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# DESIGN AND FABRICATION OF A HORIZONTAL WATER TUBE BOILER

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## ABSTRACT

*Introducing modern boiler concepts in the design of thermal power stations is nowadays becoming mandatory, not only from an economic point of view of new investments, but also as a significant and pro-active step towards the reduction of greenhouse gases & dust emissions by the enhancement of efficiency. The increase in the cycle efficiency in modern power station is mainly achieved by increasing the steam parameters. In addition to elevated steam parameters, other measures such as double reheat design and increased boiler efficiency are the key factors to achieve the desired maximization in heat rates. The aim of this project was to design and fabricate a water-tube boiler using a diesel fired burner* $(C_{13}H_{25})_9$ *to generate 80kg of steam per hour. The boiler tank is made of pure mild steel. Mild steel is used to fabricate the water tubes and other parts such as the furnace, smokestack and return chamber that make up the boiler. The heating surface area was increased for sake of efficiency and fast steam generation by reversing the direction of the gas through a second and third parallel tube (three pass). The boiler (which is fired by a diesel burner) generates dry saturated steam at a pressure of 1 bar and temperature of* $111.4^{o}C$*. It can be used for domestic and industrial purposes.*

## INTRODUCTION

Steam is a critical resource in today's industrial world. It is used in the production of goods and food, the heating and cooling of large buildings, the running of equipment, and the production of electricity. The system in which steam is generated is called a boiler or a steam generator (Woodruff *et al.*, 2004). Steam generators may be of different shapes and sizes, depending on their applications. Steam generators have been in use for a very long time and over the course of time, various inventors and engineers have developed and modified them for the purpose of academic study, as well as to suit the needs of the modern man. As a result of their continuous success, many industries today depend greatly on steam for the operation of their equipment and the production of their goods.

Steam is therefore important in engineering and energy studies. In science and engineering laboratories, there is sometimes the need to utilize steam or hot water to generate power, to carry out tests or for other heating applications. This steam or hot water can be obtained using boilers. Therefore, the purpose of this project is to design a miniature water-tube laboratory boiler that can be manufactured to meet the needs of schools for practical demonstrations and teaching aid (Rajput, 2006).

A boiler is a closed vessel in which steam is produced from water by combustion of fuel. According to the American Society of Mechanical Engineers (ASME), a steam generating unit is defined as a combination of apparatus for producing, furnishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vaporized (Rajput, 2006). Steam boilers is made up of two major parts, that is, the combustion chamber, which provides heat by the combustion of fuel, and the heat exchanger which transforms water into steam through heat exchange in the medium (Saidur *et al.,* 2010). Boiler types comprises of fire tube, water tube, modular, coil tube and cast iron respectively. Steam boilers could be used for various services, such as, steam process and heating, hot water heating, power generation, petrochemical processes, chemical recovery, nuclear, just to mention a few (Ray, *et al.,* 2003).

Several boilers are designed to withstand the stress induced in the boilers (Woodruff *et al.,* 2004). In a boiler, water is heated, steam is generated or superheated, or any combination thereof, under pressure or vacuum by the application of heat resulting from the combustion of fuel (such as in a natural gas boiler), electrical resistance heating or the recovery and conversion of normally unused energy (Rawson, 2008). Many different solid, liquid and gaseous fuels are fired in boilers. Sometimes, combinations of fuels are used to reduce emissions or improve boiler performances. Fuels commonly fired in boilers include fossil, biomass, and refuse-derived fuel (RDFs) as well as others types of fuels and fuel combinations (Boiler Fuels and Emissions, 2009). For effective teaching and learning, well equipped laboratories and subject rooms are needed. However, many educational institutions lack the necessary equipment for effective teaching and learning (Adeyinka, 1992).

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 to electricity. Generally, 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 normal operating pressure of steam-raising boilers. As steam driven engines replaced the horse, as a means of motive power, it followed that steam driven engines were rated in 'Horsepower'. Boiler design progressed from what was essentially a kettle to a relatively large-diameter flue pipe submerged in water - thus the first water-tube boiler, as power and pressure requirements increased, boilers became larger and the single-flue pipe became a larger number of smaller diameter flue tubes combined with an external, or internal, furnace for the combustion of the fuel. The modern-day 'modified Scotch Marine' boiler, generally comprising horizontal steel furnace combustion chambers) and/or fire-tube convective pass(es), in 'dry-back' or 'waterback' configurations, owes its heritage to these early multi-tube boilers and their application in ships constructed on Scotland's River Clyde (Rawson, 2008).

