DESIGN AND FABRICATION OF BIOMASS BURNER FOR GAS TO GAS HEAT EXCHANGER

KHAIRUL ANUAR B KAMARUL BAHARIN

MECHANICAL ENGINEERING

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CERTIFICATION OF APPROVAL

DESIGN AND FABRICATION OF BIOMASS BURNER WITH GAS TO GAS HEAT EXCHANGER

by

Khairul Anuar B Kamarul Baharin

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Approved by,

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AP. Dr. Hussain Al-Kayiem

Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

KHAIRUL ANUAR B KAMARUL BAHARIN

ABSTRACT

A biomass burner integrated with gas to gas heat exchanger has been designed, constructed and evaluated. The direct flue from the biomass combustion inside the burner will flow into the dryer for the drying of biomass waste product. The burner is designed to supply heated air to the existing dryer model for biomass waste drying and food drying application. The burner use three types of biomass energy fuel which is Empty Fruit Branches (EFB), wood chip and rice husk. The gas to gas heat exchanger installation is important since the combustion of biomass hydrocarbon will be producing poisonous gas and it is not suitable for food drying application. Gas heat exchanger will use extended surfaces on both side of its cylinder pattern to increase the surface area and also increased the heat exchanger efficiencies. Material selection for this design is crucial because the unit must sustain service temperature around 300ºC. Stainless alloy has been chosen as the material for the heat exchanger. The experimental result shows that the output parameter obtained from the burner is within the required value. In conclusion, the burner had been detailed design and fabricated and give the required value needed for drying application.

ACKNOWLEDGEMENT

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Nomenclature

Symbol

Q_{burner}	Heat transfer across burner
$\dot{m}_a$	Mass flow rate obtained from dryer
T_{ao}	Outlet air Temperature
T_a	Ambient Temperature
c_{pa}	Specific heat capacity of air
ρ_f	Density of flue
A	area of heat exchanger
V_f	Velocity of flue
c_p	Specific heat capacity of flue
T_{fi}	Inlet flue temperature
T_{fo}	Outlet flue temperature
Re	Reynolds number
ρ	Density
D_2	Diameter
V	Velocity in one dimensional flow
μ	Viscosity coefficient
Gr	Grasholf number
g	Gravitational acceleration

β	1/T(Kelvin)
$\bar{T}$	Mean temperature
T_{wi}	Wall in temperature
v	Kinematic viscosity
Nu	Nusselt Number
Pr	Prandtl Number
Ra	Rayleigh Number
h	heat transfer coefficient
k	thermal conductivity
υ	Prandtl-Meyer shock angle
r_1	Outlet radius of cylinder
r_2	inner radius of cylinder
Lc	Characteristic length

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Conventionally, people use sources such as electricity, gas, and biomass for furnace application to produce heat. As we all know, the depleting in sources for gas, and the increasing price of electric supply causes the usage of gas and electricity became inefficient. However, by the usage of biomass sources such as coal, the process to produce heat is more efficient. This is because coal is regenerated source in which it is come from a tree wood; people can plant the tree to get the coal sources.

This project is mainly to design a controllable biomass burner to deliberate heat for solid waste biomass fuel and food drying application. As we all know, the combustion of biomass sources is almost the same as any other hydrocarbon combustion which will create poisonous gases that is harmful to human and surely not suitable for drying food application. So the usage of the gas to gas heat exchanger is crucial to make sure that the gas that will be use for food drying application is not poisonous and clean. The gas to gas heat exchanger wall will be heated by biomass fuel combustion and the transmission of the heat to the ambient air will increase its temperature, thus will produce a heated clean air for food drying application.

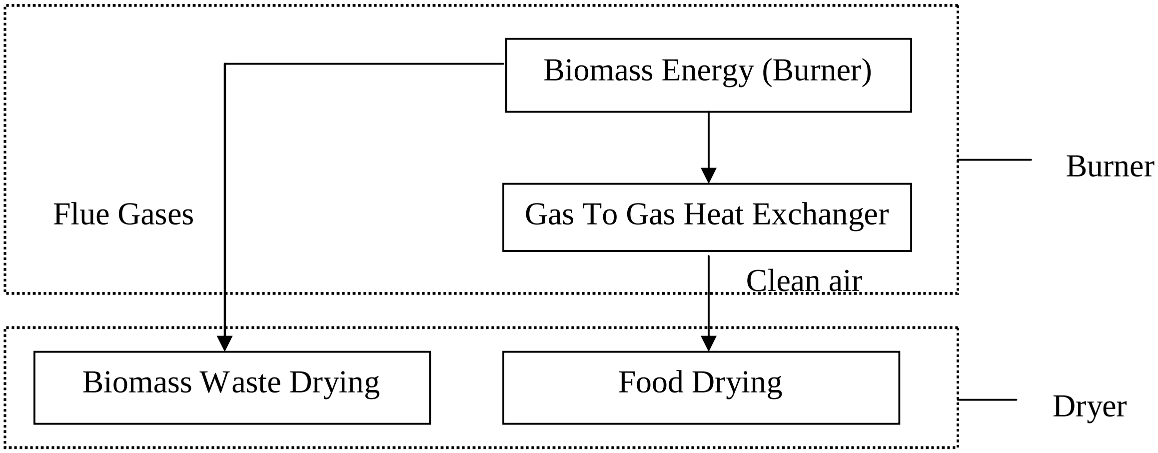


Figure 1: Biomass Burner with Gas to Gas Heat Exchanger flow diagram

1.2 Problem Statement

Open-air sub drying has been used since time immemorial to dry plants, seeds, fruit, fish, wood and other agricultural or forest products as a means of preservation. The open-air sub drying also widely used to dry solid biomass waste fuel such as agricultural waste, grass cuttings, and dried manure. An alternative to traditional drying techniques and solution to open-air sub drying problem is biomass burner dryer. The drying technique is basically to remove the quantity of water and decrease the percentage of moisture in both biomass waste fuel and foods. With the usage of biomass burner, the hot gas produce from the burner will contains some poisonous substances of hydrocarbon which is only suitable for biomass waste fuel drying, and not suitable for food drying application. But by the installation on gas to gas heat exchanger which will use another medium to absorb the heat and then transfer it to clean air, we can also dry food. From this project the biomass burner usage can be maximize and there will be the study on gas to gas heat exchanger design to suites the application needed.

1.3 Objective

The objectives of the project are as follow:

1. To design and fabricate a burner to provide suitable hot air for drying process.
2. To conduct experimental measurements to analyze the burner.
3. To suggest the best type of fuel to be used for dryer application.

1.4 Scope of Study

Most of the biomass dominant source of energy commonly burned using inefficient technologies in most developing countries such as open air burning. In order to maximize the usage of the biomass burner, the improvement to biomass burner design had to be made. The scope of study can be summarized as follows:

1. To study the working principle of biomass burner for simple application
2. To study the mechanism of heat transfer for gas to gas heat exchanger.
3. To test the performance of the burner with different types of materials.
4. To analyze the burner's efficiency.

1.5 Significant of the works

One of the most significant potential applications of biomass burner is drying. It is the common technique for preservation of agricultural and other products such as fruits and vegetables. The drying of various products and matters is intensively carried out in the industry and agriculture. Its mechanism, typically non-stationary and based on complex mass and heat transfer laws, is well known [2]. Its particularly resides in the fact that the departure if water molecules from the product is done due to the difference in water vapor partial pressure between the product surface and surrounding air [2]. This difference in partial pressure is obtained by heating of air circulating in natural convection in a collector [2].

There is a new alternative for the dependent of natural resource and electricity power to power up heater and burner for food drying industries. It is to use biomass energy with the integration of gas to gas heat exchanger to ensure that only the clean air will be use for the food drying application, whereas the flue gases can be use for solid waste biomass fuel drying. By using the biomass burner with gas to gas heat exchanger mode of operation, we can now avoid the dependent of depleting energy sources to create heat.

CHAPTER 2

LITERATURE SURVEY

2.1 The concept of heat exchanger design to heat transfer efficiencies.

A compact gas to gas heat exchanger needs large heat transfer areas on both fluid sides. This can be realized by adding secondary surface. The secondary surface is plate fin, strip fin and louvered fin. The fin extends the heat transfer surface and promotes turbulence [1].

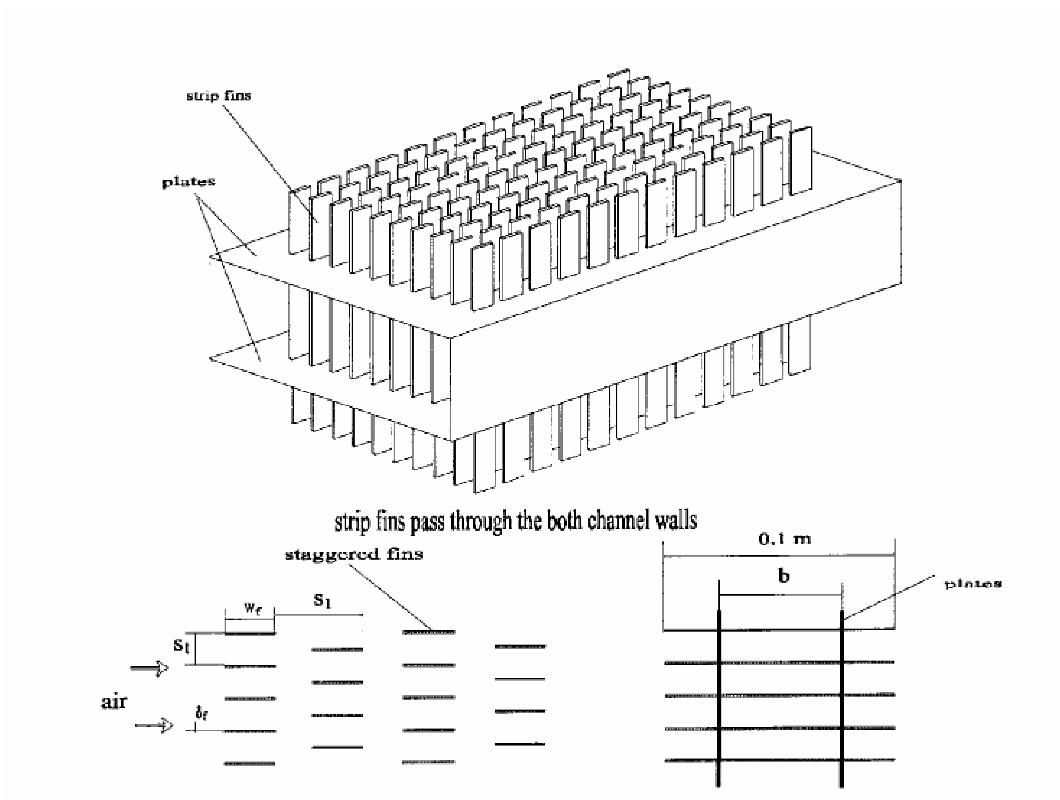


Figure 2.1 : Strip fin heat exchanger design.(Reference no. 1)

2.2 Biomass burner for drying application.

A. Madhlopa 2005 [2] had come with a model of indirect solar dryer with biomass backup heater. His design is as following figure.

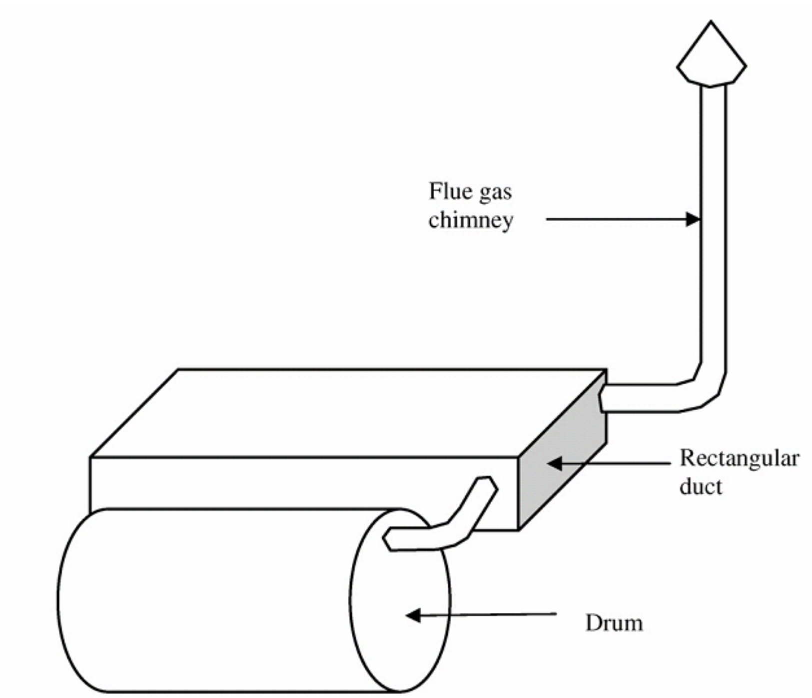


Figure 2.2a: Perspective view of biomass burner (Reference no. 2)

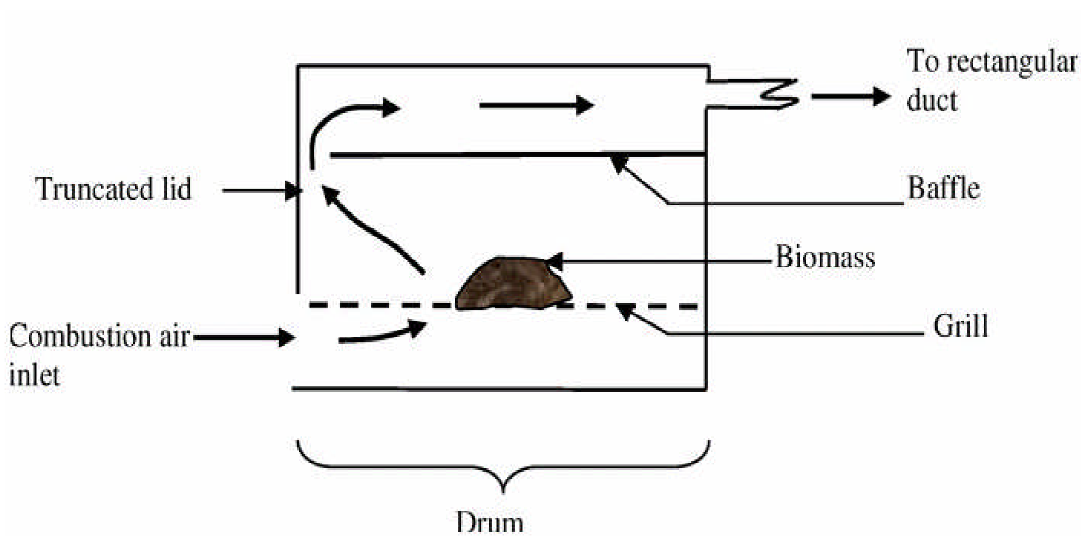


Figure 2.2b: Longitudinal sectional view of the drum, showing flow pattern of flue gas. (Reference no.2)

Referring to the burner design, it was made of a drum, rectangular duct and flue gas chimney. The drum design uses a horizontal baffle to control the air flow and mild steel grill to provide air for biomass combustion. A truncated circular removable lid was tightly fitted on the open end of the drum through which biomass was loaded into and ash removed from the drum. The design also uses a rectangular steel door (filled with vermiculite) and perforated, place on the bottom part of the drum for inlet of air into combustion chamber. The size of the perforated area was based on the estimated volume flow rate of air required for combustion.

The drum was integrated to rectangular duct with three vertical baffles spaced at equal intervals to increase the path length of the flue gas and the amount of heat transferred to the drying chamber. The type of fuel used for his design is fuelwood or wood shavings since it is a dominant source of energy and harvested sustainably and the materials used for the drum design is mild steel.

