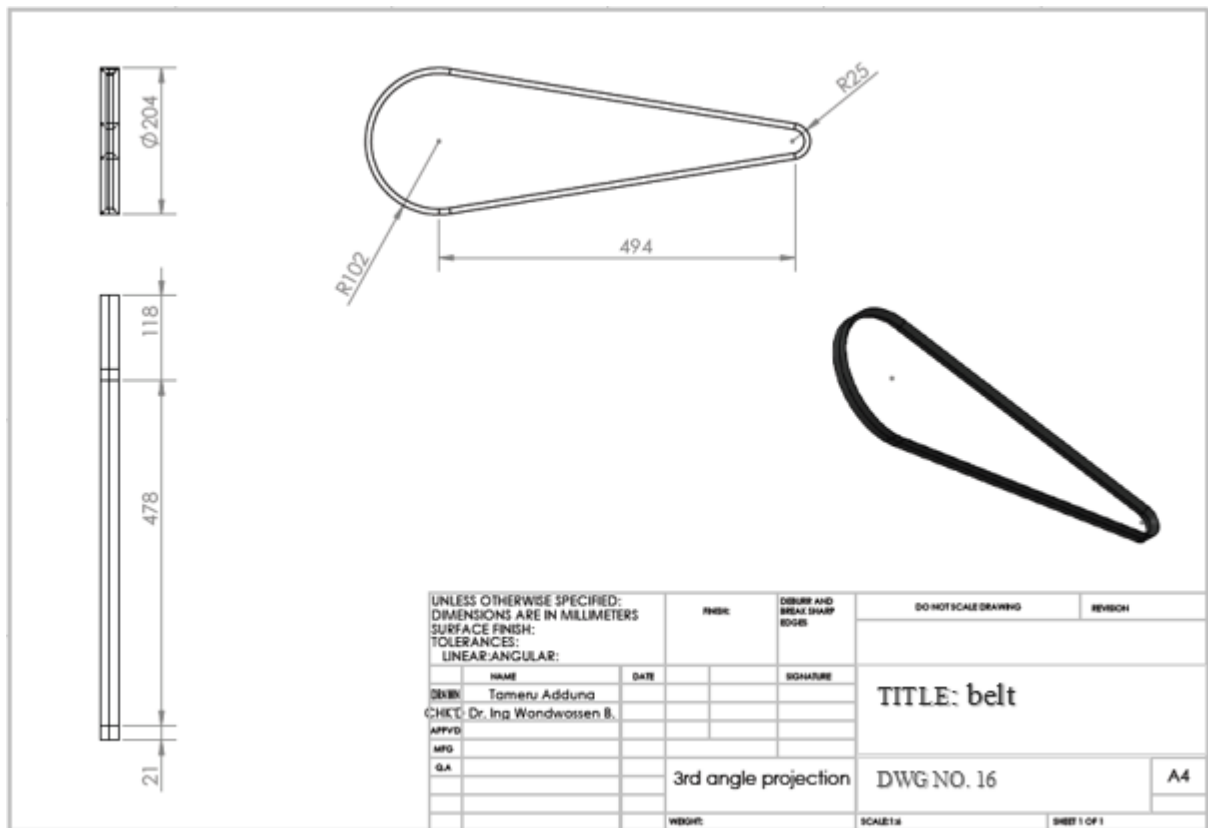
c. Feed hopper



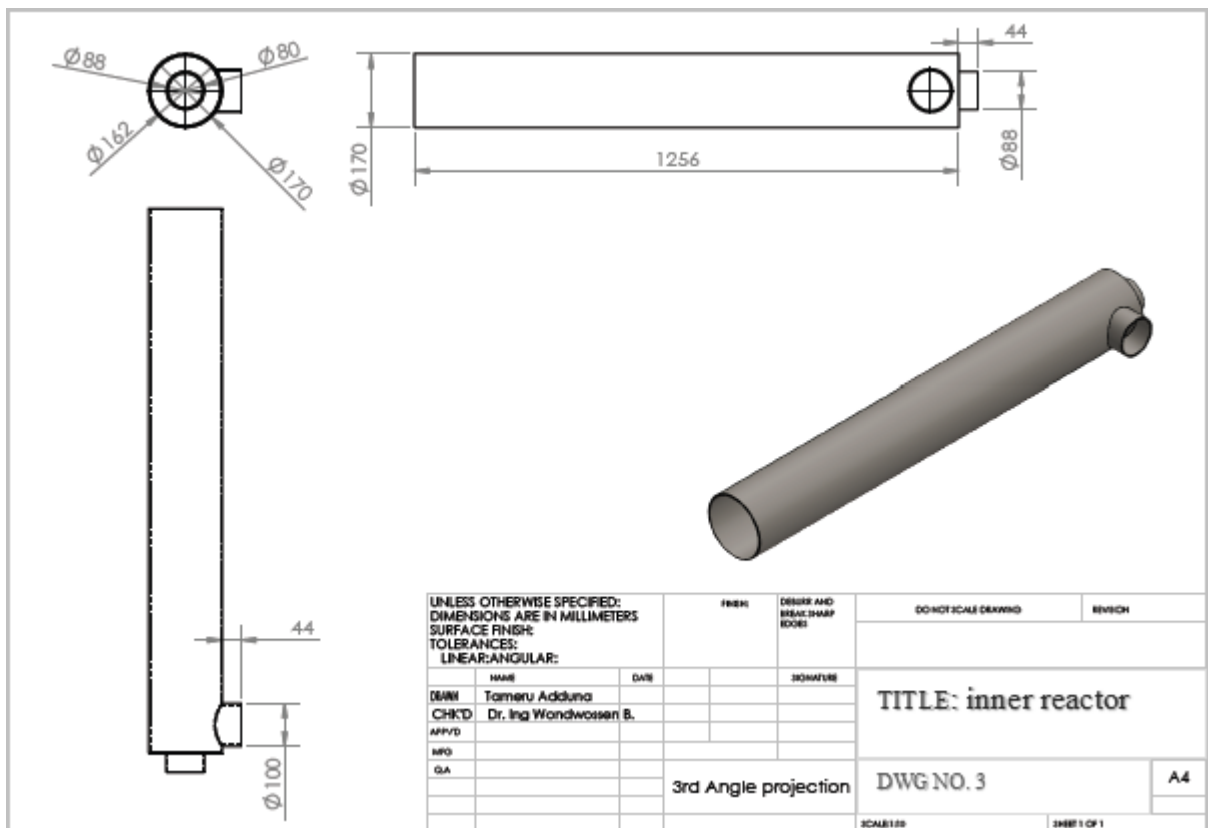
d. Combustion Chamber



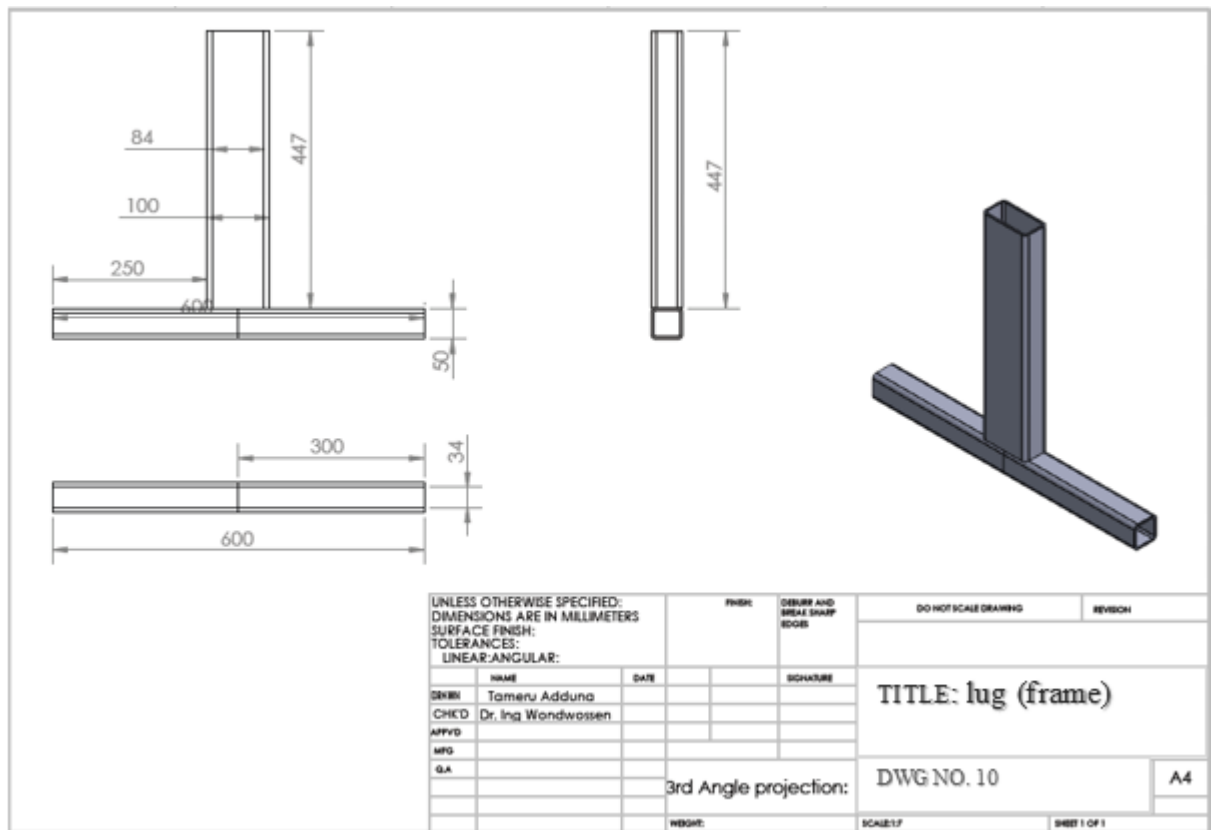
e. Belt



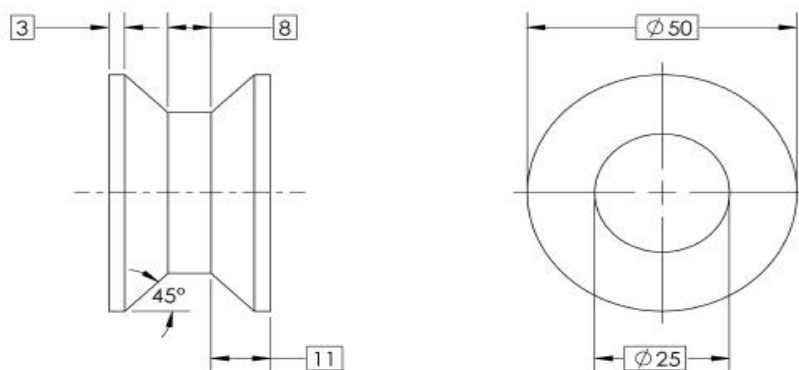
f. Internal Reactor



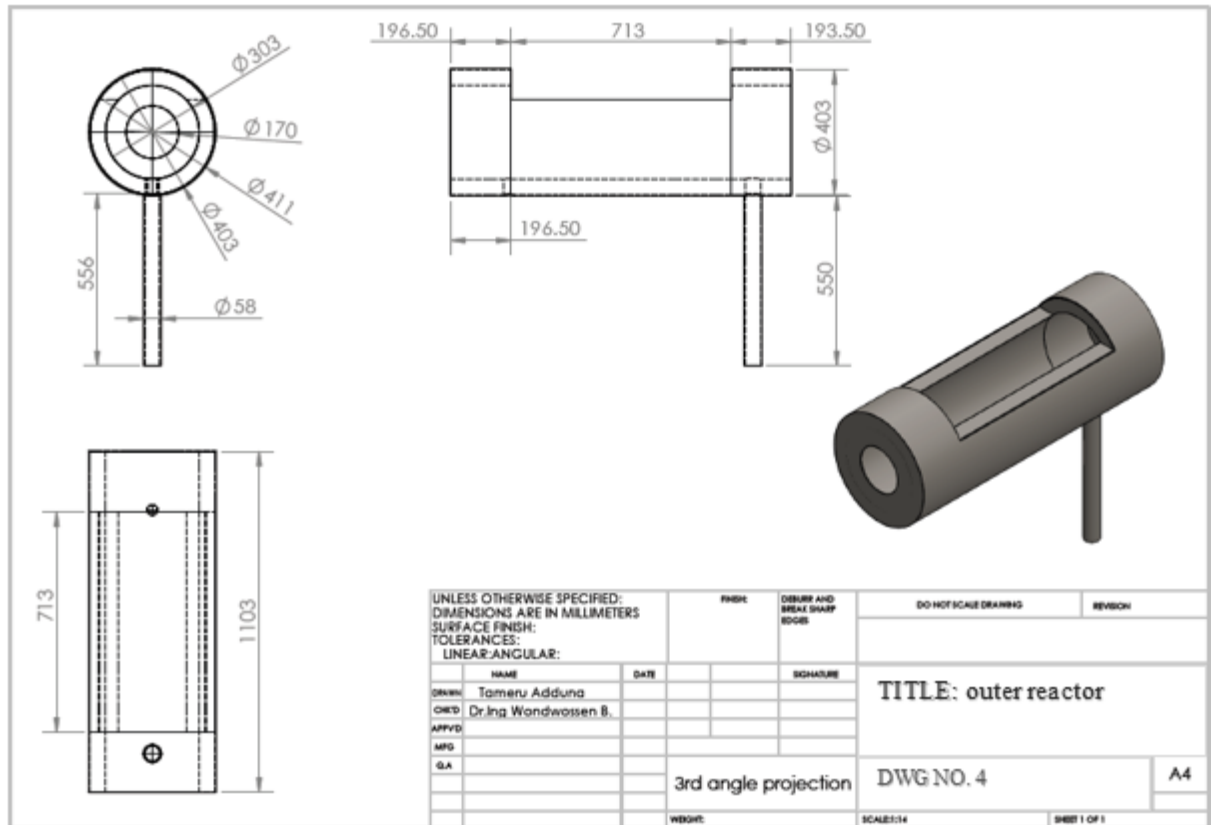
g. Frame



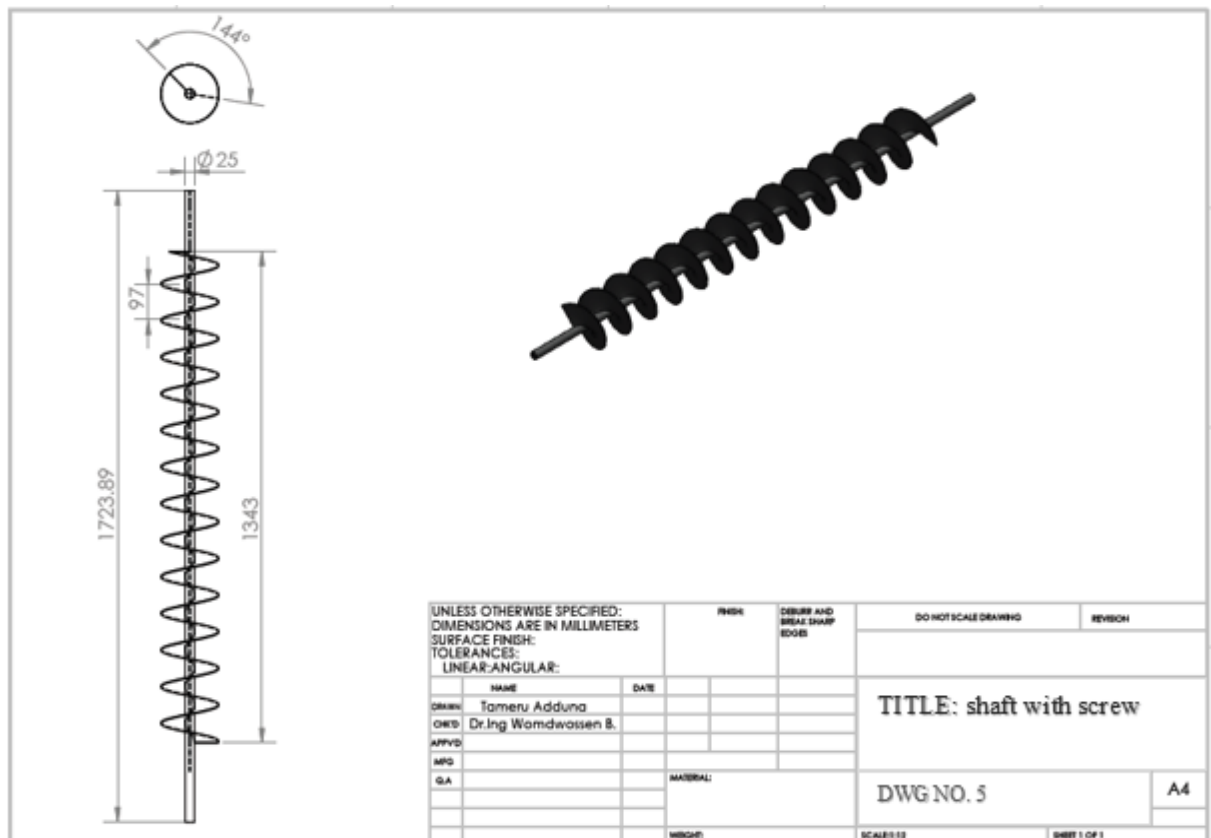
h. Pulley



i. Outer Reactor with ash insulation



j. screw conveyor with solid shaft



## C. Calculation for design of components

### C1. Design of screw shaft

Assumption and given data for design screw shaft

Assumed diameter of shaft 25mm and  $T_s = 1.2T_p$

1. Assumed diameter of shaft 25mm and  $T_s = 1.2T_p$  where  $T_s$  is The torque transmission by the shaft and  $T_p$  is torque transmitted by the belt to pulley from driven shaft
