# DESIGN OF A STEAM BOILER USING CHARCOAL

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***ABSTRACT***

*Design of a steam boiler that uses charcoal as a teaching aid would bring the concept of steam generation close to students pursuing engineering related courses. The design would have a tube, furnace, water reservoir, hopper, check valve, nozzle, flow control valve, manual blower and structural frame on which all the components are to be attached.*

**Keywords:** Design, Steam Boiler, Charcoal, Fabrication.

## INTRODUCTION

For many centuries steam boiler has been designed in different forms with the sole aim of boiling water to generate steam which is a hot gas produced when water boils. The steam generated is used for different functions and purposes. A renowned mathematician called Hero who lived in Alexandria described applications of heat to produce motions such as the expansion of air to open a temple door and use of a jet of steam to blow a hone as described in an encyclopedia. Records have shown what other persons were doing in the steam turbine field Carl Gusta Patrik de Laval (1845-1913), De Laval conceived the idea in getting the speed directly from the turbine (Dickinson, 2011).

As a teaching aid, the design brings the concept of steam generation close to students that are pursuing engineering related courses. The charcoal would be used as the fuel for the boiler because of its high calorific value and with the provision of lagging to reduce heat transfer to the surrounding. The steam boiler consists of a tube, furnace, drum, water reservoir, hopper, check valve, nozzle, flow control valve, manual blower and structural frame**.**

## STATEMENT OF THE PROBLEM

The materials used in the conventional boiler designs are expensive not quickly found, and it uses an electric heater as its source of energy or diesel fuel, which does not give room for fuel diversification, can only be operated by a professional or skilled personnel. The Industrial boiler uses a higher volume of fluid and equally required higher fuel or energy consumption.

## AIM OF THE FABRICATION

To design a prototype steam boiler that uses charcoal as a teaching aid.

## OBJECTIVES OF THE FABRICATION

i. To design a boiler using available materials
ii. To show the dimension of each component of the boiler.

## REVIEW OF LITERATURE

The boiler is an enclosed vessel in which water is heated, or vaporis generated and circulated until it turned into steam at the required pressure. (Heselton, 2014).The term 'boiler' is often used to mean the whole steam generator; Steam generators may either be classified as utility or industrial steam generators. Utility steam generators are those used by utilities for electric-power generating plants. While Industrial Steam generators are those used by industrial and institutional concerns. (El-Wakil, 1984).

Steam Power Plant continuously converts the energy stored in fossil fuels into shaft work and ultimately into electricity. (Nag, 2005). Coal is burnt inside the combustion chamber of the boiler. The products of combustion are nothing but gases. These gases which are at high temperature vaporize the water inside the boiler to steam. Sometimes this steam is further heated in a superheater. This steam at high pressure and temperature is used directly as a heating medium or as the working fluid in a prime mover, to convert thermal energy to mechanical work which may againbe converted to electrical energy. (Cengel and Boles, 1994).

The earliest reference to boilers is seen in Hero's aelopile of 200 B.C.After being little used for two thousand years, boilers became an integral part of the industrial revolution in Europe. Since those early days, boilers have come a long way, providing about 83% of the world's electricity supply. In early-nineteenth-century boilers, the steam pressure was slightly above the atmospheric pressure. This was largely due to the difficulty of building large pressure vessels from riveted plates. The invention of the water tube boiler removed this barrier. Boiler pressure began to rise steadily, reaching supercritical levels. Between the 1970's and 1990's utility industries operated conservatively by bringing down the steam pressure used in boilers. There has been a renewed interest in the use of high-efficiency supercritical boilers. (Prabir, Cen & Louis, 2012).

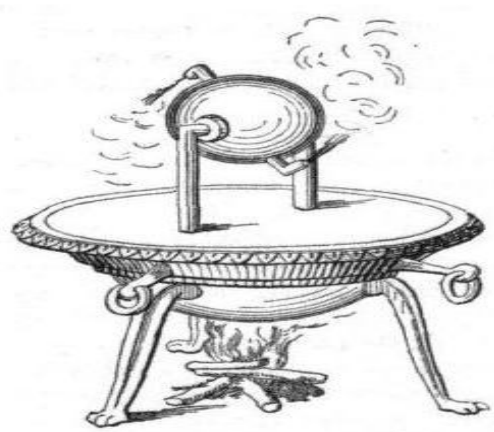

Figure 1: Hero's Engine (Prabir, Cen & Louis, 2012).