S.-A.B. Al-Omari [3] has designed a biomass furnace for experimental and investigation on combustion and heat transfer characteristics using unconventional biomass fueled (date stones and palm stalks). The schematic design of the furnace is as follows:

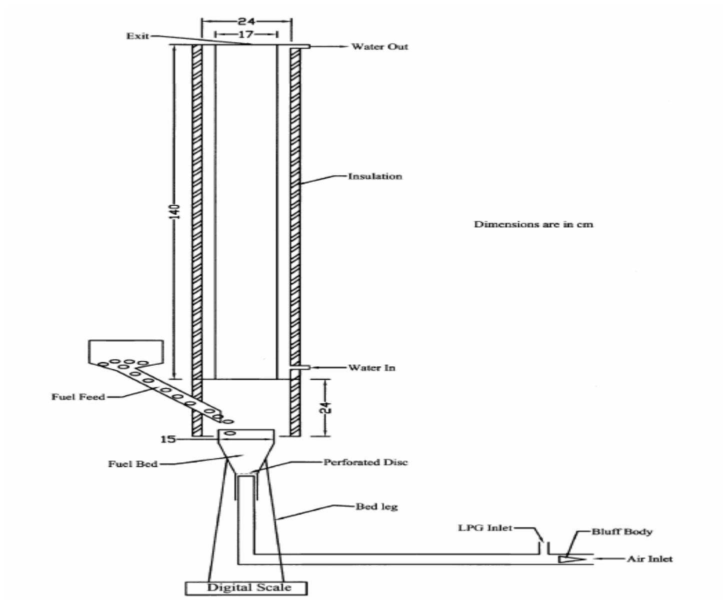


Figure 2.3: Schematic of the investigated furnace (Reference no. 3)

The furnace is a vertical cylinder with and overall height of 164cm. A solid fuel bed with the shape of a truncated cone is installed at the bottom of the cylinder furnace. The solid fuel is supplied to the top of the bed from one side of the furnace as indicated from the figure. Combustion air is supplied through the bottom base of the bed. The furnace wall is insulated form outside.

The variation of the mass in the bed with time during the combustion process is monitored by placing the bed on a digital weighing scale and recording the mass in the bed at different time during the operation. To initiate the combustion, an initial source of heat is needed for a few minutes. The researcher had tested a several way to ignite the solid fuel and found out that the usage of LPG gas is more convenient and effective. The combustion of LPG burned in this ducted is stabilized by means of a conical bluff body to guide the LPG to penetrate through the solid fuel during ignition.

Benon Bena 2000 [4] had come out with a drying technology for small scale processors of dried fruits and vegetables in non electrified areas of developing countries. The burner was designed to provide 400 W_m of energy to the drying cabinet, and used steam as the heat transfer medium. The sawdust burner was constructed as a separate component, rather than being integrated with the drying cabinet.

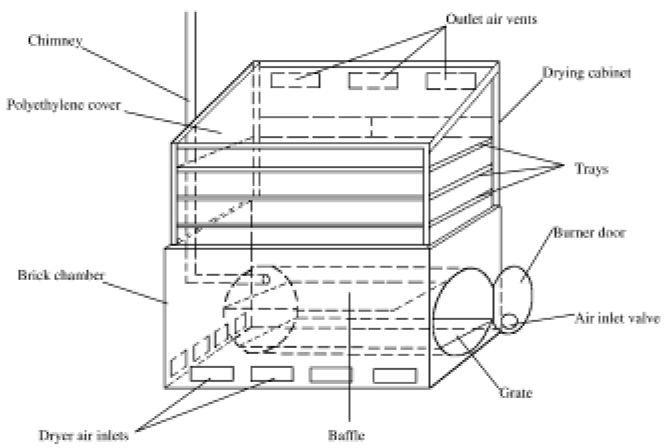


Figure 2.4: Natural convection solar dryer with biomass back up heater

(Reference no.4)

Biomass particularly used in this burner is fuelwood since it is the most common source of energy in rural areas of developing countries and provides unsustainable pressure. Fuelwood can be a greenhouse gas neutral source of energy, if usage is balanced by new plantings.

The dryer consists of a drying cabinet mounted on the top of a brick chamber that encloses a simple biomass burner (Figure 2.4b). There are three drying trays, with each a wire mesh base and in total, this area provides effective drying area of $3m^2$. The cabinet was constructed using radiate pine and was covered with a single layer UV stabilized polyethylene film. An aluminium mesh is fitted to the underside of the dryer to prevent insects reaching the crop through the brick chamber air inlets.

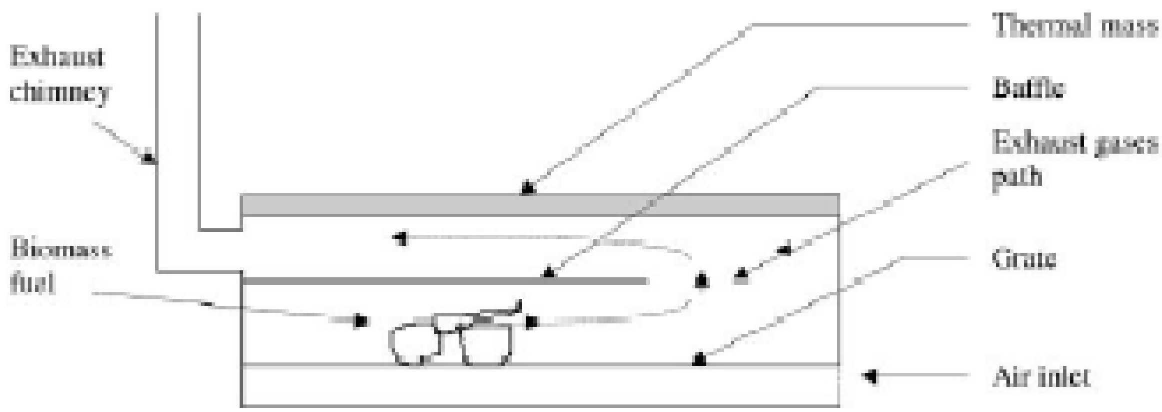


Figure 2.5 : Cross section through biomass burner.(Reference no 4)

The biomass burner, designed primarily for fuelwood was constructed from a drum laid on its side (Figure 2.4b). The burner grate was constructed on rails riveted to the inside walls of the drum. A spinning valve is used to regulate the flow of air into the burner. To lengthen the flow path of combustion gases and maximize the transfer of heat to the drum walls, a metal baffle is inserted above the grate and below the exhaust gas exit. They use 50kg of concrete to the outside of the top surface of the drum to prevent excessively high air temperature in the drying cabinet, particularly when the burner had just been lit. The brick chamber that supports the drying cabinet had 12 rectangular holes, around the perimeter at ground level. The drying cabinet was fixed to the chamber with metal stripping mortared into the top layer of brick work, and any gaps were sealed with mortar.

The back up heater is operating during zero solar radiation to supply heat energy for drying purposes. The combustion gases heat up the drum surface, which in turn warms the air as it moves over the outer surface. The warm air rises up into the drying chamber, evaporating and picking up crop moisture as it passes through the trays and then escaped through the top vents. By regulating the amount of air entering the burner, the heat delivery rate can be controlled. Type of heat and location of fuel in burner also will influence the amount of heat generated and the period over which it is released.

Jaishree Prasad 2004 [5] had done experimental studies on drying of Zingiber officinale, Curcuma longa l. and tinospora cordifolia in solar biomass hybrid dryer. The biomass stove is designed based the fact that the heating in indirect, i.e flue gases from the chimney and the drying air could not be mixed. This is protecting the product from contamination by smoke, soot and ash of the flue gases.

Next this stove is design so that the temperature of air could be controlled, by maintaining the combustion in the stove with the opening or closing of the primary air supply gate. Lastly the biomass burning could be carried out for extended period of time, unattended.

In order to lengthen the flow path of exhaust gases and maximize the transfer of heat to the stove walls, three metal baffle plates are inserted at a distance of 0.1 m above the grate and below the chimney in the burning chamber. The brick has 13 rectangular holes for fresh air entry and one biomass feeding hole.

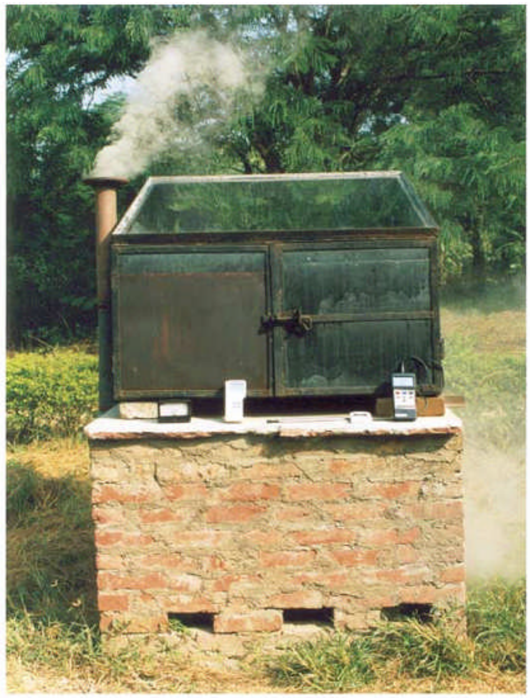


Figure 2.6: Solar- biomass hybrid drier. (Reference no. 5)

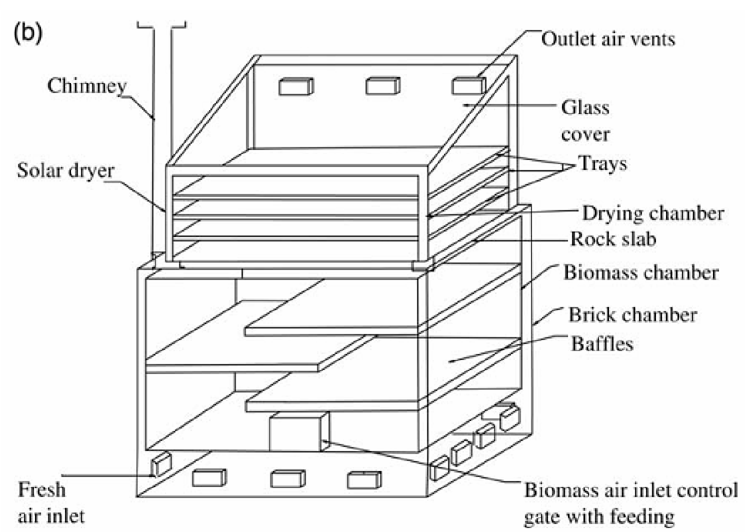


Figure 2.7: Schematic diagram of solar biomass hybrid drier.(Reference no.5)

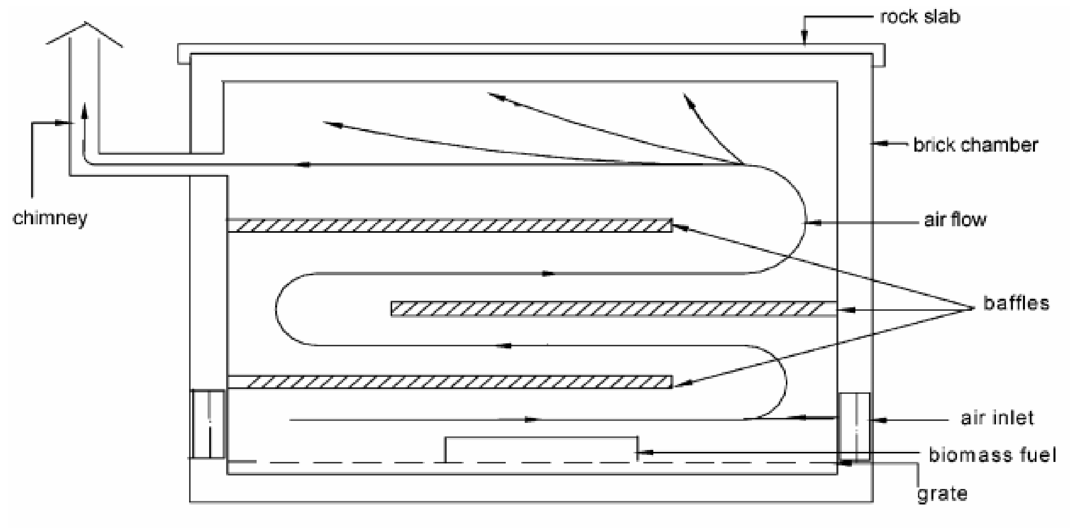


Figure 2.8: Sectional view of biomass stove.(Reference no. 5)

For presenting the result, the author use an analytical method to plot moisture content vs drying time, variation in temperature vs drying time and the comparison of open sun, only solar and solar biomass with respect to the oil volatility of the fuel.

2.3 Gas to gas heat exchanger design.

Lei Fang had done a research on clamshell heat exchanger in residential gas furnace. The focus of his research is to analyze the heat transfer, fluid flow and combustion process for a heat exchanger design typically used in residential heat exchanger. The heat exchanger design is as follow:

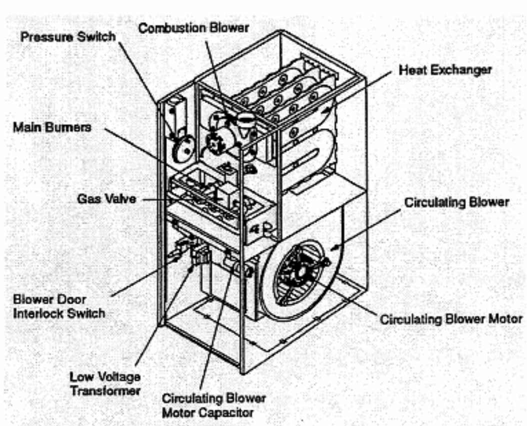


Figure 2.9: A non-condensing residential gas furnace with clamshell heat exchanger

(Reference no. 6)

The clamshell is created by joining two steel panels containing half channel in a manner similar to joining the two halve of a sandwich. The half channels are stamped or molded into the panels forming complete gas channels at assembly to guide the flow of combustion gases inside the channel. The steel panel is usually joined by spot welding or crimping process. This heat exchanger had a rate for firing power of 7.3 kW.

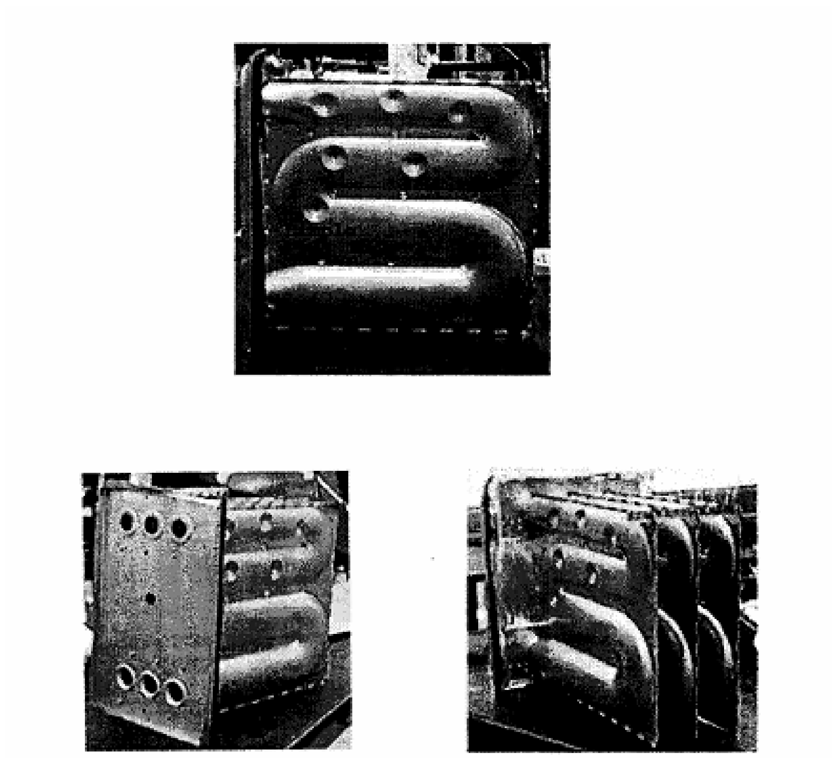


Figure 2.10: An Assembly of clamshell heat exchangers (Reference no 6)

The furnace heat exchanger separates the high temperature flue gas stream from the low temperature circulating air stream while at the same time transferring thermal energy from the former to the latter. The material used for the heat exchanger is aluminized steel (low carbon steel covered with a very thin layer of aluminum coating for protection).