2. The permissible working stresses and shear stresses are 84MPa and 42 MPa respectively.
3. Based screw conveyor available on the market assumed the important dimensions such as screw diameter, clearance between screw and tube, pitch of screw, shaft diameter, thickness of screw flight and length of shaft are 160mm, 2mm,100mm, 25mm, 3mm and 1.724m respectively.
4. Weight of flight is(  $8kg \times 10m/s$  )/1343mm and the weight of the pulley is  $3kg \times 10m/s$

The torque transmission by the shaft due to power calculated from the torque transmitted by the belt to pulley

$$T_s = 1.23T_p = 1.23 \times 200Nm = 246Nm$$

The maximum bending moment of the acting on the shaft

$$M_{max} = FxL_s = 2960.625N \times 0.130 = 384.88Nm$$

According to maximum shear stress theory, equivalent twisting moment of solid shaft given

$$T_e = \sqrt{M^2 + T_s^2} = \frac{\pi}{16} \tau \times d^3$$

$$\frac{\pi}{16} \tau \times d^3 = \sqrt{384.9^2 + 246^2} = 456.8Nm = \frac{\pi}{16} \times 42 \text{ MPa} \times d^3 = 456.8Nm$$

$$d^3 = \frac{456.8Nm}{8246680.716N/m^2} = 5.54 \times 10^{-5}$$

$$d = 0.0381m = 38.1mm$$

From standard shaft diameter the diameter of the shaft is selected to be 40mm. the diameter of shaft used for this system 25mm less than 40mm the shaft diameter which calculated from power used in this continuous screw system so the shaft design is saved.

The rotational speed of larger pulley and screw conveyor is equal so that the rotational speed of this system is calculated as follows:

$$T_s = \frac{60P}{2\pi N}$$