Fuel may be chemical or nuclear. A chemical fuel is a substance which releases heat energy on combustion. The principal combustible elements of each fuel are Carbon and hydrogen. Though sulfur is a combustible element to its presence in the fuel is considered to be undesirable (Rajput, 2009). Fuel burns in the furnace of a boiler, generating heat, which is then absorbed by the heating surfaces located around it and further downstream water. Water is pressurized to the required pressure by a feed water pump. It is then preheated in a heat exchanger called an economizer. The preheated water then enters the evaporator section of the boiler, which forms the vertical walls of the boiler furnace. These walls absorb heat from the combustion of fossil fuels in the boiler furnace. While traveling through the evaporative tube the water picks up the heat, but does not necessarily rise in temperature because the heat is used in transforming water (liquid) to steam (gas). (Gunn & Horton, 1989).

**BOILER MATERIALS**

Boilers require a variety of steels, starting from low-strength low-carbon steels to high strength high-alloy steels and even stainless steel for various parts. The limiting temperature and the strength required are the main factors that decide the appropriate metallurgy (Rayaprolu, 2009).

**BOILER CONSTRUCTION**

The construction of a boiler can be attributed to many things, but the principal ones are code compliance and cost. The key to building a boiler is to make the cheapest one that will do the job. Low price boiler should provide the required steam or hot water with the lowest combined price, installation, fuel and maintenance cost over its expected life. Any fired boiler has some refractory that can withstand the heat right next to a fire. Looking like cement or regular brick that will not melt under normal furnace conditions. There are three types of refractory, brick or tile, plastic, and castable. The casing is the name we use to describe the outside of the boiler enclosure when it is typically made up of steel plate, and not the same as Lagging. Lagging can range from steel plate to painted canvas but usually is thin sheet metal covers used to protect insulation applied to a boiler. (Heselton, 2014)

**Cast Iron and Tubeless Boilers**

Cast iron boilers are made up of cast pressure parts bolted together or connected by piping. The corrosion resistance of cast iron makes the cast iron boiler very durable. The tubeless boiler uses the outside of its shell as part of the heat exchange surface. The flue gases exit the furnace through a nozzle that connects the furnace and shell then makes a couple of passes along the shell between fins formed by welding steel flat bar to the shell before exiting the stack. (Heselton, 2014).

**Heat transfer in boilers**

There are three ways that heat is transferred, conduction, radiation, and convection and all the three means occur in a boiler. Conductive heat transfer is the flow of heat through a substance molecule by molecule. Convective heat transfer uses transport to get the heat from one spot to another. There are two types of convection heating, natural and forced. Forced convection is the result of a fan, pump or blower forcing the movement of the fluid over a heated surface where it picks up the heat then on to another surface where it gives up that heat. The steel parts of a boiler are selected for their ability to transfer heat with as little temperature difference as possible. (Heselton, 2014)

Coal is most widely used fuel in utility boilers. Earlier coal was burned as lumps, but most widely coal is burned at about 0.1 mm particle (Teir. 2002). Coal is mostly burned in pulverized coal firing (PCF), where coal is ground into an excellent particle size and fired in burners, similar to oil and gas burners. Pulverized coal burns like gas and, therefore, fires are easily lighted and controlled. The main advantage of pulverized firing is the high heat release rates and high temperatures that can be achieved. (Teir. 2003).

**Steam boilers and safety.**

The boilers, which contained the steam, were prone to explode. This occurred for a variety of reasons: undetected corrosion or furring of the heated surfaces, clumsy repairs, or failure to keep the water up to the required level, so causing firebox plates to overheat. A safety device, called a lead plug, was invented. The plug was designed to melt if the firebox crown became overheated and released steam before worse damage was done. (Teir, 2003)

## DESIGN CONSIDERATION

In constructing a micro steam boiler as a teaching aid model, some requirements that will suit the design must be considered. The basic areas include; specification and requirement, conceptual design, evaluation of designs, preliminary design of the chosen concept, relevant mathematical calculations and assumptions.