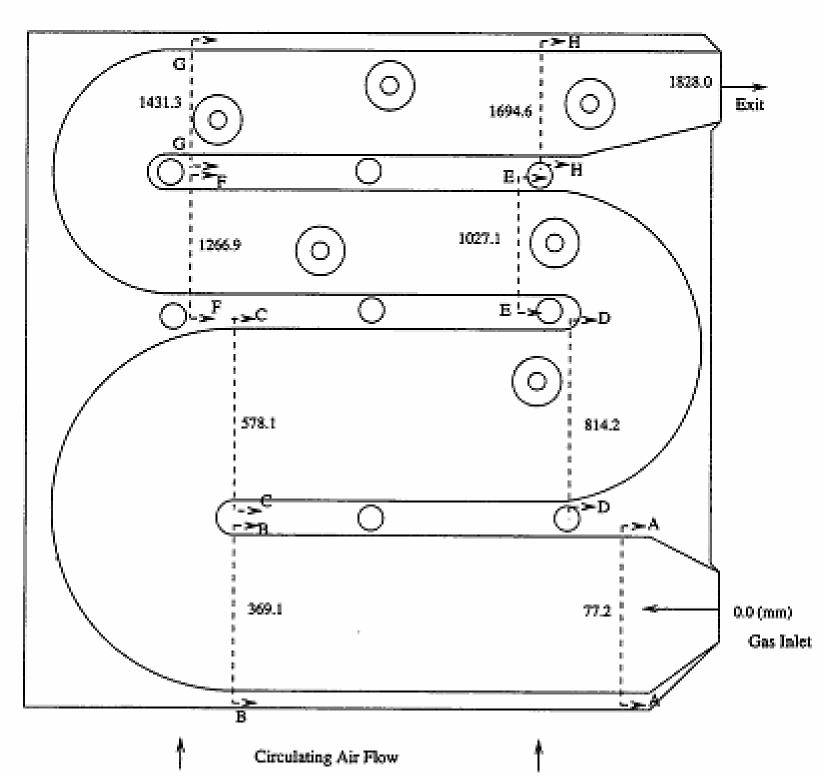


Figure 2.11: Location of several cross sections of the heat exchanger. Also shown are the distances from inlet to exit along the center of gas channel.(Reference 6)

It is clear that the geometry of the gas channel changes along the direction of gas flow. As the flue gas is cooled while travel downstream, its density increases so that its volumetric flow rate decreases. The reduction of cross sectional area helps to maintain or even increase flue gas velocity so that a relatively high value of heat transfer coefficient can be maintained.

T. Tomimura 2003 [7] had done an experimental study on multi layered type of gas to gas heat exchanger using porous media. The gas heat exchanger proposed is based on its effective energy conversion method between flowing gas enthalpy and thermal radiation. It also shows that this type of heat exchanger had much higher overall heat transfer coefficients then the conventional heat exchanger and also exhibit excellent reaction characteristics as a steam reformer.

The heat exchanger has three layered structure and consists of following section, a low temperature section, a high temperature section and a heat recovery section. Each section is equipped with a circular porous metal plate and is separated by an opaque solid wall. The heat recovery section is essential to reduce the outer wall temperature of the heat exchanger and the total amount of heat recovered by adding the heat recovery section is roughly double on averaged.

The new design proposed by the researcher is a new multilayered type of gas to gas heat exchanger equipped with porous metal plate. The porous metal plate used in this process is a extremely high porosity material and give a large temperature drop and larger amount of converted radiant energy.

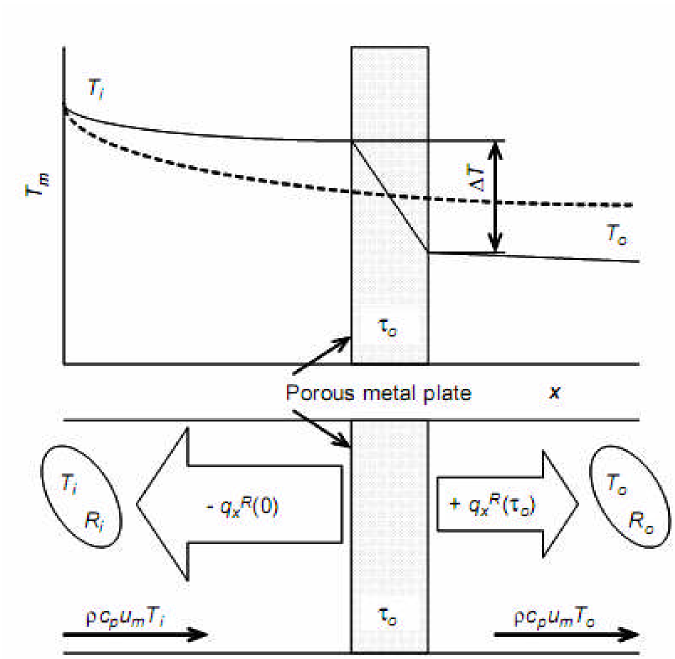


Figure 2.12: Schematic sketch on effective energy conversion.(Reference 7)

The enthalpy of the high temperature gas is effectively transferred to the porous metal plate via extremely high heat transfer coefficient between the flowing gas and the porous plate with fine mean pore size, at the same time a substantially large surface area of the porous for heat transfer.

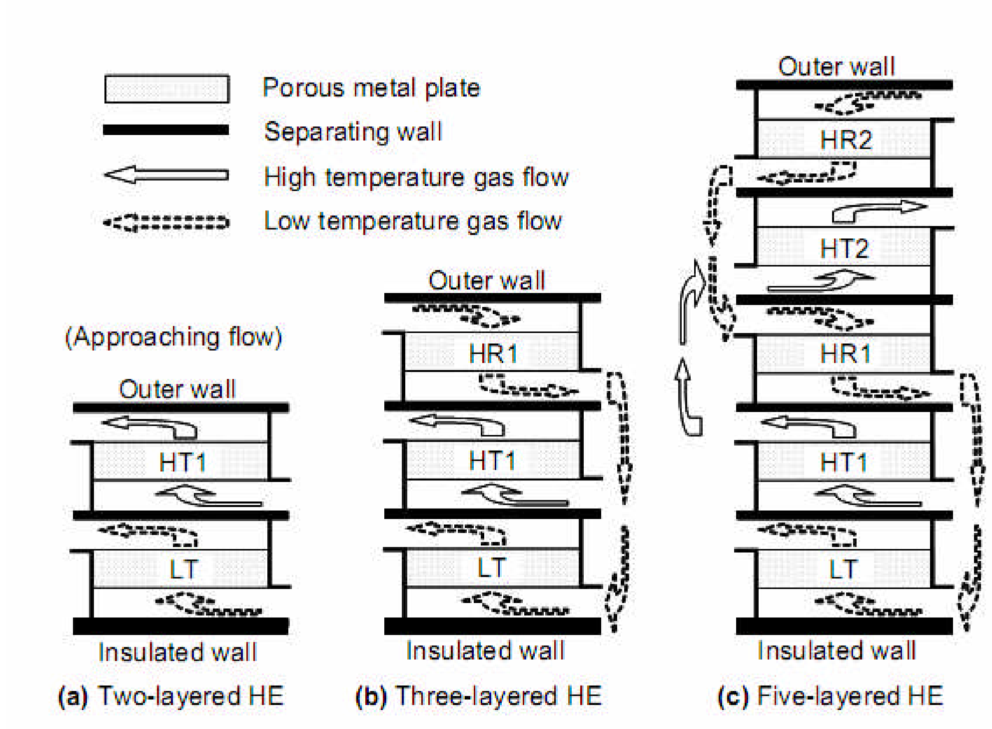


Figure 2.13: Schematic of multi layered type of gas to gas heat exchanger (Reference 7)

Figure show the series of experiment that were carried out for four kind of heat exchanger. The body of the heat exchanger is insulated with heat resisting black paint on the inside of the body. The separating walls are made of heat resisting stainless steel plates or also call bare wall. For the experimental study, the wall also spot welded with zigzag shaped fins to increase the total heat recovery rate especially at the lower region. The porous metal plate place in each section is made of nickel and chromium foamed alloy and the porosity , specific surface area and the absorption coefficient are 93%, 1700m^2/m^3 and 258m^{-1} respectively.

2.8 Ways to optimize efficiencies and emission in pallet burners.

The development of pellet burners has so far been focused on achieving low emissions of unburnt which resulted in increasing high emission of nitrogen oxides. However the usage of well known technique such as air staging can reduce the emission of nitrogen oxide significantly [8]. In order to control the air supply, the gas concentrations need to be measure. Lambda sensors are used to control the oxygen level in the boilers.

The researchers divide his project into four stages which is:

1. Gas analyses in the combustion zone of a modified commercial pellet burner.
2. Computer simulation (Chemkin) to study proper reaction times and temperature for optimal nitrogen oxide reduction.
3. Detailed laboratory reactor studies of important parameter.
4. Demonstration in a prototype burner.

To ensure low emission of nitrogen oxide, sensors for fast on line measurements of unburnt were studied. The requirement for a sensor to be used in small scale application can be summarizes as follows:

1. To enable fast responses, the sensor should be placed close to the combustion zone and the surface must withstand high temperature.
2. The sensor signal should not be sensitive to the moisture content.
3. The sensor should give a stable signal also in the absence of oxygen.
4. The sensor needs to be inexpensive.

The objectives were to study the stability and dynamic response of a sensor when exposed to the flue gases from biomass combustion at various concentrations of unbunrt.

CHAPTER 3

METHODOLOGY

3.1 Analysis Techniques

For the start, the process is focusing more on study of a journal and other paperwork prepared by previous researcher. It is based on their design concept and criteria used.

The study will be carried out by two analysis techniques:

a. Mathematical modeling and analysis.
b. Experimental modeling and measurement.

3.2 Procedure Identification

The project begins with the research work on previous journals and books that been published for the references throughout the project. Most of the objective much more related to the design criteria, material selection and the effectiveness of the biomass burner with gas to gas heat exchanger.

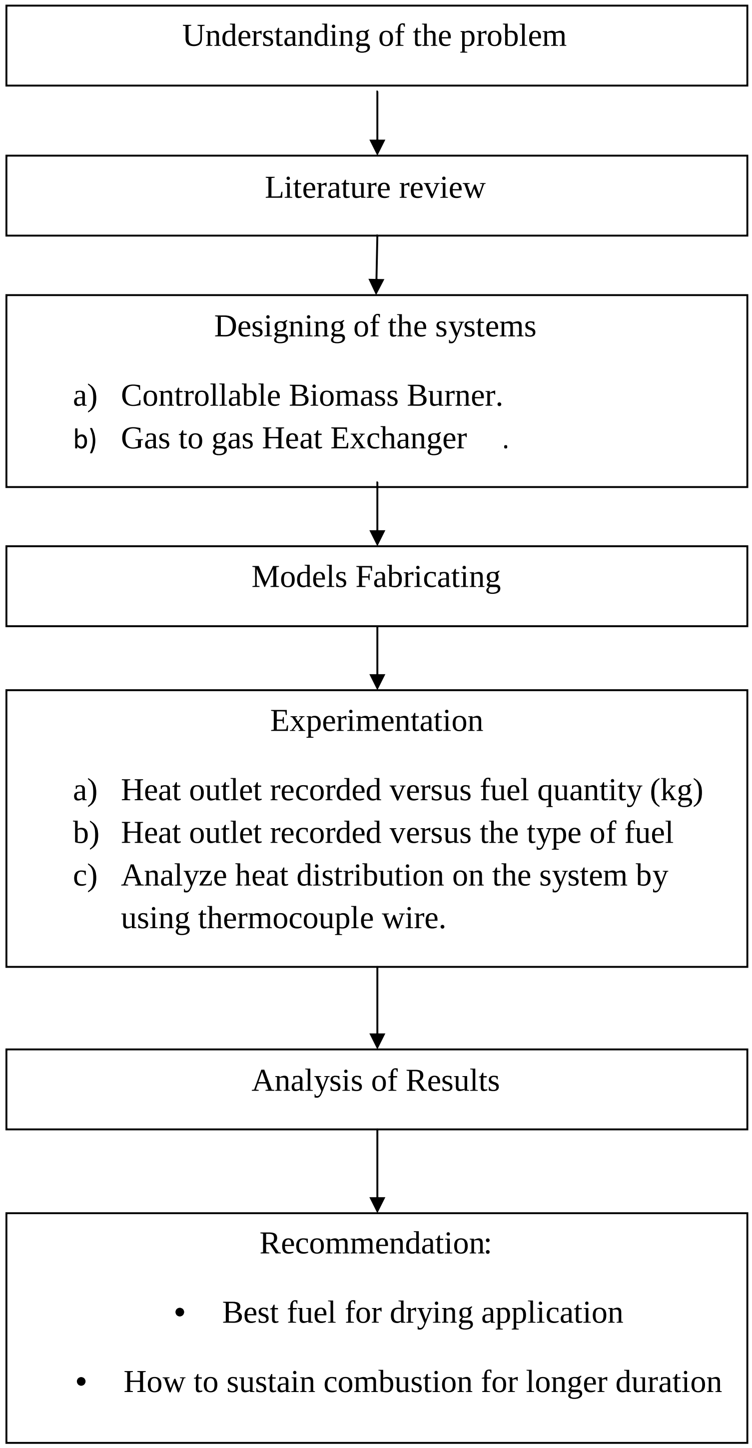


Figure 3.1: Shows the Project Work Flow diagram.