$$N = \frac{60P}{2\pi T_s} = \frac{60 \times 297.825}{2\pi \times 246} = 11.56rpm = 11.6rpm$$

The total vertical load acting on screw shaft by pulley assume the mass of pulley 3kg

$$W_p = T_1 + T_2 + m_p g$$

$$W_p = 2850N + 890.625N + 30N = 2960.625N$$

From equilibrium equation of force acting on the shaft

$$\sum F_y = 0 = R_A - W_{sk} + R_B - W_p = 0$$

$$R_A + R_B - 40N - 2960.625N = 0$$

$$R_A + R_B = 3000.625N$$

$$R_A = 3000.625N - 3282N = 281.375N$$

Bending moment at point A and B is zero.

$$\sum M_A = 0$$

$$0 = 40N \times 0.9165m - R_B \times 1.588m + 2960.625N \times 1.748m$$

$$36.66Nm - R_B \times 1.588m + 5175.1725Nm = 0$$

$$1.588mR_B = 5211.8325Nm$$

$$R_B = \frac{5211.8325Nm}{1.588m} = 3282N$$

## C2. V-belt design calculations

The given data for design V-belt as followed:

1. Power transmitted to gear box = 3kW is the power of a motor
2. Output speed from gear box 58rpm (reduced by gear box from input speed)
3. Outer diameter of larger pulley (D) is 204mm
4. Density of belt material (Balata) = 1100kg/m<sup>3</sup>
5. Allowable stress for belt material is 4MPa
6. Assumed Cross sectional area of the belt is 720mm<sup>2</sup>

7. Coefficient of friction between the belt and the pulley ( $\mu = 0.3$ )

The speed ratio of the v-belt calculated as follows:

$$\frac{N_1}{N_2} = \frac{D_2}{D_1} \text{ and } \sin \alpha = \frac{r_2 - r_1}{x} = \frac{D_2 - D_1}{2x}$$

So the angle of contact on driving and driven pulley with the v-belt are  $\theta_1 = 180^\circ - 2\alpha$  and  $\theta_2 = 180^\circ + 2\alpha$  respectively (Figure 4.2).