**Design specification and requirements**

This discusses both the functional and design specification as well as outlining ways on how to feed and operate an efficient steam boiler as a teaching aid. The steam plant should be kept in an environment where air flow freely because the smoke generated during charcoal burning.

**Functional requirements**

The success of steam boiler depends on its ability to function in order to achieve the desired result. Given this, the functional requirement includes the followings:

The boiler should be able to release smoke at a minimum of 5% to the atmosphere.

The Boiler should be able to use charcoal as a source of fuel.

The Boiler should be able to be used as a teaching aid model for the teachers and students.

**Design Requirements**

Affordability and ease of operation can be attained by an efficient and effective design requirement. Design requirement plays a vital role in the following ways:

The fuel feeding is manual

The boiler is easy to operate

The boiler should be affordable

The boiler can work with hand drove fan/blower

The boiler has a means of emptying the ash after usage which is known as ashtray

**Conceptual designs**

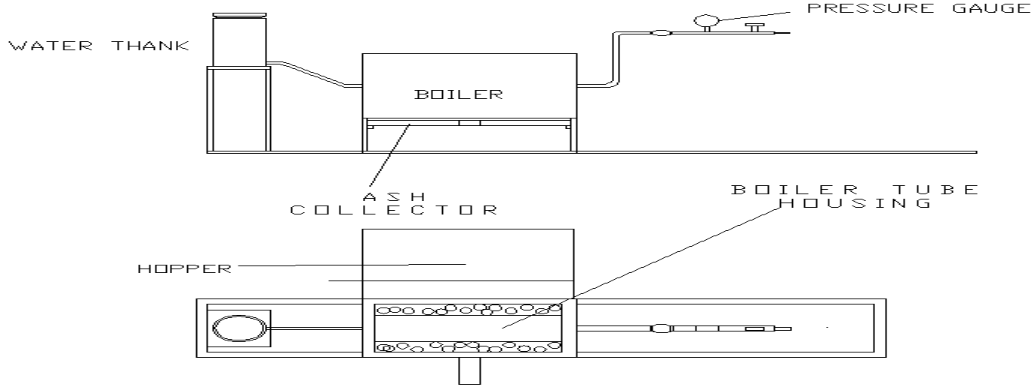


Figure 2: Horizontal type Boiler (Source: Authors work, 2016)