3.3 FYP Gantt Chart and milestone.

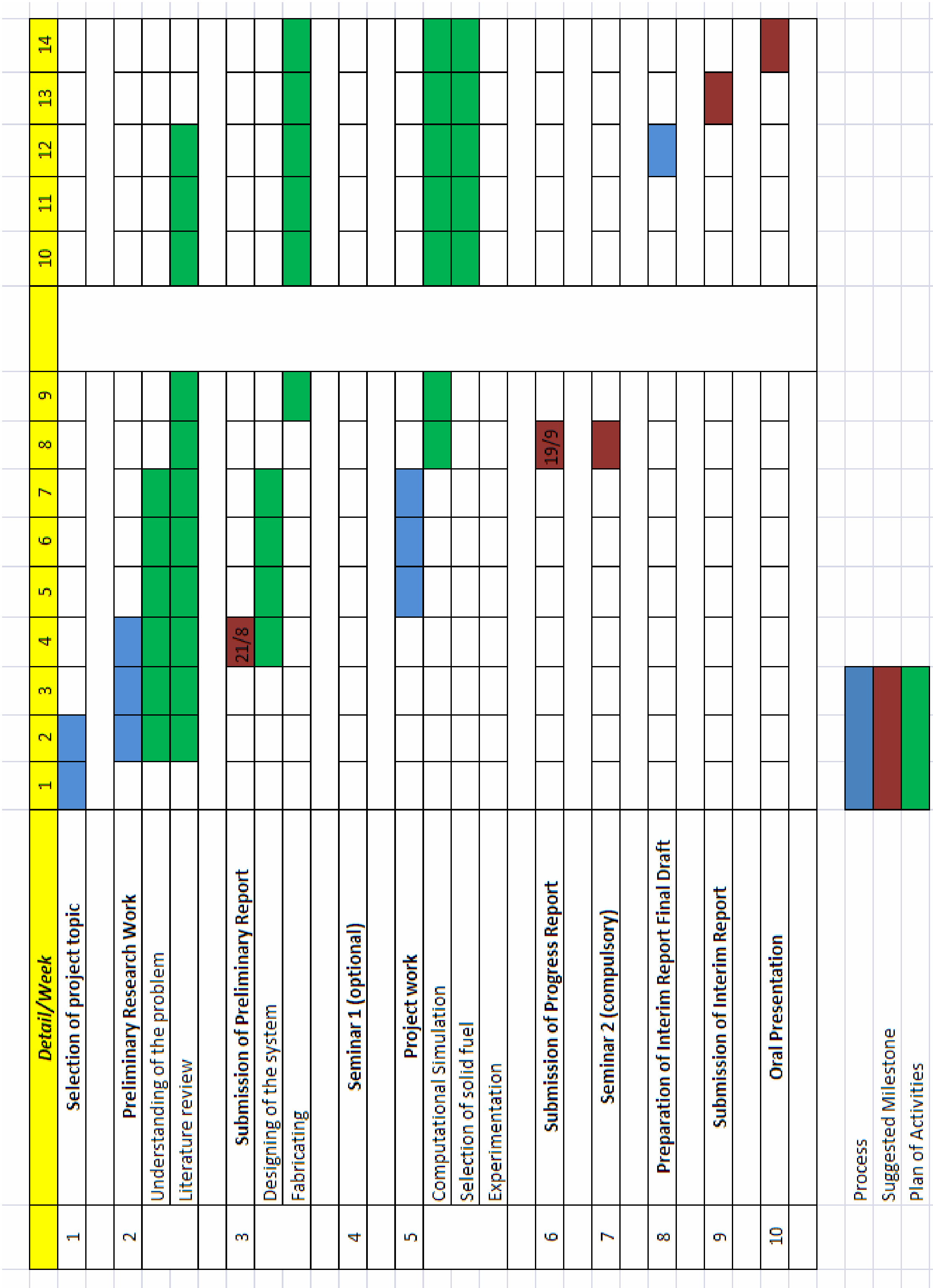


Figure 3.2: FYP 1 Gantt Chart

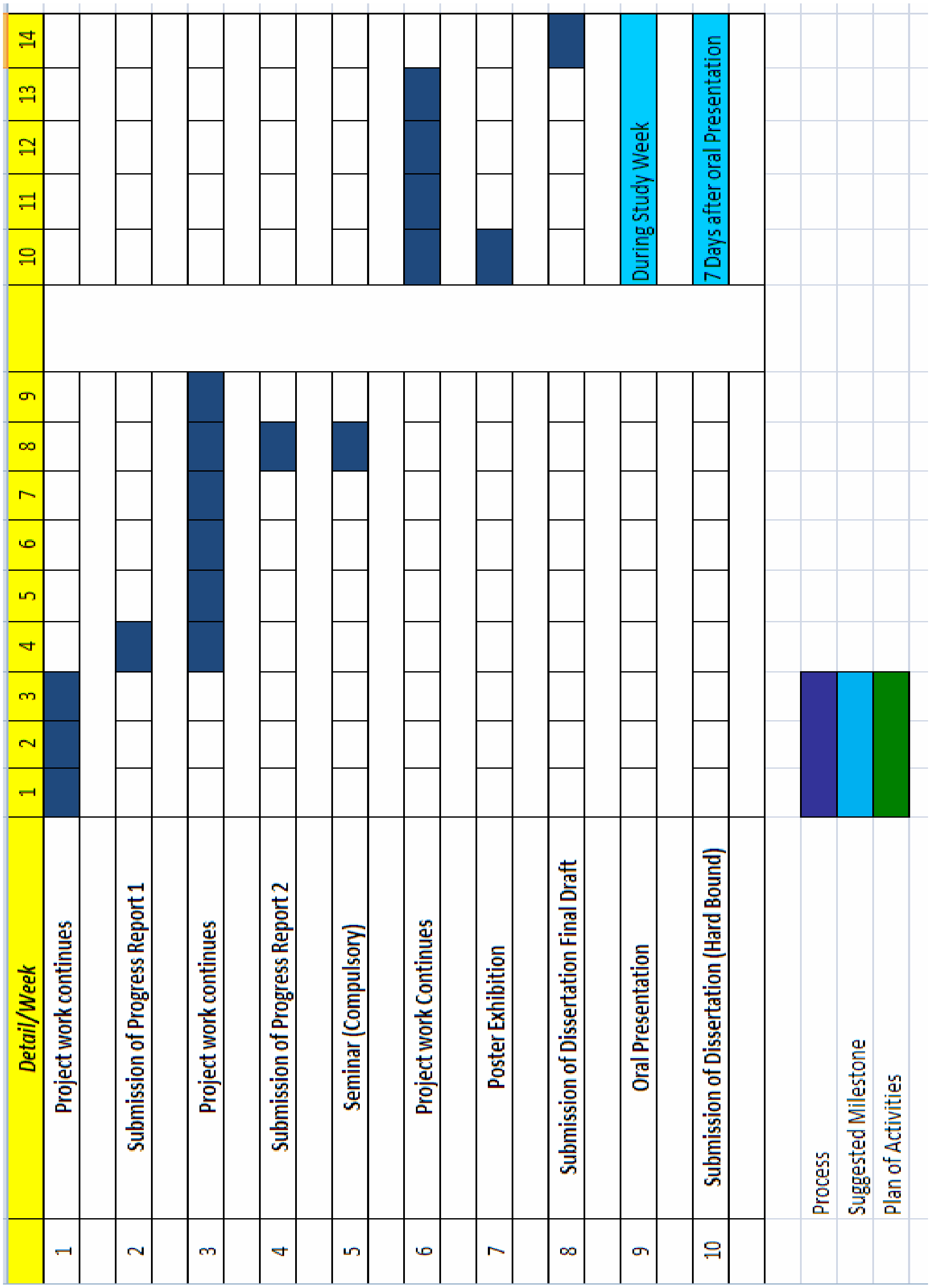


Figure 3.3; FYP 2 Gantt Chart

3.4 Required equipment and software

For designing and drawing, AutoCAD is the main software that been utilized to produce the drawing. AutoCAD is being used because it is simple and there is a lot of book reference regarding it. For iteration and mathematical calculation, both Excel spreadsheet and Matlab were use.

Measuring instruments:

- Thermocouples wire
- Thermocouples probe
- Weight scale
- Hot wire Anemometer
- Digital Thermometer
- Infrared Thermometer

CHAPTER 4
MATHEMATICAL MODELLING

4.1 Detailed Calculation

There are three major assumption made for the analytical analysis, first only convection occur inside the system, internal flow and wall thickness is neglected. The overall design of the burner is shown as follow.

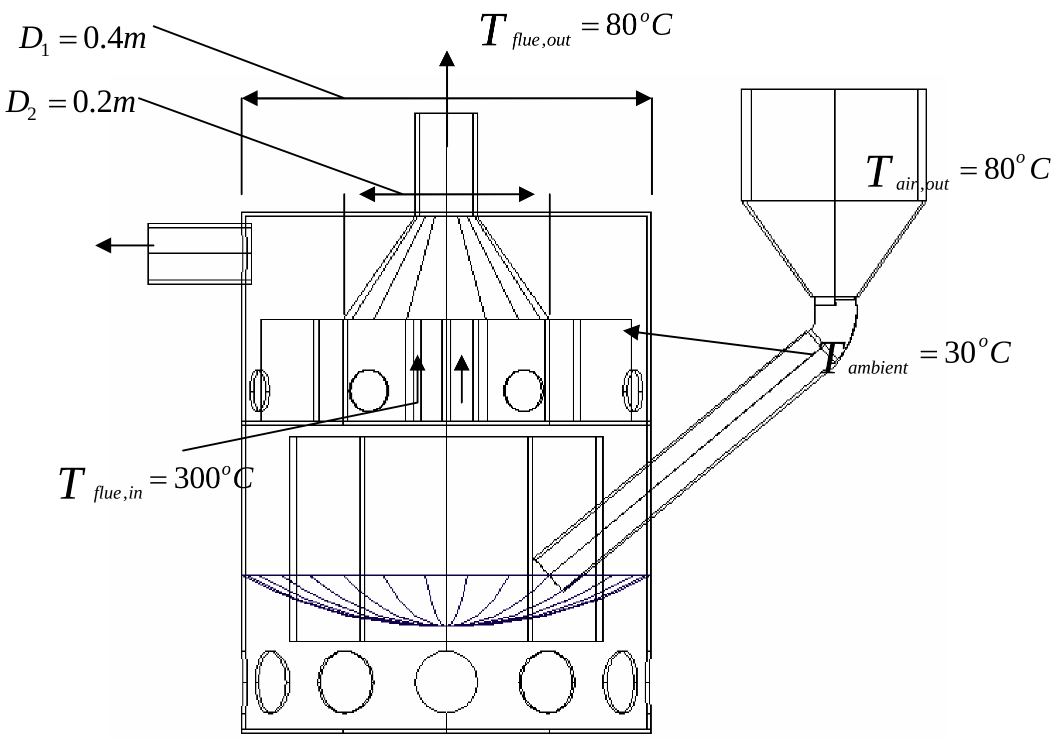


Figure 4.1: The overall unit design and the parameter assumption.

To calculate the heat supplied from the heat exchanger and the outlet temperature of flue, the following equation is use.

$$Q_{burner} = \dot{m}_a c_{pa} (T_{ao} - T_a) \qquad (1)$$

Where:

$\dot{m}_a$ = mass flow rate obtained from dryer (kg/s)

c_{pa} = specific heat capacity of air (J/kg. K)

T_{ao} = outlet air temperature (K)

T_a = ambient temperature (K)

In the flue flow side,

$$Q_{burner} = \dot{m}_f c_{pf} \Delta T_f = \rho_f A V_f c_{pf} (T_{fi} - T_{fo}) \qquad (2)$$

Where:

ρ_f = density of flue (kg/m³)

A = area of heat exchanger (m²)

V_f = velocity of flue (m/s)

c_p = specific heat capacity of flue (J/kg.K)

T_{fi} = inlet flue temperature (K)

T_{fo} =outlet flue temperature (K)

The type of flow for flue is determined by calculating *Re* numbers as in

$$\mathrm{Re} = \frac{\rho_f V_f D_2}{\mu_f} \qquad (3)$$

Where if

- Re<2300 : Laminar flow
- Re>2300 : Turbulent flow

Ratio of Gr/Re^2 can be using to determine the mode of convective heat transfer:

- $0.1 < Gr/Re^2 < 10$; Natural convection + Forced convection, i.e. combination
- $Gr/Re^2 < 0.1$; Forced convection
- $Gr/Re^2 > 10$; Natural convection

Grasholf number:

$$Gr_L = \frac{g\beta(\overline{T}_f - T_{wi})D_2^3}{v^2} \qquad (4)$$

Gr is calculated by the different of mean flue temperature $\overline{T}_f$ and inside wall temperature T_{wi} of heat exchanger.

Next in order to get the nusselt numbers, first we must choose the best equation of nusselt number base on its type of flow, and also the mode of flow. From Re number, we already can determine the type of flow which is laminar or turbulent. Then based on Gr/Re^2 ratio, we can know the mode of convective heat transfer which is forced, free of combined.

For laminar flow and forced convection, there are two type of Nusselt number equation that seems fit, where:

a. Nu= 3.66 , where T_s is constant (if Nu is less than 3.66,consider Nu is 3.66)
b. For combined entry length , the Siedar and Tate correlation is more suitable

$$\overline{Nu}_D = 1.86\left(\frac{\mathrm{Re}_D \Pr}{L/D}\right)^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14} \qquad (5)$$

$$L_t = 4.4D\,\mathrm{Re}^{1/6} \qquad (6)$$

For laminar flow and free convection,

$$Nu = CRa_L^n \qquad (7)$$

where C=0.59 for laminar, n=0.25

for turbulent C=0.1 and n=1/3

Rayleigh number, Ra is

$$Ra_L = Gr_L \Pr \qquad (8)$$

Pr= Prandtl number

For more accurate

$$Nu_L = 0.68 + \frac{0.67 Ra_L^{1/4}}{[1 + (\frac{0.492}{\Pr})^{9/16}]^{4/9}} \qquad Ra<10^9 \qquad (9)$$

Lastly for laminar flow and combined convection,

$$Nu_{comb} = (Nu_f^3 + Nu_n^3)^{1/3} \qquad (10)$$

Now for Turbulent flow in forced convection

$$Nu_D = 0.032 \operatorname{Re}_D^{0.8} \Pr^{0.3} \qquad (11)$$

Where n=0.3 for cooling and n=0.4 for heating.

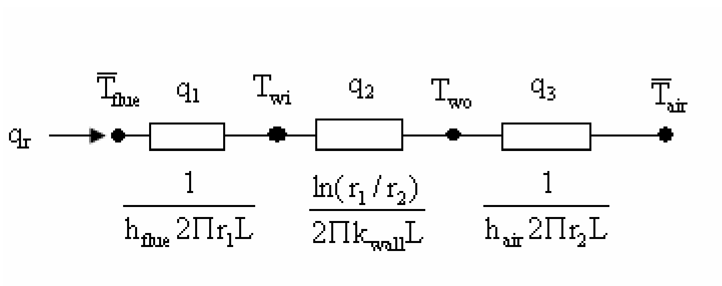
Turbulent flow and free convection

$$Nu = [\frac{576}{(Ra_s \frac{s}{L})^2} + \frac{2.87}{(Ra_s \frac{s}{L})^{0.5}}]^{-1/2} \qquad (12)$$

After the Nu number obtained, the equation (13) is use to get the heat transfer coefficient h_{flue}

$$h_{flue} = \frac{Nu.k_f}{D_2} \qquad (13)$$

The illustration of heat transfer across the wall of heat exchanger is shown in figure 4.1



Same heat amount is transfer from heat exchanger to burner,so

$$Q_{dryer} = Q_{system} = q_1 = q_2 = q_3 \qquad (14)$$

The heat transfer from the flue to the inside wall:

$$q_1 = h_{flue} A_f (\overline{T}_f - T_{wi}) \qquad (15)$$

Across the wall of heat exchanger:

$$q_2 = \frac{2\Pi k_{wall} L (T_{wi} - T_{wo})}{\ln(r_1 / r_2)} \qquad (16)$$

From the outside wall of the cylinder to air:

$$q_3 = h_{air} A (T_{wo} - \overline{T}_{air}) \qquad (17)$$

Where;

A_f = flue side thermal area (m^2)

A = air side thermal area (m^2)

h_{air} = air convection coefficient ($W/m^2.K$)

h_{flue} = flue convection coefficient ($W/m^2.K$)

r_1 = outlet radius of cylinder (m)

r_2 = inner radius of cylinder (m)

$\overline{T}_{air}$ = mean air temperature (K)

T_{wo} = wall out temperature (K)

Total area of the heat exchanger is

$$A = A_{cylinder} + A_{fins} \qquad (18)$$

Where

$$A_{cylinder} = L_c \Pi D_2$$

$$A_{fins} = 2nL_c (L_f / 2)$$

Lastly the characteristic length can be determined from the developing equation

$$L_c = \frac{Q}{h_{air} A(T_{wo} - T_{air})} \qquad (19)$$

All of this equation then be converted to programming language which is MATLAB to do the iteration until the parameter setting of error is 0.001.

4.2 Iteration using Matlab

The final boundary condition of the unit design is shown in table 4.1. The mathematical modeling for the governing equation has been converted into programming language which is MATLAB. The programming is divided into two parts, the flue side is to calculate h_{flue} and the air side across the heat exchanger is to calculate the correct height Lc which is involved the iteration process as shown in Figure 4.2 and Figure 4.3.

No.	Items	Value
1	Mean Air Temperature	55°C
2	Heat required, Q (obtained from dryer)	154 Watt
3	Volumetric flow rate (from dryer) with SF 1.2	10 m^3/hr
4	Velocity of flue inside burner,	0.5 m/s
5	Burner diameter, D_1	0.4m
6	Heat exchanger diameter, D_2	0.2m
7	Number of fins,n	8
8	Length of fins, L_f	0.08m
9	AISI 304 thermal conductivity, *k*	14.9 W/m.K
10	Assumed length characteristic, Lc	0.4 m