$$\sin \alpha = \frac{102 - 25}{420} = \frac{204 - 50}{2 \times 420} = 0.183$$

$$\alpha = 10.56^\circ$$

Now the angle of contact on smaller pulley

$$\theta_1 = 180^\circ - 2 \times 10.56 = 156.88^\circ = 2.738 \text{ rad}$$

Angle of contact of larger pulley

$$\theta_2 = 180^\circ + 2 \times 10.56 = 201.12^\circ = 3.51 \text{ rad}$$

According to Hannah and Stephens (1970), the power transmitted by belt is given by

$$P = (T_1 - T_2)v_b$$

$$v_b = \frac{\pi D N_1}{60} = \frac{\pi \times 0.05 \text{ m} \times 58 \text{ rps}}{60} = 0.152 \text{ m/s}$$

$$2.3 \log \left( \frac{T_1}{T_2} \right) = \mu \theta \operatorname{cosec} \beta$$

Mass of the belt per meter length will be

$$m_b = \text{area } (A) \times \text{center distance of pulleys } (X) \times \text{density of belt}$$

$$m_b = 0.000720 \text{ m}^2 \times 0.420 \text{ m} \times \frac{1100 \text{ kg}}{\text{m}^3} = 0.33264 \text{ kg/m}$$

Based on mass and speed of belt calculate the centrifugal tension of belt

$$T_c = m_b \times v_b^2 = 0.33264 \text{ kg/m} \times (0.152 \text{ m/s})^2 = 0.00769 \text{ N}$$

$$\text{The maximum tension in belt: } T_{max} = \sigma \times A = 4 \text{ N/mm}^2 \times 720 \text{ mm}^2 = 3000 \text{ N}$$

Assumed factor of safety of belt 5% so that the tension of the belt is given as the followed

$$T_1 = T_{max} - 0.05 T_{max} - T_c = 3000 \text{ N} - 150 \text{ N} - 0.00769 \text{ N} = 2850 \text{ N}$$

When the pulleys have different angle of contact, then refer from design of pulley which have smaller the values of angle of contact when coefficient of friction between the belt and the pulley ( $\mu = 0.3$ ) and angle of groove ( $\beta = 45^\circ$ ) of two pulley are the same. Since the angle of smaller pulley is small, therefore the design was based on smaller pulley.

$$2.3 \log \left( \frac{T_1}{T_2} \right) = 0.3 \times 2.738 \times \operatorname{cosec} 45^\circ = 1.16$$

$$\log\left(\frac{T_1}{T_2}\right) = 0.5$$

$$\frac{T_1}{T_2} = 3.2 \text{ Then } T_2 = \frac{T_1}{3.2} = \frac{2850N}{3.2} = 890.625N$$

The torque transmitted by the belt to pulley from driven shaft and the torque acting on the pulley

$$T_P = (T_1 - T_2)R_P = (2850N - 890.625N) \times 0.102m = 199.86Nm$$

Where  $T_1$  and  $T_2$  are tensions in the tight side and slack side of the belt respectively and  $R_P$  is radius of the pulley. The torque of screw shaft and the pulley are equal.

Power transmitted from smaller pulley to larger pulley by belt

$$P = (T_1 - T_2)v_b = (2850 - 890.625) \times 0.152 = 297.825Nm/s = 0.297825kW$$

### C3. Design of inner and outer reactor

The inner volume of the cylindrical reactor would be as follows

$$V_i = \pi L_i r_i^2$$

Based on the selection of screw conveyor standard dimension and 2mm clearance volume of inner reactor is  $0.0275m^3$ . From above equation the length of the inner reactor is determined at diameter of inner reactor is

$$d_i = d_{sc} + 2C \text{ Where } C \text{ clearance between screw and inner reactor}$$

$$d_i = 160 + 2 \times 2 = 164mm$$

$$L_i = \frac{V_i}{\pi r_i^2} = \frac{0.0275m^3}{\pi \times 0.082^2} = 1.302m = 1302mm$$

The outer volume of the cylindrical reactor would be as follows

$$V_o = \pi L_o r_o^2$$

The reactor double cylindrical reactor so that assume the space between the outer and inner reactor and the length of outer reactor are 67.5mm and 1100mm respectively.

The volume of outer reactor is

$$V_o = \pi L_o r_o^2 = \pi \times 1.1 \times 0.1525^2 = 0.0804m^3$$

### C4. Dimensions of Cyclone separator

The inlet of the cyclone is equal to the diameter of the internal reactor and the rest dimension of the cyclone will be determined as follows

The diameter of upper cyclone is 1.88 diameter of inner reactor.

$$d_u = 1.88d_i = 1.88 \times 0.17 = 0.3196m = 320mm$$

The length of the upper and bottom of cyclone are equal and total length is 4.96 of diameter of inner reactor and exit diameter cyclone is 100mm

$$L_c = 4.96 \times 170 = 843mm$$