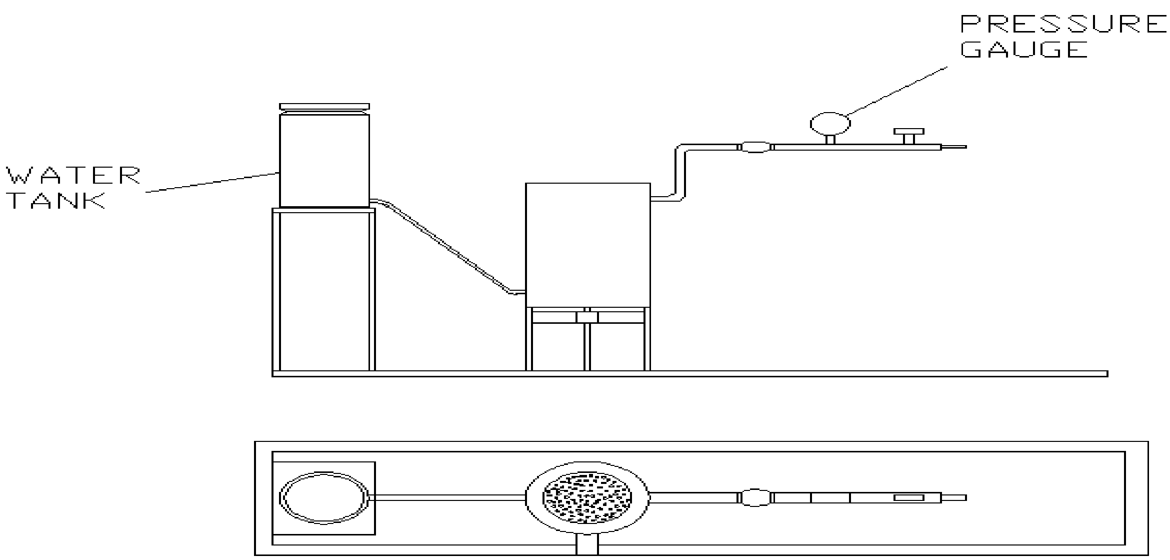


Figure 3: Vertical type Boiler (Source: Authors work, 2016)

## EVALUATION OF DESIGN

Evaluation of design is a key to a safe, reliable, efficient and low production cost of a steam boiler. The evaluation of a design can as well facilitate ease of manufacturability, reliability, safety, efficiency and low cost as indicated below.

### Safety

Accidents involving exploding boilers have killed people, damaged plant andtroubled production. These accidents resulted from problems such as inadequately designed boilers, wrongly sited or wrongly installed boilers as well as boilers that were not correctly operated or maintained. An efficient, reliable boiler is an essential requirement for many businesses, and the downtime caused by a failed boiler can have a significant effect on production, plant, and people. The word ‘boiler,' in everyday use, covers a wide range of equipment, from simple domestic hot water boilers to boilers housed within a power generation plant to convert fossil fuel into electricity. Domestic hot water boilers do not produce steam and should operate at low pressure. While some combination boilers now operate at the pressure of the incoming cold water mains, this is still far below the standard operating pressure of steam-raising boilers. Inherent safe design and operation where possible, containment of pressure when the valve is closed rather than relief overpressure, the heat outside the walls of the boiler must be bearable to the operator and the environment, preventive and contingency measures in all cases.

**Manufacturability**

The manufacturability is dependent upon the availability of material**, f**ormability of the proposed design**, f**easibility of manufacturing process and low cost of manufacturing.

**Reliability**

Reliability can be defined as the probability that a system will satisfactorily perform its task for a given period under predetermined operating conditions. Inherent failures deal with failures built into the system and are mostly dependent on the components that make up the system. Dependent failures are failures that can be traced back to specificevents, for example, operator-induced failures, wear out, maintenance-induced failures, the life expectancy of the steam boiler and the possibility of failure of the proposed design of boiler must be taken care of.

**Maintainability**

Reliability is essential due to the possibility that a breakdown can cause prolonged outages and other costly problems. When a failure of some kind has occurred, it is essential to rapidly be able to correct the problem and return to operation. Maintenance is a series of actions that are executedin order to keep a system component or installation in an active operational state. In the case of the recovery boiler, it is always the goal of a maintenance shutdown to be as quick, safe and cost-effective as possible due to the high costs of production losses during the shutdown. Serviceability and availability of steam boiler parts, ease removal of fuelwood ash when burned, ease of removal and fitting of the coil during servicing.

**Cost**

The cost of production is based on the expenditure for raw materials, the cost of manufacturing, labor and overhead maintenance cost. Machine and labor cost cannot be changed in relation with make-up along with raw materials expenditures, the bulk of production cost when a material is selected for a particular job, the process including the machine may be automatically specified or if a machine is available the raw material that can be used may be limited.

**Efficiency**

Boiler Efficiency is a term which establishes a relationship between energy supplied to the boilerand energy output received from the boiler. It is usually expressed in percentage. The efficiency of a boiler may be classified into following three major types: Combustion Efficiency, Thermal Efficiency, and Fuel-to-Steam Efficiency, the rate of steam production, the rate of a pressure release for co-generation and the rate of the heat generating for boiling the water.