Table 4.1 : Boundary condition of the Burner

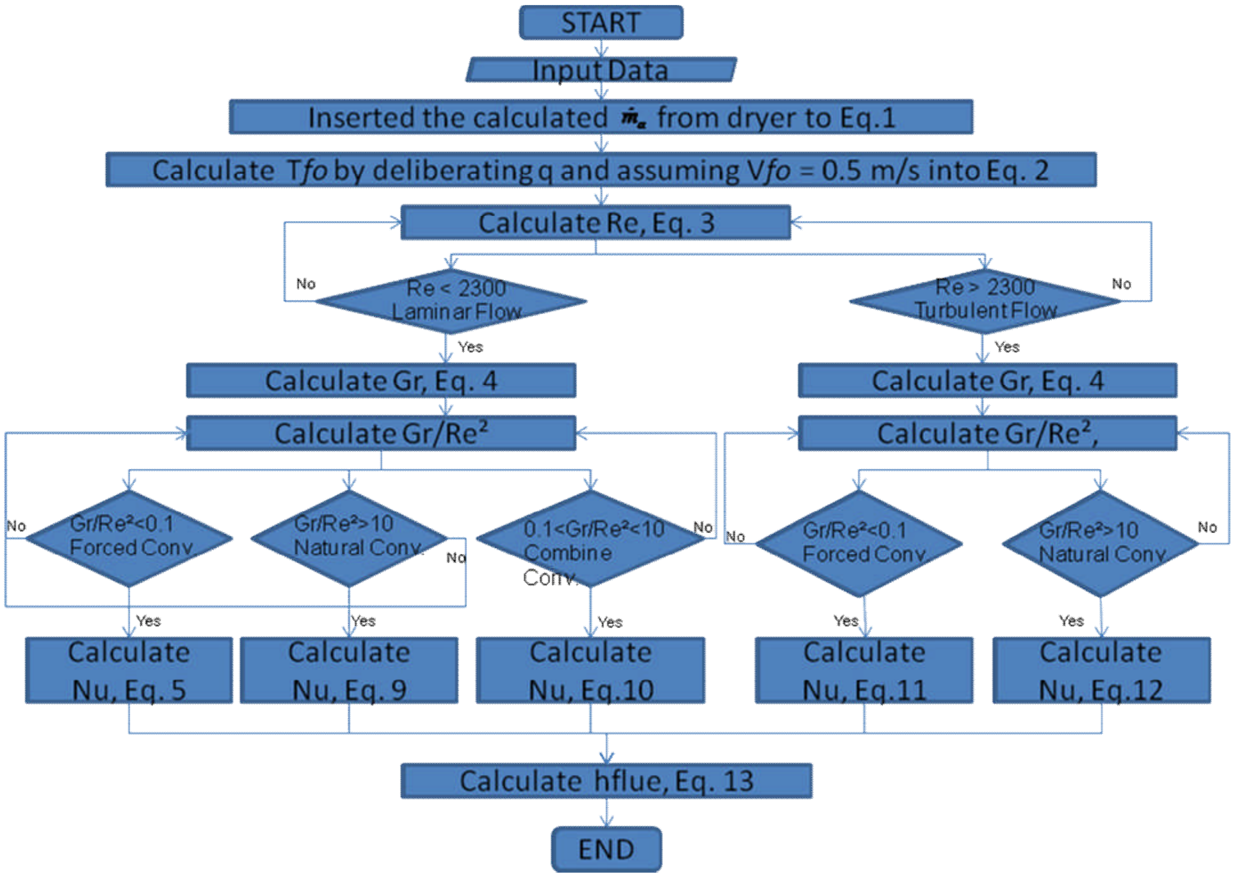


Figure 4.2: The algorithm design calculation for the flue side

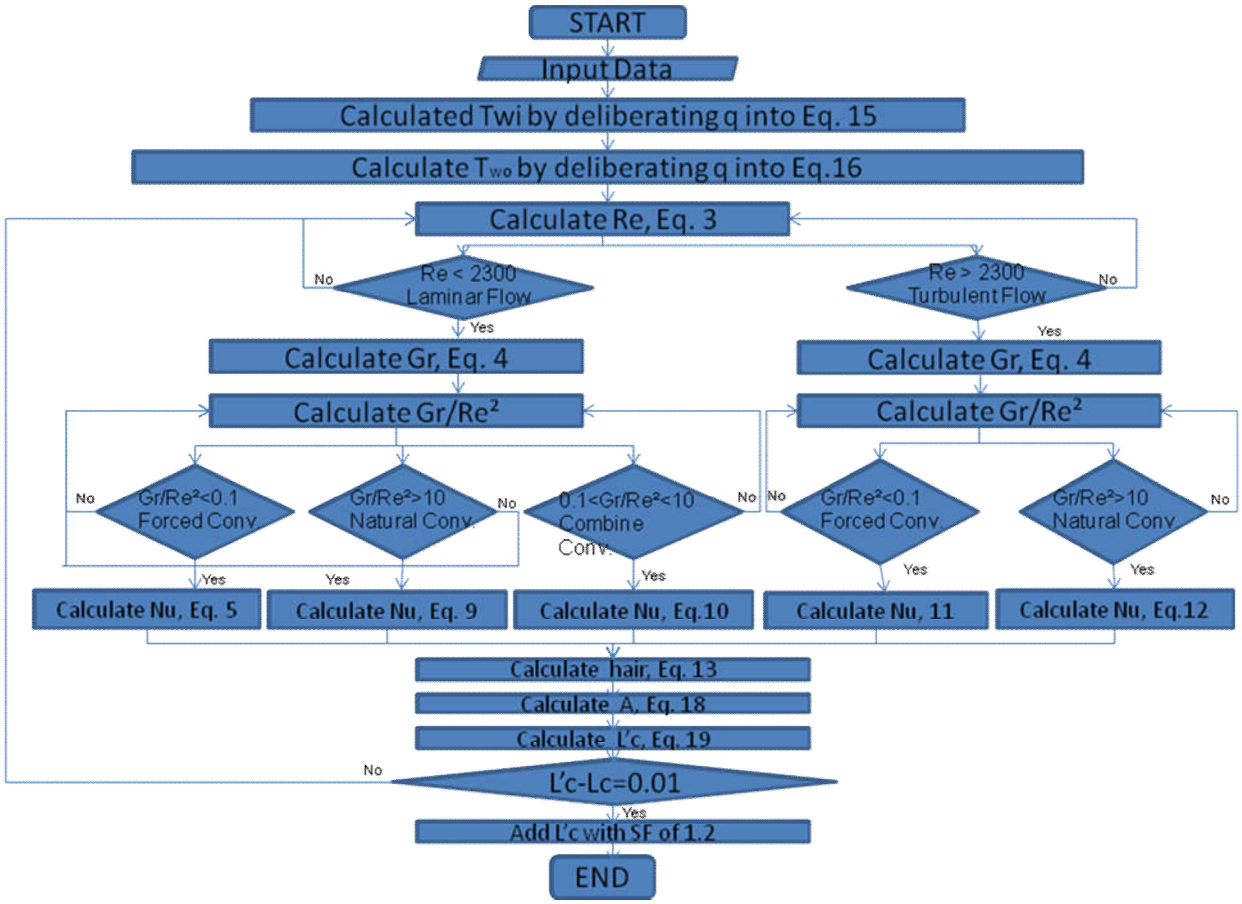


Figure 4.3: Algorithm design calculation across the heat exchanger

The initial characteristic length Lc is 0.4 m and the finalize length is obtained from the iteration until the difference of error between the new and old length reaching approximately 0. The result of the iteration is show in figure 4.4. At the beginning of iteration, the value of Lc decreased from the initial assumption value. However, on the next iteration the value become constant, Lc equal to 0.32 until its difference of error is 0.

The calculated heat required, Q form the dryer design was 154 Watt and this value is used by deliberating with the burner design calculation. The convective heat transfer coefficient, hflue calculated from the first part was 3.41 $W/m^2.K$. In the second part, the calculated Re was 319.17 which is a laminar flow with air convective heat transfer coefficient hair of 4.78 $W/m^2.K$.

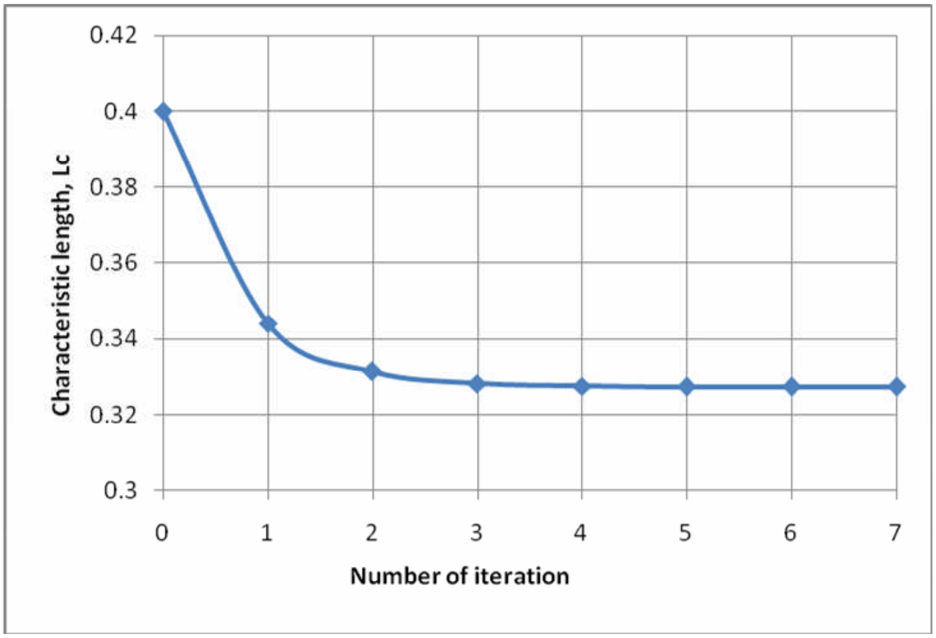


Figure 4.4: Characteristic length,Lc versus number of iteration

No.	Item	Value
1	Inner wall temperature, Twi	132.5°C
2	Outer wall temperature , Two	132.5°C
3	Convective heat transfer coefficient, hflue	3.41 W/m².K
4	Heat from burner, Qburner	154 Watt
5	Hydraulic diameter for circular tubes, Dh	0.19m
6	Reynolds number, Re	319.17 (Laminar)
7	Grashof number, Gr	1.295×10^{8}
8	Ratio Gr/Re²	1272 (Natural convection)
9	Nusselt number, Nu	57.98
10	Rayleigh number, Ra	9.327×10^{7}
11	Convective heat transfer coefficient , hair	4.78W/m².K
12	Characteristic length , L'c	**0.3273m**

Table 4.2 Result of Burner Design Calculation with Initial Assumption of Lc=0.4m at iteration 8

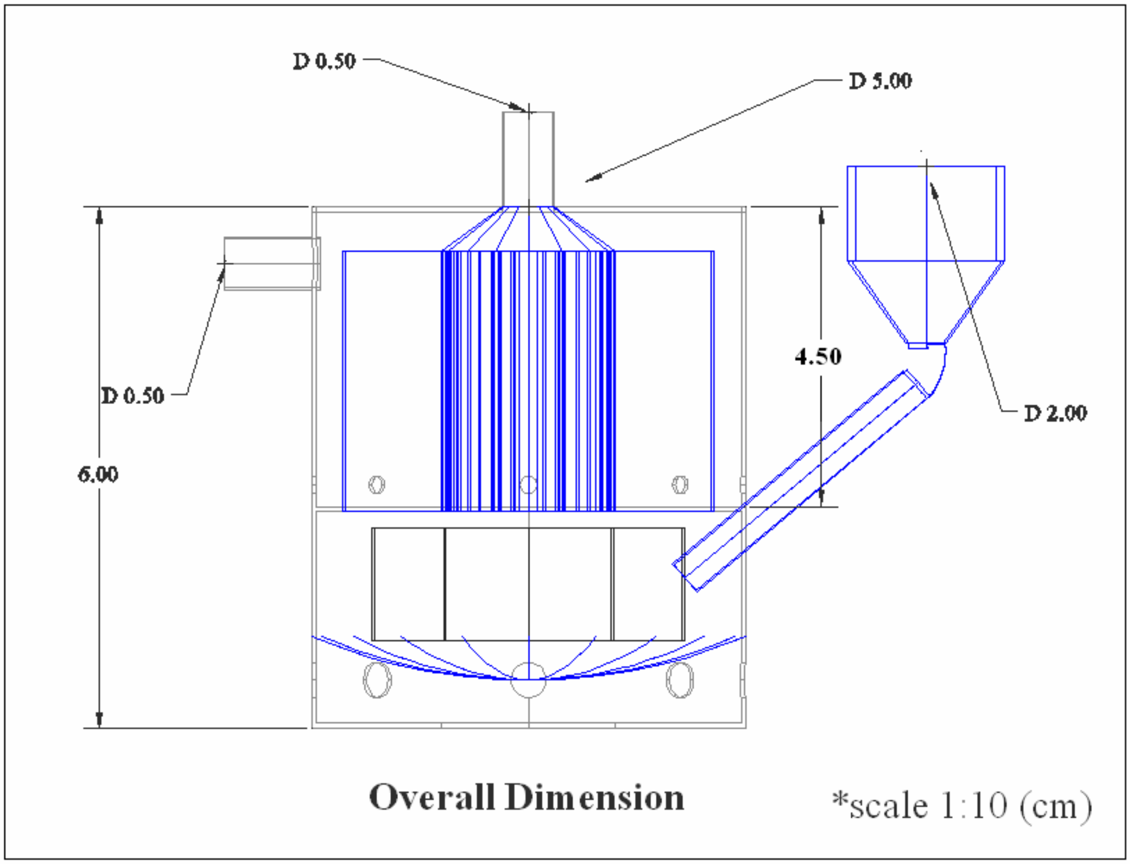


Figure 4.5: The final design of the burner

CHAPTER 5
DESIGN AND FABRICATION

Ordered studies had been made in order to come out with an efficient design of the controllable biomass burner with gas to gas heat exchanger. The operation, the characteristics of each fixtures design and also the types of material used are been investigated.

5.1 The solid waste as fuel burnings.

Combustion of biomass as fuel has many environmental and economic advantages since it is cheap, clean and a type of renewable source of energy. Biomass fuel also produces less harmful gases to the environment compared to hydrocarbon fuel.

The calorific value of biomass is an indication of the energy chemically bound in it and in the combustion process it is converted into heat energy [9]. Calorific value is the most important property if a fuel which determines the energy value of it. The design and control of a biomass combustor are depending strongly on the calorific value of the biomass fuel. In order to obtain the calorific value of biomass fuel, experimental study must be carried out or it can be calculated from ultimate and/or proximate analyses result of it.

From the survey to find the suitable type of fuel, the author had visited some factory to collect the sample. The beautiful thing about all these factory is, there are currently producing their own electricity by burning the biomass waste such as rice husk and EFB. The electricity is supply throughout their factory so that they do not need to buy it. This biomass fuel also comes in a very cheap price, since it is a solid waste after all.

For the author scope of research, the biomass fuel that is going to be used as a biomass fuel and biomass solid fuel for drying purposed is as follows:

No.	Type of Biomass	Calorific Value kJ/kg
1	Rice Husk	13, 800
2	Empty Fruit Branches (EFB), palm oil waste	17, 000
3	Wood Chip	16, 320

Table 5.1: Type of biomass fuel investigated and its calorific value. [9] [10] [11].

The outlet temperature gain from the rice husk, EFB and Wood chip will be compared to the required assumption value to investigate the performance of this unit, and its potential to be used as a backup heater for solar dryer.

Figure 5.1; Empty Fruit Branch EFB samples.

Figure 5.2; Wood chip samples.

Figure 5.3; Rice Husk samples.

5.2 Gas to Gas Heat Exchanger Design.

Gas to gas heat exchanger is a device to control the production on heated clean air from heated flue air. The clean air here is the ambient air that is going to be heat up inside the heat exchanger that is integrated to biomass burner, while the flue air is the direct smoke produce from the combustion of biomass fuel with excessive air inside the burner itself. The direct smoke will later on been used as a medium to dry solid fuel biomass waste inside the dryer and the clean heated air will be used to dry food. The gas to gas heat exchanger application is crucial since the combustion of biomass fuel produce harmful and poisonous gases which is not suitable for the food drying application.

The criteria needed for this gas heat exchanger is:

a) High heat transfer coefficient.
b) Excellent reaction characteristics as a steam reformer.
c) Produce clean air.

The design of the gas heat exchanger is as follows:

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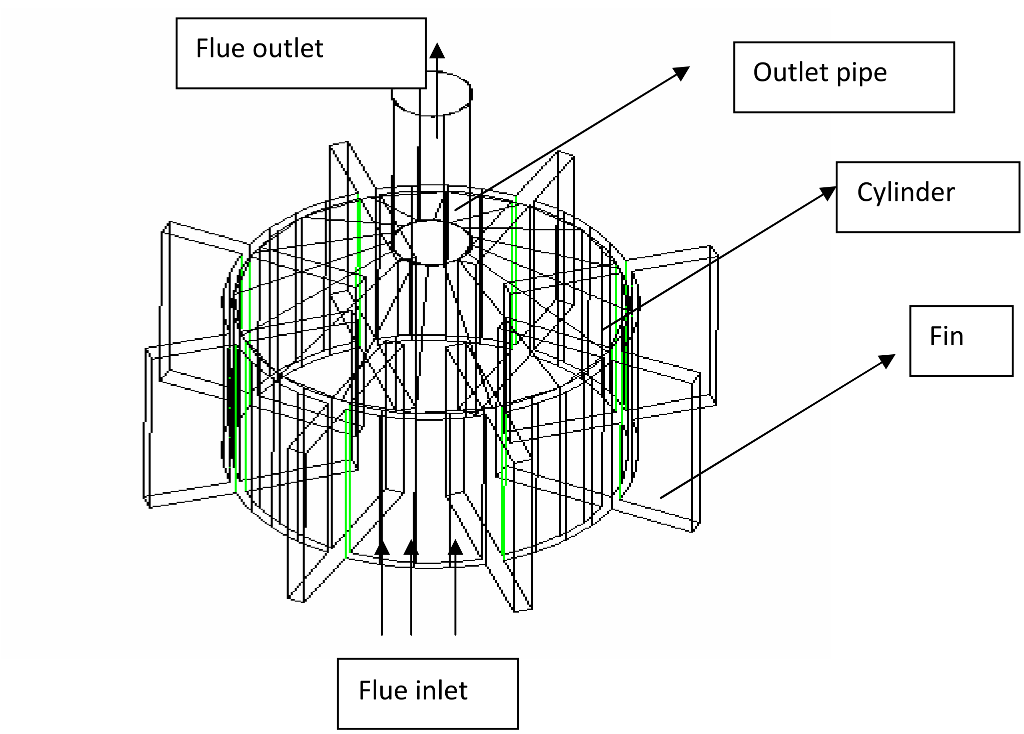

Figure 5.1: The gas heat exchanger design and its component.

5.2.1 The gas heat exchanger material.

Material selection is the main concern of the gas heat exchanger design. The same type of material will be use to all of the heat exchanger part. Heat exchanger cylinder has a function as a major heat transfer surface, and also as a barrier to prevent flue gas to mix with the clean ambient air. The cylinder must have a good characteristic in the required criteria which is melting point, corrosive, assembly easiness, thermal conductivity, and price.

For this design, six types of material are consider reliable for the process. Table 5.2 represents the decision matrix leading to the final choice. All the materials are rating between 0 and 5 to each cell of the table, bound to the influence of the corresponding. Based on the material selection table below, Stainless Steel is chosen because it scores the highest mark during the evaluation.

	A	B	C	D	E	Total
Pure Copper	5	3	2	5	3	18
Low carbon steel (AISI 1010)	4	3	5	2	4	18
Aluminum	4	5	3	3	2	17
Stainless steel (AISI 304)	**4**	**5**	**5**	**1**	**4**	**19**
Titanium	5	5	3	2	1	16

Table 5.2 : Decisional matrix for the choice of material.

Criteria : A: Melting point; B:Corrosive; C:Assembly easiness; D:Thermal conductivity E:Price.

Choice : 1:very bad; 2:medium; 3:good; 4:very good; 5:perfect.

5.2.2 The gas heat exchanger fin

Fin is a medium used to increase the surface area of the gas heat exchanger. Since the convective heat transfer coefficient of the air is too low and the temperature different between the hot flue and the outlet flue is not too large, thus to produce a good heat transfer rate, a large surface area is needed.

For this design, currently rectangular plate fin is inserted on both side which is the inlet fins, and outlet fins. The thickness of the fins is neglected since it is considered as a thin plate. As per Figure 5.1, there are eight fins which will increase the surface area.

5.3 Biomass burner design.

As for biomass burner design, the author had adopted the design from the previous researcher [13] since the burner only need some improvement in the design of its fuel feeder, combustion bed and its air inlet. The best material for this section as per previous researcher is galvanized ion. Galvanized ion is chosen because it has a good fire resistance characteristic which can sustained up to 1500°C.Galvanized ion are also having fair corrosion resistance and it is very excellent for joining especially welding.

5.4 Additional Features

The design need some additional features before it can work efficiently with the dryer.There are three main features need to be adding on to this design:

a. Chimney

We had fabricated a high chimney of height 1.5 m with a diameter of 2.5 inch. The chimney is crucial to create a buoyancy effect which can increase the velocity of the air inside the burner and provide proper channel for the outlet gases.

b. Insulator

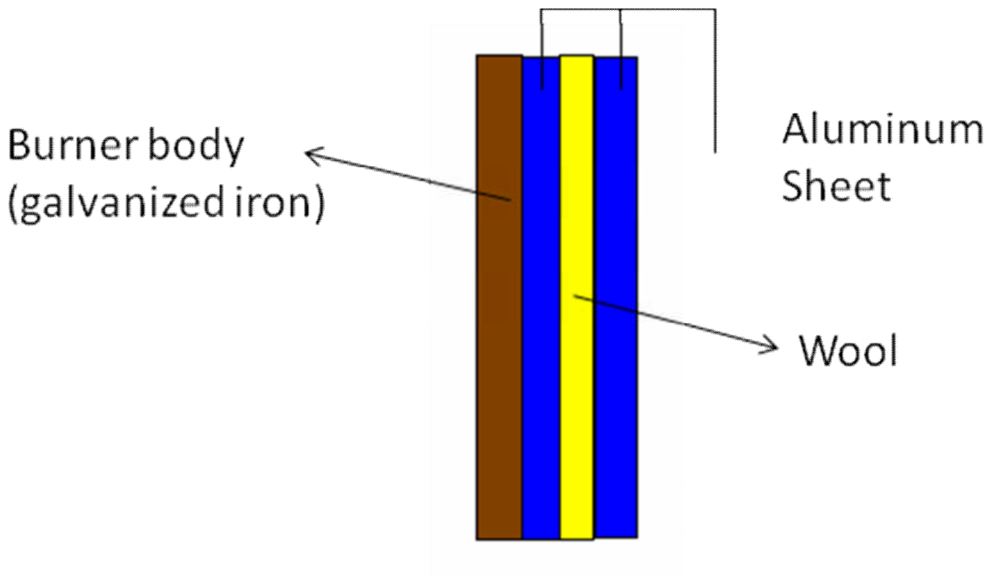

Figure 5.2 : Cross section of the insulator for burner body.

Insulation is important to prevent heat loss from the burner to the environment since we want to maximize the heat created for the use of the dyer.For this project, we are using 2 layers of insulator, first is wool, and the second is aluminum sheet.

c. Hose connector

Hose connector is the pipe use to supply the heated air of flue from the burner to the dryer. The hose are able to trap the heated air and reduce the heat loss to the environment. To increase the hose efficiency, insulator is also used for the hose connector which is wool.

5.4 Biomass and Gas Heat Exchanger Design.

The dimension and drawing for each part is as per Appendix A. The complete assembly of all the part in the design is as follows:

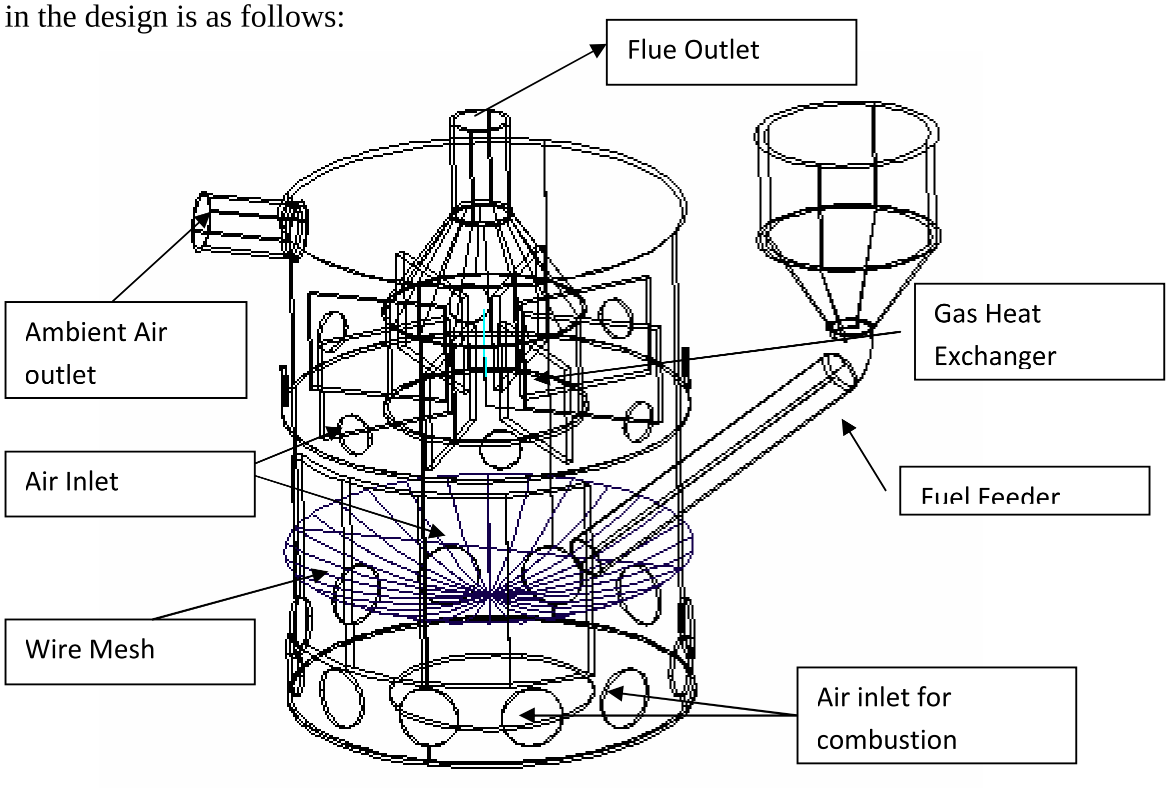

Figure 5.3: Complete Design of the Model.

Figure 5.4 Complete Design of the Model

Figure 5.5; Chimney configuration to the burner

CHAPTER 6

RESULT AND DISCUSSION

The unit itself is the result for this project; however the author had decided to proceed with several experimental measurements to obtain a further knowledge and experienced.

6.1 Temperature outlet.

After the fabrication process is completed, the functionability and effectiveness of the model is tested by burning three type of biomass fuel which is Rice Husk, EFB and Wood chip. The experiment is carrying out with different feeding rate for 4 hours to obtain the required temperature and velocity that is suitable for drying application. The experiment setup is as per Appendix D, and the measurement data taken as per Appendix H.

6.1.1 Burning of Rice Husk.

A general observation was that rice husk has a slow combustion rate, since rice husk combustion was hardly to have a fire. It is more to gasification where more smoke were produce when new fuel is feed into the combustion bed. It is also very hard to initiate fire to the rice husk; there is where turpentine was spray to the fuel in the combustion bed to initiate the fire. The other main challenge in combustion of rice husk is, it is very difficult to maintain the fire while the new fuel that is been feed to the combustion bed usually will not easily burn.

Experiment is conduct with three different weights which is 500g, 1000g and 1500g for 4 hours of operation. These weights were chosen to ensure that the fuel can supply enough heat and can sustain for the 4 hours of experimentation. The result is tabulated in Appendix K, and the clean air outlet graph is as follow:

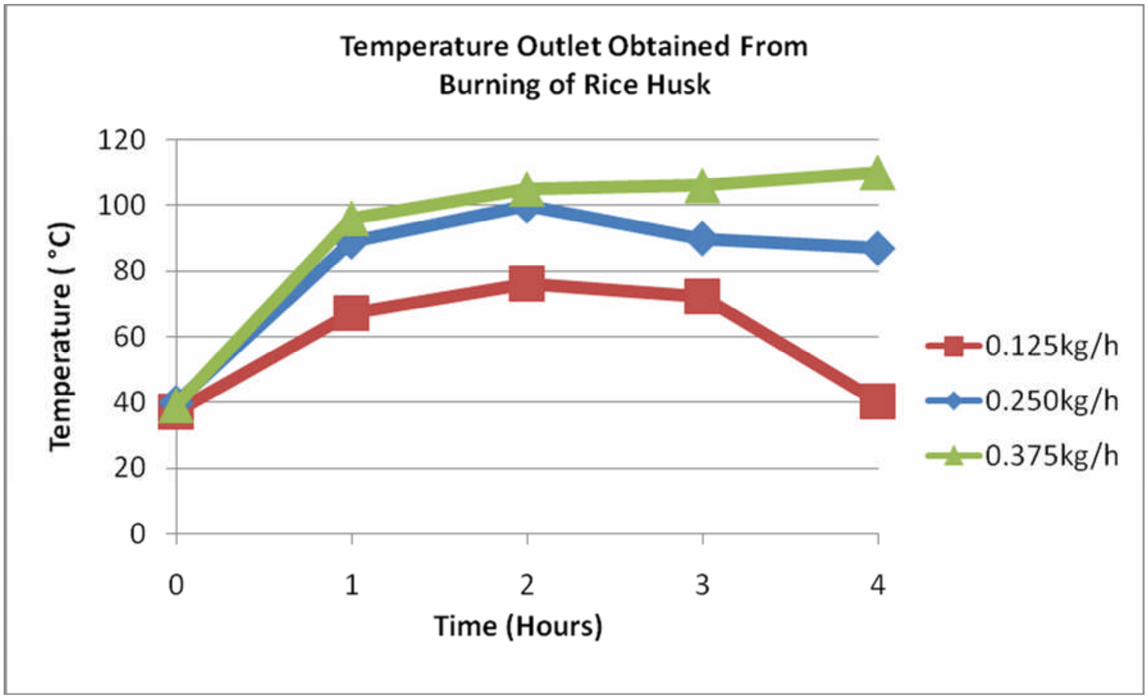

Figure 6.1: Temperature Obtained from burning of rice husk

All these 3 sets of experiment is conduct in the afternoon where the initial ambient temperature is 38^{o}C in average. The ambient air somehow already heated up the model since the model is made of metal and gives the initial temperature outlet of 40^{o}C even though the burning process is not yet started. For the first experiment with feeding rate of 0.125 kg/h, it is observed that the burner takes about 2 hours to be heated up and produce the heat air of 76 ^{o}C which is within the required temperature (70 ^{o}C -100 ^{o}C). The required temperature range is obtained after considering the heat loss along the wire hose so that the temperature that reaches the dryer is within (60 ^{o}C -75 ^{o}C). However during the 2nd hours to 3rd hours the graph shows declining in temperature outlet due to insufficient fuel to be feed to the burner. During the 3rd hour, the fuel is already finished and the temperature drops to 40 ^{o}C when the experiment ends. For rice husk, it is observed that feeding rate of 0.125 kg/h is insufficient to sustain the required air temperature for 4 hours.

The experiment is then carried out with feeding rate of 0.250 kg/h and graph shows that the burner only took an hour to reach the within the required temperature. The temperature outlet during the first hour is 80^{o}C and it is keep increasing until 90 ^{o}C until the end of the 4 hours.

Lastly the experiment is repeated with feeding rate of 0.375kg/h and it is observed that the temperature for the first hours is already almost 100 °C and it is keep increasing till the end of the experiment. This feeding rate give a maximum of 110 °C for the temperature outlet and it is far beyond the required temperature and it is surely can affect the quality of drying product if it is were to be used for the drying application.

6.1.2 Burning of Empty Fruit Branch (EFB)

EFB is obtained directly from the nearest Palm Oil Factory (FELCRA), and it is very high in moisture. It is not suitable for combustion until it has been dried under open sun for several hours. General observation was that EFB fire is hard to be maintained, and it needs to be stirred regularly in order to ensure all of the fuel is completely burn. This is due to the present of different properties of particles in EFB such as empty shell which is quite hard and press fiber which is very light. EFB also need the use of turpentine as a fuel igniter and to maintain the fire throughout the experiment. When good fire is obtained, high temperature and small ashes were produce and it shows that EFB is completely burn.

EFB is burn in three different weight 1000g, 1500g and 2000g for four hours, the result for this combustion is as per Appendix J and the result of clean air graph is as follow:

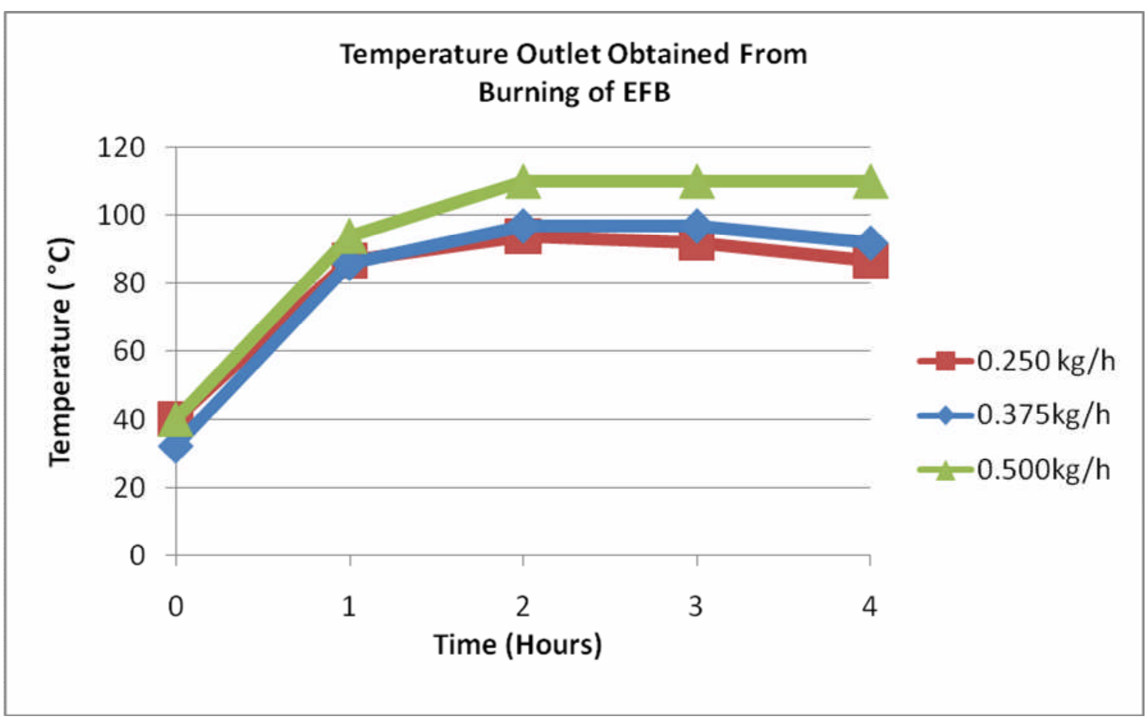

Figure 6.2: Temperature Obtained from burning of EFB

During the pre test experiment, EFB is observed to have a fast burning rate since its come is shredded properties and light in weight. Therefore the experiment were started with 1000g of EFB with feeding rate of 0.25 kg/h. EFB deliberate a good burning heat when it only takes one hour to reach within required temperature (70 ^{o}C -100 ^{o}C). The maximum temperature obtained from this feeding rate is 94 ^{o}C and by referring to the chart, temperature almost constant until the end of the 4 hours. For the second feeding rate which is 0.375 kg/h, the maximum temperature obtained is 97 ^{o}C. The result is almost similar with the first experiment even though it uses more weight. This is because the second experiment is conducted in the morning where the ambient temperature is 32 ℃, so more fuel is needed during the first hour to increase the temperature outlet to the required heated temperature.