**Determination of the thickness of combustion chamber, lagging material and galvanized steel by heat transfer process**

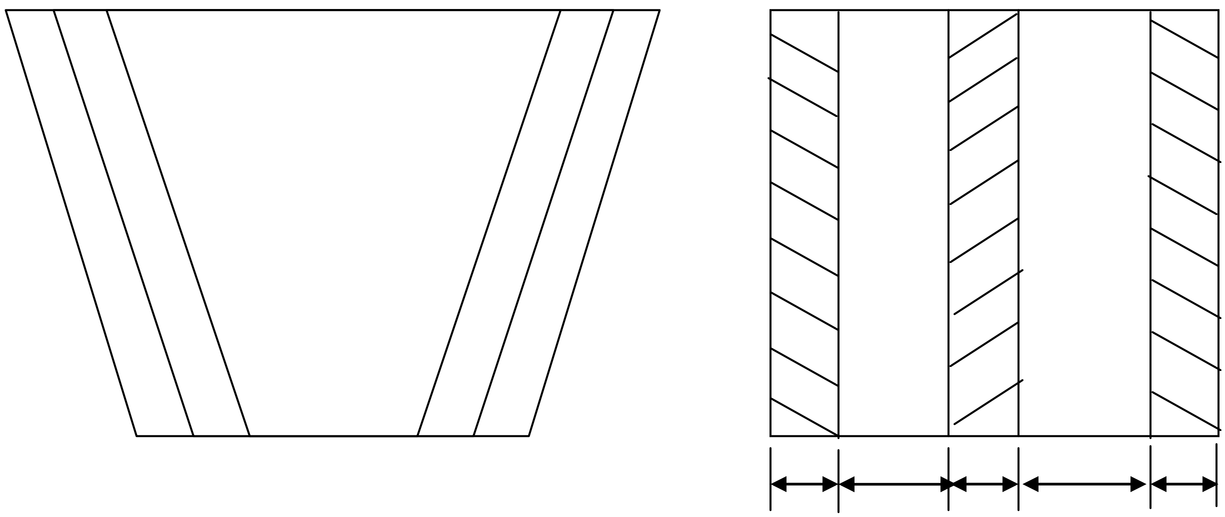

Figure 4: Cross-section of a steam boiler furnace

**Definition of terms**

$L_1$= Inside diameter of combustion chamber (steel)
$L_2$= Outside diameter of the combustion chamber (steel)
$L_3$= Inside diameter of the lagging material
$L_4$= Outside diameter of the lagging material
$L_5$= Inside diameter of the zinc sheet
$L_6$= Outside diameter of the zinc sheet
Let $t_{1,}$ $t_{2,}$ and $t_3$. Represent the corresponding value of $L_{1,}$ $L_{2,}$ $L_3$, $L_4$, $L_{5,}$ and $L_6$respectively
h = Height of the boiler furnace

Also let
$t_{st}$ = thickness of combustion chamber
$t_{br}$= thickness of lagging material
$t_{zn}$= thickness of zinc sheet

Then:

$t_{st} = L_2 - L_1$ = 3mm = 0.003m
$t_{br} = L_4 - L_3$ = 1”= 0.0254m
$t_{zn} = L_6 - L_5$ = 1mm = 0.001m

**Known parameters in the boiler furnace**

h = 8.5”= 215.9m
$t_{st}$= 3mm = 0.003m
$t_{br}$= 1”= 0.0254m
$t_{zn}$= 1mm = 0.001m
The maximum expected temperature of boiler furnace $800^0$C
The maximum ambient temperature (bearable to the operator) of the steam boiler $T_a = 37^0$C.The average surrounding temperature expected. $T_{sur}= 25^0$C. The maximum power produced.

**Boiler Efficiency**

$$\eta_B = \frac{m_{s\,(h_2-h_1)}}{m_f \times c_v}$$

Where
$\eta_B$ = Boiler efficiency
$m_s$= mass of the steam
$h_2$= Enthalpy of saturated state
$h_1$= Enthalpy of steam
$m_f$= mass of fuel
$c_v$= Calorific value of fuel

$$\eta_B = \frac{m_{s\,(h_2-h_1)}}{m_f \times c_v}$$

$$\eta_B \times m_f \times c_v = m_s(h_2 - h_1)$$

$$m_s = \frac{\eta_B \times m_f \times c_v}{(h_2 - h_1)}$$

From steam table
$h_2 = h_g$ = 2707 KJ/Kg
$h_1 = h_f$ = 505KJ/Kg
$C_v$ of charcoal = 30,000KJ/Kg
Let assume the boiler efficiency to be 53%
Let
Mass of fuel ($m_f$) = 1Kg
Pressure = 2bar