For the last experiment, 2000g of EFB were burned with the feeding rate of 0.5 kg/h. It is observed that during the 2nd hour, the temperature is already more than 110 ^{o}C which is more than the measuring equipment limit. Digital thermometer were use for this purpose with maximum temperature reading of 110 ^{o}C. When the temperature exceed more than 110 ^{o}C the equipment had to be remove to avoid from damaging it and the actual temperature could not be measured. However the actual temperature is not worth knowing since the limit temperature for this experiment is between (70 ^{o}C -100 ^{o}C). The equipment is place once every one hour to get the reading, and shows that the temperature keeps rise beyond 110 ^{o}C until the end of the experiment.

6.1.3 Burning of Wood Chip

Wood chip is the excess form craft process of wood and come in very small thickness. Wood chip need to be perfectly dry before the experiment is started. For the first experiment, 1000g of wood chip is use with feeding rate of 0.25 kg/h. Wood chip is observed burn in a fast rate and require constant feeding of the fuel to maintain the combustion. During the first hour, the temperature outlet from the burner is 98 ^{o}C, which shows that wood chip is a good source of fuel because it heated up the burner in a fast rate. Until the end of the experiment the temperature is remains in the required range and not exceeding 100 °C. For the second experiment, with feeding rate of 0.3125kg/h, the burner produce heated air with excessive temperature that is more than 110 °C. The result is almost similar to the third experiment result with feeding rate of 0.375kg/h with 110 °C is the limit of the measuring equipment. The result from wood chip burning is tabulated in Appendix I.

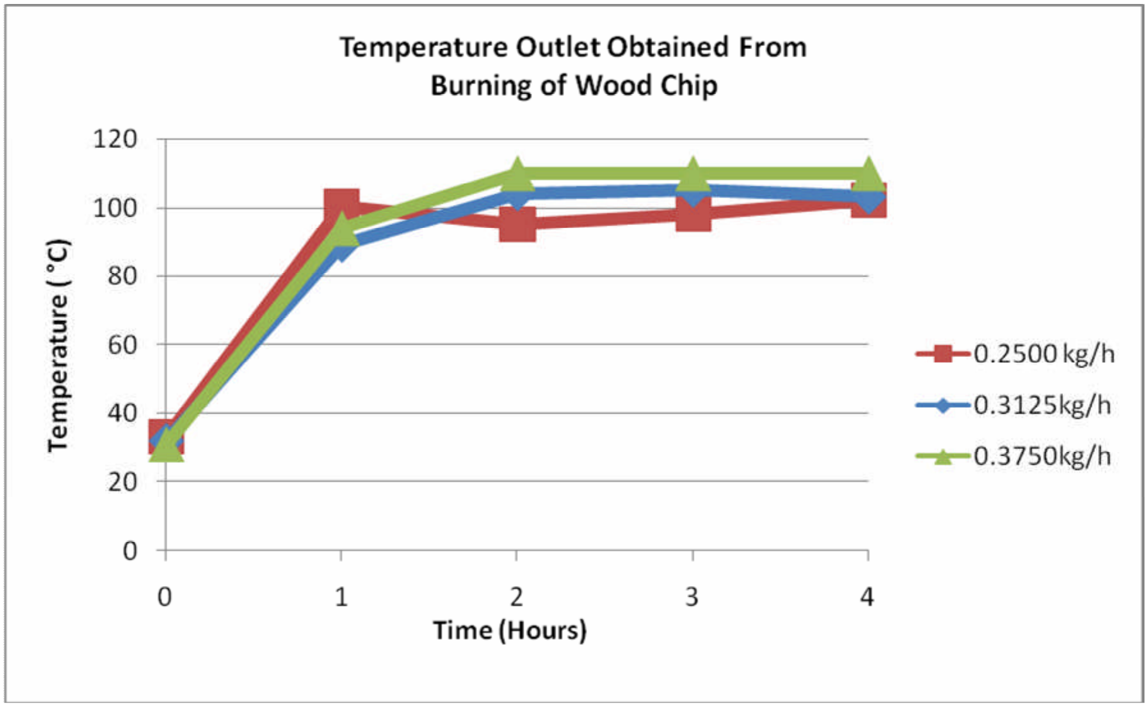

Figure 6.3: Temperature Obtained from burning of rice husk

The main observation from this experiment is wood chip are a good biomass fuel because it is easy to initiates fire and easy to sustain the fire. In order to ensure continuous combustion inside the burner proper feeding and monitoring is needed since the wood chip burn in a fast rate.

6.2 Mathematical Modeling Vs Experimental Result.

To prove mathematical modeling is correct, we can compare it with the experimental value obtain. For this analysis, author has chosen the best fuel type with the best feeding rate to compare with the mathematical modeling result. Based on the experiment result, wood chip with

0.25 kg/h feeding rate is consider the best fuel and feeding rate with respect to its temperature outlet and air velocity produced. The result of the calculation is tabulated in the table as follow;

	Item	Mathematical Modeling	Experimental Result	Percentage of difference (%)
1	Inner wall temperature, Twi	132.5°C	140°C	0.05
2	Outer wall temperature , Two	132.5°C	126°C	0.05
3	Convective heat transfer coefficient, hflue	3.41 $W/m^2.K$	3.27$W/m^2.K$	0.04
4	Heat from burner, Qburner	154 Watt	200 Watt	0.25
5	Convective heat transfer coefficient , hair	4.78$W/m^2.K$	4.85$W/m^2.K$	0.02
6	Characteristic length , L'c	**0.3273m**	**0.5410m**	**0.40**

Table 6.1: Comparison between Mathematical Modeling and Experimental results.

6.3 Burner Performance

During initial tests of the biomass burner using rice husk, it proved to be difficult to control the combustion of the fuel. So fire starter were used at first, however it is failed to ignite the rice husk since rice husk come in small particle size. Then turpentine was used and it proved success to ignite the fire, but the fire cannot last longer. Fired rice husk cannot sustain its fire for long enough until it can burn all of the other fuel. This is where the author starts to properly monitor and controlling the fire from the feeding door using a stick to stir the rice husk evenly to obtain good fire. Same goes with EFB, once it is on fire, it need a proper stir effect to ensure that there will be good fire and good distribution of fire to the fuel. Unlike rice husk and EFB, wood chip had a different characteristic of combustion. Wood chip is considered as the best fuel among those three fuels by considering the fire produce, and the rate distribution of fire.

Once good fire is managed to be obtained with the temperature at the combustion bed ~400 ^{o}C, the outlet air and flue velocity is measure using hot wire anemometer. However the velocity is significantly small 0.1m/s, and often been interrupted by the ambient velocity. Hence 2 type of chimney were design, which is one straight chimney with 1.5 m height, and the other is L-shape chimney with 1.5 m height. The straight chimney is for the flue side and the L shape is for the air side. After the installing of the chimney, and proper set up of equipment, the result velocity of the outlet is improved to 0.9m/s in average.

Based on the experimental result, the burner is observed to produce heated air in required temperature after 1 hours of burning process. This is due the material used for the burner, and the thickness of the plate inside the heat exchanger. The thick extended surface inside the heat exchanger is performed as an absorber which can store heat for hours. It is a very important property to ensure the temperature inside the dryer is remains above the ambient air temperature in the early hour when the fuel is finish, thus preventing the re-absorption of moisture by the drying product.

6.4 Burner efficiency

Overall thermal efficiency of burner can be define as ration of useful heat transferred to the drying air to the energy potential of fuel. This efficiencies is a product of combustion efficiency and the efficiency of heat that is been transferred to the air. Ideally these efficiencies could be evaluated separately, so that areas of improvement could be identified. However this was not practical for this project and therefore an overall efficiency was calculated as

$$\text{Overall efficiency of the heater} = \frac{\text{heat transferred to air entering the dryer}}{\text{calorific value of fuel used}} \qquad [2]$$

From the result obtained during 4 hours of experiment, and overall efficiency of the heater was found to be 18% based on the calculation from Appendix G.

CHAPTER 7
CONCLUSION AND RECOMMENDATION

7.1 Conclusion

A simple integrated burner has successfully been design and fabricated using appropriate software and skills. The burner consists of 3 main parts, biomass burner, gas to gas heat exchanger and solid fuel feeder. Initial boundary condition and assumption were obtained from previous researcher who successfully designs a solar dryer. The critical part of this project is during the designing phase where lots of equation and theory developed prior to achieve the objective. Extended surfaces were use to increase the contact area in the heat exchanger and the dimension of the design is properly calculated. Proper material selection is also been done to ensure the model working perfectly and within the funding budget.

The result shows the most suitable biomass fuel to be use for this simple burner is wood chip by considering their rate of burning, ability to sustain fire for longer and the simplest method for operating. EFB and rice husk combustion need a larger facility with proper fire ignition system to burn and maintain the fire. The unit which is already been tested, prove that it can supply the suitable hot air for both food and biomass waste drying application with an acceptable velocity of flow.

7.2 Recommendation

Further improvement in the operation and performance of the burner can be achieved through further modification, which includes:

- The fuel feeder needs major modification since the designed model is not working at all due to improper joining which create obstacle. This obstacle had prevented the movement of biomass fuel to flow onto combustion bed even after the valve is open. For improvement, the fuel feeder has to be redesigned by considered increasing diameter and angle of the feeder pipe so that fuel can fall down easily.
- The feeding of the fuel is done manually by the author using feeding door. This method is very tedious and not practical for this type of operation because drying process normally took days or weeks to dry its product, thus the integration of controllable mechanism that can control the rate of feeding is highly preferred. This mechanism can ensure the continuity in fuel burning and result in good temperature outlet. Installation of controllable mechanism also can allow the user to control the temperature outlet so that the temperature entering the dryer is within the required limit.
- Improvement to combustion bed is also prior in order to ensure a good combustion process. Observation from the burning of the three type or biomass fuels shows that all of these fuel produce raw ashes which the thickness is larger than the size of the wire mesh. The ashes is trapped between the wire mesh, and when it is not remove, it can cause insufficient air for combustion. However, if we are using a larger size of wire mesh, the fuel itself cannot stay on the bed for combustion. So the improvement needed is a drain hole somewhere to the side of the wire mesh so that the user can remove all the ashes while or after the operation by using a stick.
- Controllable air inlet valve is also needed to control the rate of fuel burning. For example, the wood chip burn in a fast rate and the only parameter to control its burning rate is the

supply of its inlet air. When we able to control this parameter, we can feed the burner with excessive fuel and yet still the fuel will not be burn at once. Thus the combustion could sustain longer without any fuel feeding and proper monitoring.

- Adding a stir machine on the combustion bed also can helps in spreading fire for rice husk and EFB. It is observed that these two fuel is very hard to maintain its fire, however stirring effect prove to successfully can maintain its fire. This can be an add on to the controllable fuel feeder since once the fuel is dropped to the combustion bed, the stir machine can help the new feed fuel to mix and burn with the fired fuel on the bed.

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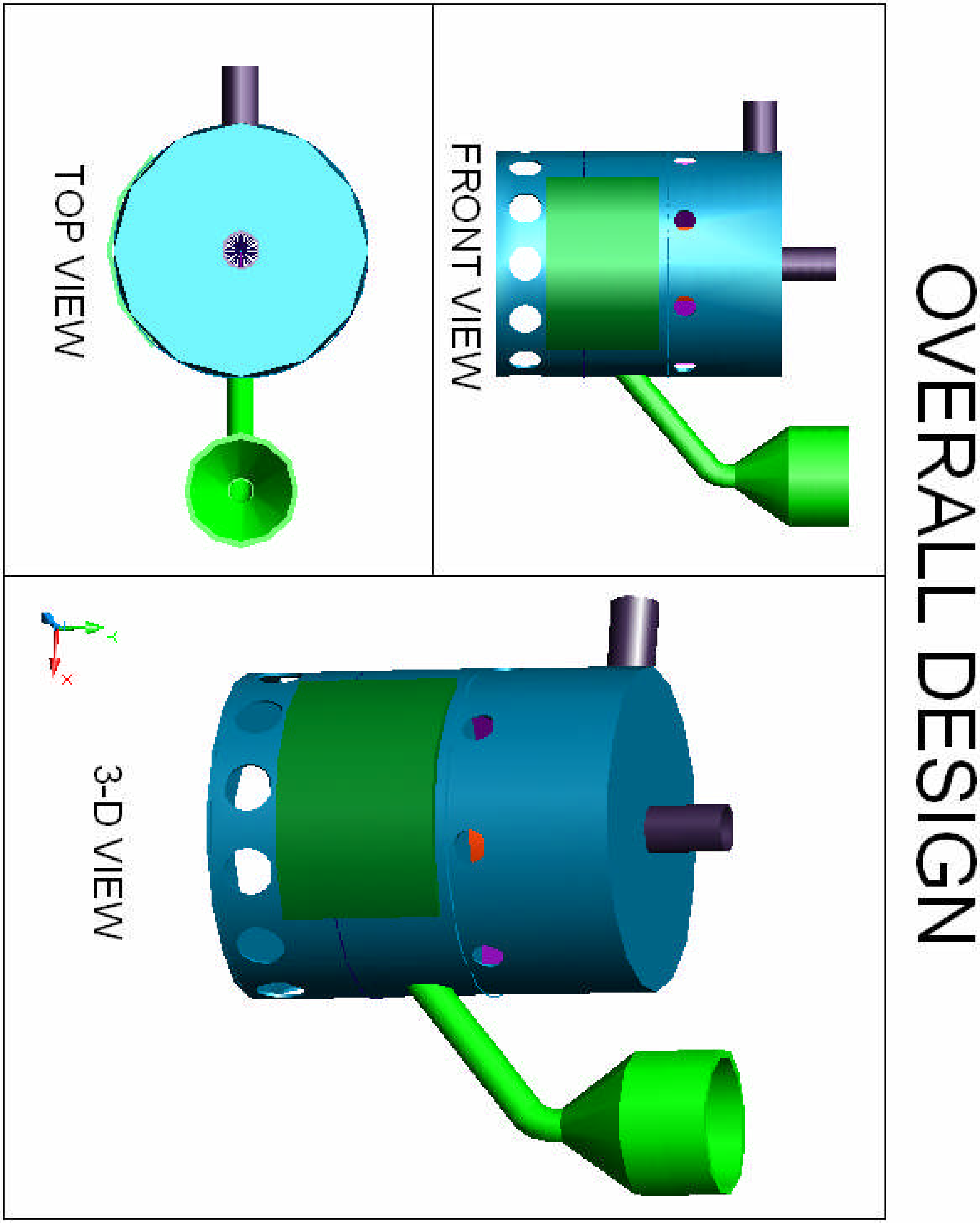
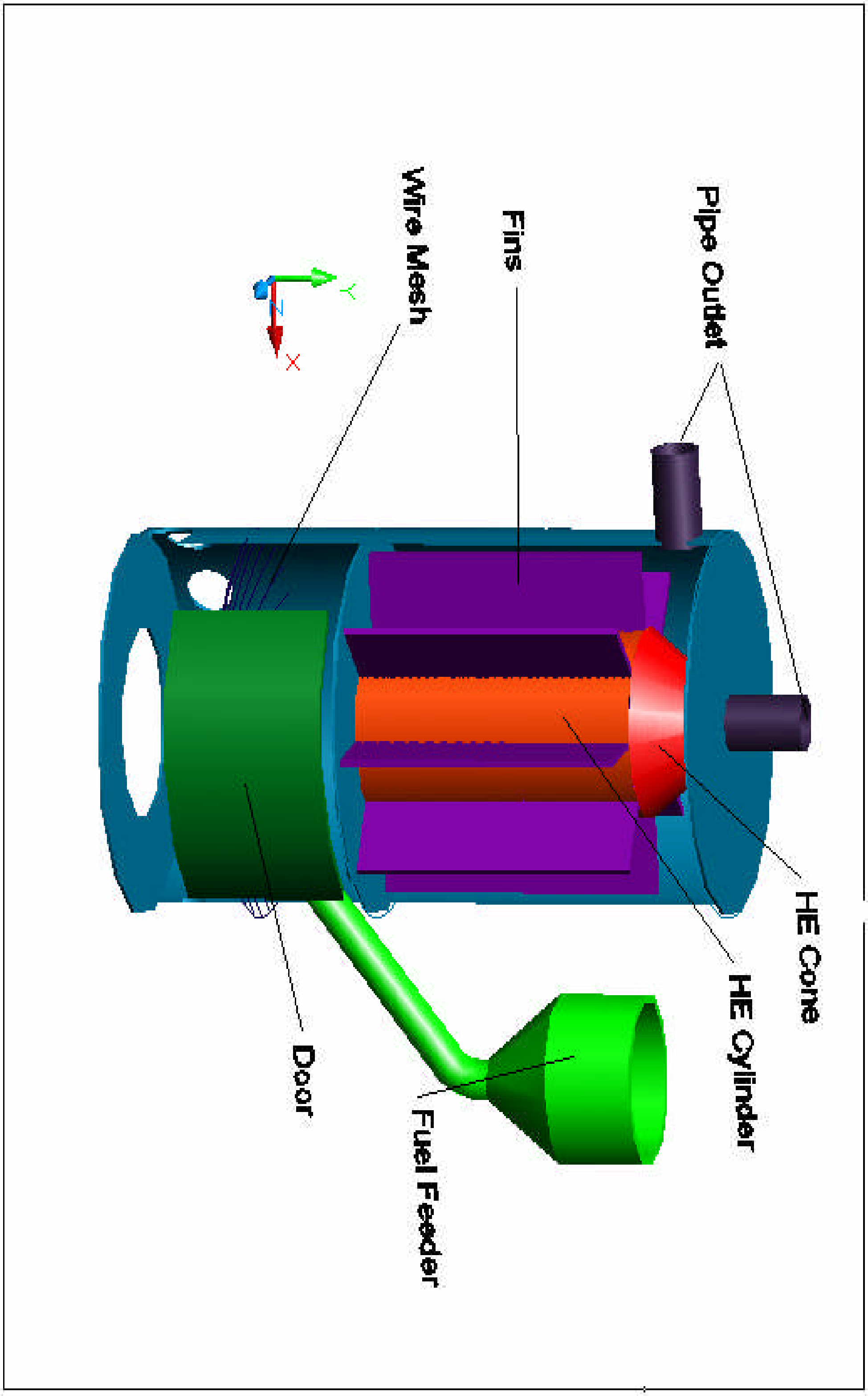
Appendix