$$\therefore m_s = \frac{\eta_B \times m_g \times C_v}{h_2 - h_1}$$

$$= \frac{53 \times 1 \times 30000}{2707 - 505}$$
$$= \frac{1590000}{2202}$$
$$= 722.07\text{Kg}$$
$$= \frac{722.07}{60}\ \text{Kg/hr}$$
$$= 12.034\text{Kg}$$
$$= 12\text{kg}$$

The equations for combustion will now be considered, 40% excess air being appropriate for coal firing in medium-sized boilers (less in large water-tube boilers).

*the basic equation for combustion of carbonis* $C + O_2 \rightarrow CO_2$
*for hydrogen the equation of combustionis* $2H_2 + O_2 \rightarrow 2H_2O$
*for sulphur the equationis* $S + O_2 \rightarrow 2SO_2$

From the above equations, the calculations on the mass basis will enable the gas mass flow through the boiler to be readily established for heat transfer calculation.

**Heat Transfer through the composite of wall Boiler furnace**

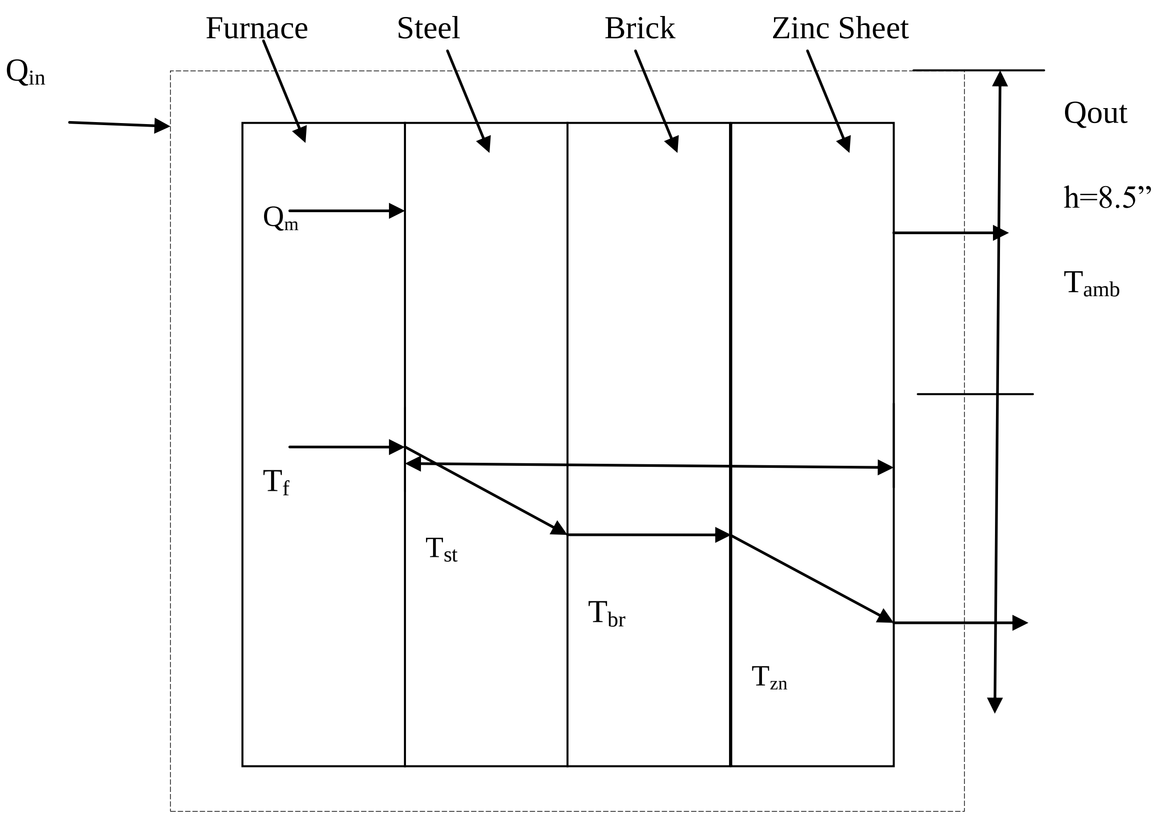

*Figure 5: Steady State Condition of Boiler Furnace*

Where
$Q_{in}$= Rate of heat transfer into combustion chamber
$Q_m$= The net rate of heat energy in the combustion chamber
$Q_{out}$= Rate of heat transfer out of the combustion chamber
$T_f$ = The maximum temperature inside the furnace
$T_{st}$= The maximum temperature in the steel
$T_{br}$= The maximum temperature of the lagging
$T_{zn}$= The maximum temperature of the zinc sheet
$T_{amb}$= Ambient temperature

Thermal conductivity for steel 'k' = 50.2w/m$^0$c
Thermal conductivity for Brick 'k' = 0.8w/m$^0$c

Thermal conductivity of galvanized zinc sheet 'k'= 113w/m$^0$c
$Q_{in}$ = Heat flow rate across the walls.
A = Heat transfer area.
k = Thermal conductivity of the wall materials.
ΔT= Change in temperature.
R = Thermal resistance.
L= Length of the composite walls.
h = Height of the wall.

$$Q = kA\frac{\Delta T}{x}$$

$$Q = A\frac{\Delta T}{\frac{x}{k}}$$

$$\frac{x}{k} = \frac{material\ \ thermal}{thermal\ \ conductivity} = \mathrm{R}$$

$$R = \frac{x}{k}$$

$$Q = A\frac{\Delta T}{R}$$

$$R_{st} = \frac{x}{k} = \frac{0.003}{50.2} = 5.98 \times 10^{-5}\mathrm{m}^{2\,0}\mathrm{C/W}$$

$$R_{br} = \frac{x}{k} = \frac{0.0254}{0.8} = 0.3175\ \mathrm{m}^{2\,0}\mathrm{C/W}$$

$$R_{zn} = \frac{x}{k} = \frac{0.0015}{113} = 1.327 \times 10^{-5} m^2 °C/W$$

$$R_{total} = 5.98 \times 10^{-5} + 0.03175 + 1.327 \times 10^{-5}$$
$$= 0.0318 m^2 °C/W$$

A is the area of the composite walls
A = $lenght \times height$

$$Q = A\,\frac{\Delta T}{R_{total}}$$
$$= 4.102\left(\frac{900 - 37}{0.0318}\right)$$
$$= 4.10\left(\frac{863}{0.0318}\right)$$
$$= 111267.296W$$
$$= 111.3kw$$

## METHOD OF FABRICATION

The method of fabrication to be chosen would start from the

1. Material selection. Suitability of materials for the fabrication depends upon the function the designed part would perform considering the physical and chemical properties of the materials.
2. Measurement of the required length of each part to be produced.
3. Marking out: Marking out would be carried out and according to the dimension of the parts to be fabricated.
4. Cutting of the individual part of the boiler to be fabricated using hacksaw and shear machine.
5. Drilling of holes for the use of bolt and nut in mounting the hopper to the frame.
6. Joining of the components together with the used of electric arc welding, gas welding, bolt, and nut or lap and seam joint after rolling the sheet metal where necessary.
7. Filing of the edges of the metal components or protruding left in the cause of welding or cutting
8. Assembling of all the parts to form a single whole component, i.e., boiler.
9. Lagging of the wall with a clay soil to reduce the heat transferred or loss to the surrounding environment.
10. Coupling of the pressure gauge and other plumbing materials using spanners.

## FINDINGS/RESULTS

### Evaluation Matrix

The above designs are evaluated base on the matrix table below, where the best result will be determined and inculcate into the preliminary design.