APPENDIX-A	Overall Design
APPENDIX-B	Section View
APPENDIX-C	Dimension of Fins
APPENDIX-D	Thermocouple wire setup
APPENDIX-E	Digital Thermometer
APPENDIX-F	Infrared Thermometer
APPENDIX-G	Burner Efficiency Calculation
APPENDIX-H	Picture of Measurement or data taken
APPENDIX-I	Wood Chip Experiment Data
APPENDIX-J	EFB Experiment Data
APPENDIX-K	Rice Husk Experiment Data

Appendix A

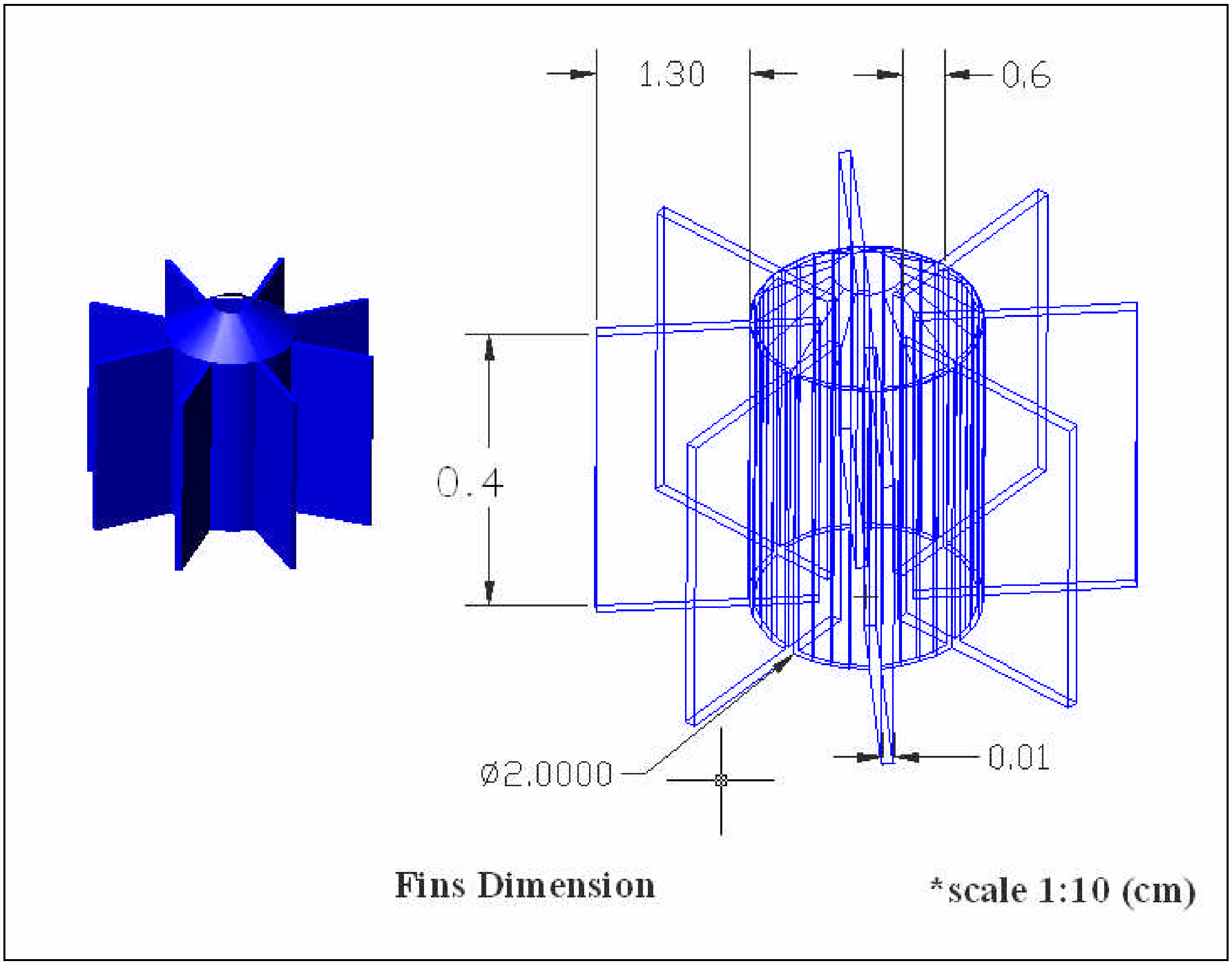


Appendix B


Section View
Pipe Outlet
Fins
Wire Mesh
HE Cone
HE Cylinder
Fuel Feeder
Door
Y
Z
X

Appendix C

Dimension of Fins



Appendix D

Thermocouple wire setup

Appendix E

Digital Thermometer

Appendix F

Infrared Thermometer

Appendix G

Burner Efficiency Calculation

$$\text{Overall efficiency of the heater} = \frac{\text{heat transferred to air entering the dryer}}{\text{calorific value of fuel used}}$$

From experimental calculation, we obtained

Q=200 W.

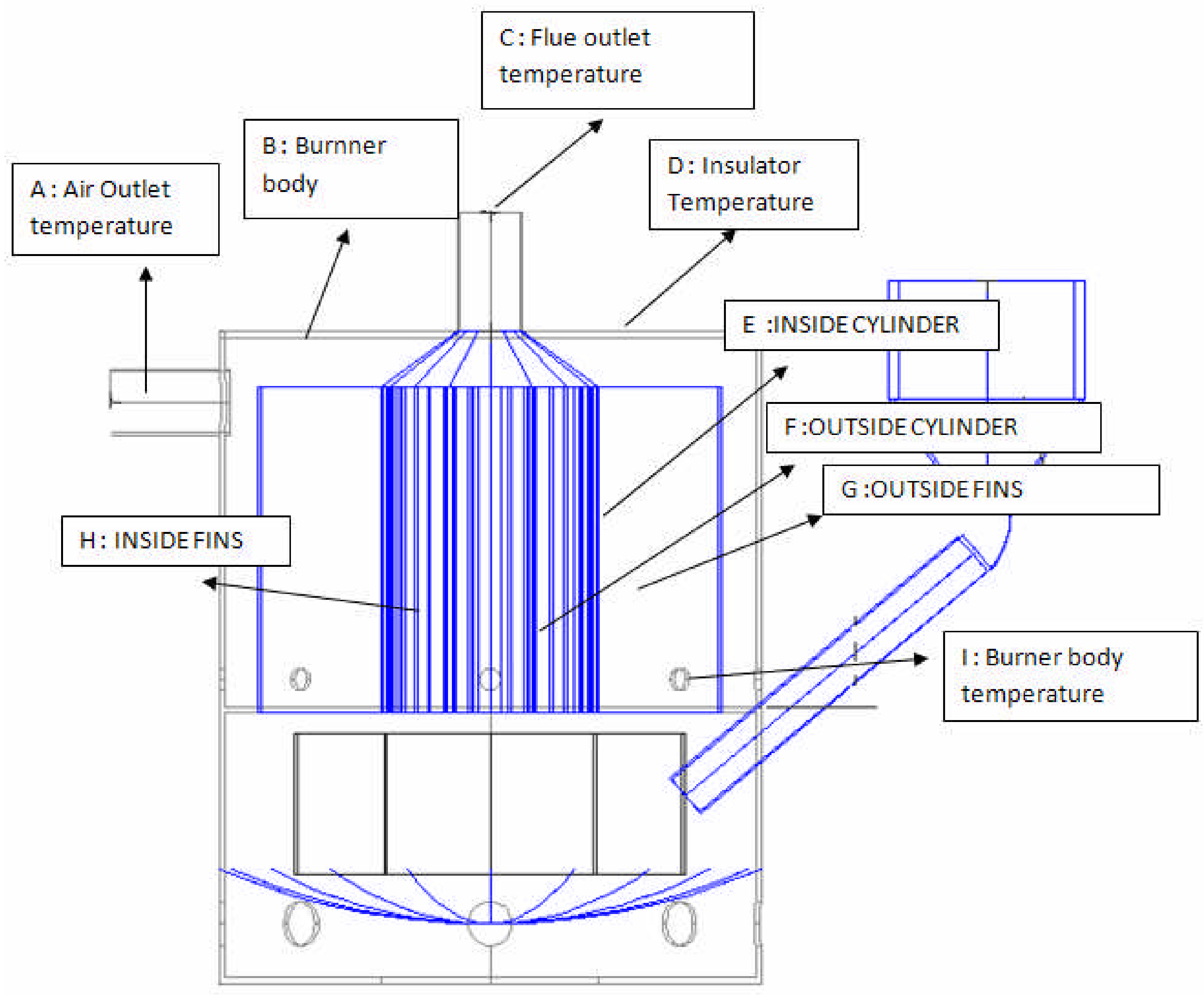
Calorific value of Wood Chip is = 16 320 KJ

$$\text{Overall efficiency of the heater} = \frac{200\ \text{Wr}}{\frac{16320000}{4}/3600}$$

Overall Efficiency = <u>18 %.</u>

Appendix H

Picture of Measurement or Data Taken



Appendix I

m=1000g	Wood Chip															
	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
Time\Point	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	33	35.6	35	35.4	25	26	28	28	34.2	33	33	1.2	1.3		1.1	28.9
1	100	78	56	67	140	120	112	140	105	100	105	2.1	1.3		1.2	38
2	95	77	55	65	135	115	110	135	106	95	95	1.9	0.9		1.1	39
3	98	82	58	65	158	136	118	140	98	98	99	1.6	1.1		1.2	40
4	102	92	68	68	127	132	124	122	98	102	110	2	1.2		1.6	40.7

m=1250g																
	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
Time\Point	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	31	30	35	33	32	32	32	32	30	32	31	1	0.8		0.9	27
1	89	71	72	48	160	210	180	160	68	89	110	2.5	1.2		1.6	33
2	104	100	75	65	170	160	204	172	99	104	112	2.3	1		1.1	38
3	105	103	75	65	180	185	180	175	120	105	120	3.3	0.9		0.9	38
4	103	110	65	76	120	124	118	120	110	103	113	3	1		1.3	40

m=1500g																
	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
Time\Point	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	31	30	35	32	32	32	33	32	30	31	30	2	0.9		0.8	31
1	94	83	70	70	140	130	118	138	90	94	98	3.7	0.8		0.9	33
2	>110	96	77	80	200	192	140	198	108	>110	>110	1.2	1		0.8	37
3	>110	105	80	83	190	183	165	188	110	>110	>110	1.6	1.2		0.7	38
4	>110	106	83	83	192	185	166	190	112	>110	>110	1.9	1.3		0.6	40

Appendix J

m=1000g	EFB															
	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
Time\Point	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	40	41	38	38	32	34	36	35	41	40	38	2.5	1.1		1	40
1	87	74	58.3	50	150	150	145	140	72	87	90	3.1	1.4		1.1	39
2	94	80	55	51	155	124	116	150	90	94	97	1.5	1.1		0.9	39
3	92	84	56	50	135	121	115	140	90	92	93	1.2	0.8		0.9	38
4	87	82	50	44	110	103	100	120	80	87	90	1.8	0.9		0.8	35

m=1500g																
	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
Time\Point	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	32	35	32	33	29	28	28	29	30	32	32	2.4	0.4		0.8	31
1	86	90	62	60	130	125	123	128	70	86	90	2	0.9		0.9	35.1
2	97	100	65	65	128	124	120	130	90	97	100	1.9	0.8		0.8	37
3	97	105	70	65	130	110	125	120	100	92	94	1.8	1.5		0.6	38
4	92	98	63	60	120	110	105	110	98	92	90	2.3	0.9		0.7	38

m=2000g																
	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
Time\Point	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	40	55	50	45	50	52	52	50	43	40	39	2	0.7		0.7	36
1	98	65	51	60	140	135	135	142	80	98	98	2.3	1		1.2	37
2	>110	120	70	70	178	164	163	180	120	>110	>110	2.3	1.6		2	37
3	>110	151	73	75	238	220	210	240	145	>110	>110	1.9	1.1		1.6	37
4	>110	145	80	72	201	198	190	200	130	>110	>110	1.5	0.8		0.7	36

Appendix K

m=500g	Rice Husk															
Time\Point	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	39	38	37	38	38	36	35	34	35	37	37	1.5	0.9		0.8	38
1	67	58.8	41	34	89.4	80.4	60	84	54	67	80	1.5	0.8		0.7	31
2	76	50	50	34	117	99	90	123	68	76	90	1.4	0.9		0.7	32
3	72	50	46	43	78	77	74	77	40	72	80	1.4	0.8		0.6	34.7
4	experiment ended because not enough fuel															

m=1000g																
Time\Point	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	40	38	37	40	41.5	39.6	39.6	38	37	40	39	1.3	0.7		0.7	37
1	89	74	56	56	142	125	105	138	100	89	90	2	0.8		0.7	38
2	101	60	57	44	127	110	108	125	95	100	100	1.7	0.9		0.6	38
3	90	67	45	36	103	90	99	99	82	90	92	1.5	0.8		0.7	39
4	87	61	35	34	99	97	99	99	70	87	90	1.2	0.7		0.6	35

m=1500g																
Time\Point	Temperature distribution									Outlet Temperature		Air Velocity		Flue Velocity		Tambient
	A	B	C	D	E	F	G	H	I	Air	Flue	inlet	outlet	inlet	outlet	
0	39	38	39	37	37	39	38	33	36	39	32	1.1	0.7		0.6	34.7
1	96	83	80	40	160	130	100	154	100	96	110	1.8	0.9		0.9	37.6
2	105	84	81	45	162	128	105	150	106	105	110	1.2	0.9		0.7	38
3	106	90	85	50	170	131	106	158	110	106	110	1.3	0.8		0.6	35.3
4	110	92	100	51	142	122	94	138	94	110	115	1.2	0.7		0.9	36