**Table 1: Evaluation Matrix**

| Grade | Interpretation | Value |
|---|---|---|
| A | Excellent | 5 |

| | | |
|---|---|---|
| B | Very good | 4 |
| C | Good | 3 |
| D | Credit | 2 |
| E | Poor | 1 |

**Table 3: (Source: Authors work, 2017)**

Table: Evaluation Matrix

| **Design Criteria** | **Horizontal Type** | **Vertical Type** |
|---|---|---|
| Safety | B | B |
| Manufacturability | A | C |
| Reliability | A | B |
| Efficiency | B | C |
| Cost | B | D |
| Maintainability | B | C |
| Total Score | 26/30 = 86% | 19/30 = 63.3% |

**(Source: Authors work, 2017)**

**Preliminary Design of the Chosen Concept**

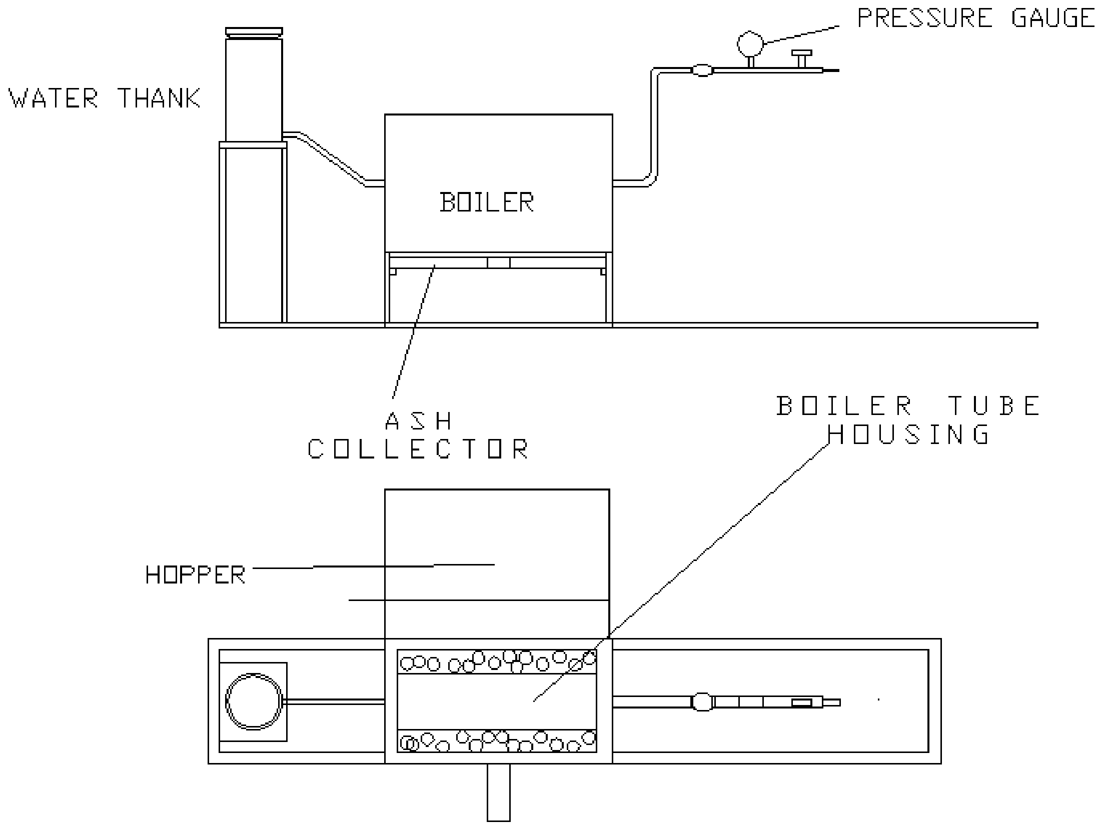


Figure 6: Horizontal type Boiler (Source: Authors work, 2017)

## CONCLUSION

The boiler would be able to give the practical demonstration to the engineering students on how the steam can be generated through the use of charcoal and would induce the understanding of steam generation without acquiring the conventional boiler, there would also be a higher expectation of getting steam at a higher pressure which can be used for other engineering purposes.

## RECOMMENDATION

The fuel that would be used for this fabrication is charcoal which is readily available and can easily be sourced. We also recommend combining the turbine and dynamo to form a complete power plant for the student demonstration.

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