The primary application of the boiler was still motive power; whether for pumping water from mines, driving machinery in mills, propelling steam locomotives or ships. Therefore, boiler ratings were based on the size of the steam engine that they were capable of driving. The quantity of steam required to operate a 1 horsepower steam engine became known as 1 Boiler Horsepower. (Note that the watertube boiler was not prevalent until after the first water-tube boiler design patent of 1867; thus, the term Boiler Horsepower (Bhp) has been associated with fire-tube boilers from the earliest days of boiler development) (Rawson, 2008).

Boilers often contain elements that become corrosive when concentrated far beyond normal values as a result of the design problem. The frequent contributor to waste heat boiler problem is the uneven distribution of gases across the inlet tubes at the hot end. This causes unequal stresses and distortion and leads to mechanical stress and fatigue problems (Rawson, 2008).

The use of horizontal hairpin tube configurations with inadequate forced circulation of water through the tubes often permits stratification of steam and water. This often leads to stream blanketing of caustic corrosion problem.

Due to the high demand of electricity to power our electronics and other systems which make use of electricity. We find the use of boiler to generate steam which will be used to turn turbines useful. The turbine will on the other hand generate electricity as its end product which every living thing will benefit from (Rawson, 2008). In order to find alternative means to generate power apart from solar, hydroelectricity generation, boiler is used to generate steam which will be used to turn turbine and the material use for the production are locally available and cheap. The objective of the project is to design and construct a horizontal water tube boiler.

## MATERIALS AND METHOD

### Basic Design Requirements

Criteria which govern the design and manufacture of the water-tube boilers include:

- Compliance with the ASME Boiler and Pressure Vessel Code.
- Compliance with required safety and installation Codes.
- The ability to meet the required efficiency and other performance standards.
- The ability to meet the required level of pollutant emissions,
- Compliance with the requirements of the National Board of Boiler and Pressure Vessel Inspectors through local
- The ability to meet the perceived needs of the customer in terms of operational performance, reliability and maintenance costs.
- The ability to produce a competitively priced product

Water-tube boiler manufacturers have established over the years that these criteria can be satisfied with varying heating surface specifications.

### Design Specification

The water tube boiler consists of various components and it will be of great importance to have a detailed specification before the design. The arrangement of the water-tube boiler is illustrated below. The diesel burner used to heat up the furnace of the water-tube has the following specifications:

- Mass firing rate = 2.5 – 5 kg/hr
- Orifice diameter for exit (d) = Ø0.0005 m
- Motor rating = 0.5 horse power.

The burner is connected to the furnace by the means of both external and internal circular flange (a projecting collar, rim, or rib on an object for fixing it to another object, holding it in place or strengthening it. Flanges are often found on pipes and shafts) of both the burner and furnace respectively. The flange specifications are given as follows;

- Outer diameter of circular flange (do) = Ø0.017 x 2 m
- Inner diameter of circular flange (di) = Ø0.013 x 2 m
- Number of opening for bolts and nuts of flange = 4 openings
- Diameter of the bolts and nuts used (db) = Ø00.014 m

The furnace which is located inside the boiler pressure vessel (shell) and situated at one end of 5 section of longitudinal water-tubes connected to it serially which elongates the path of the hot gases, thus expanding the heating surface. The idea of placing the furnace inside the boiler shell is to maximize the heat of the boiler rather than losing it to the surrounding. The furnace serves as a pre-heater in this case as it raises the temperature of the water.
The water-tubes extend to a compartment known as the return chamber situated at another end in the boiler vessel (shell). The return chamber itself which is serving as an intermediary for hot gases transfer has another set of 5 water-tubes connected to it in the same manner as that at the furnace. This was done to further increase the heating surface area by making the gases reverse direction through a second 5 sets of parallel tubes. The heat emitted by this other set of 5 longitudinal water-tubes at the return chamber goes out from a smoke stack. The following are the specifications of the inner components in the boiler vessel (shell):

i. Total of 15 pieces of water-tubes
ii. A furnace
iii. Two return chamber
iv. Smoke stack.

## Design Consideration for Material Selection

For an intelligent design to be done, the knowledge of the materials available as well as the properties they possess are very important For the selection of the proper material to be used for the design of the water-tube boiler, we shall consider the factors which affect the choice of material selected and used for design and there reasons.

**Factors considered are:**

1. Suitability of the material for the working conditions in service, considering characteristics such as; appearance, thermal conductivity, rate of emissivity, strength, stiffness, creep, etc.
2. Availability of the material: the ease at which the materials are seen or purchased in the market.
3. Workability of the material: considering possible methods of processing material selected into desired shape such as; weldability, machinability, formability, and workability.
4. Expected load or force as well as adequate strength in conformity so as to function satisfactorily without failure.
5. Cost of the material (economic consideration).

## Choice of Material

Based on the above considerations, the materials used for the design of the water-tube boiler were thus selected and tabulated below;

Table 3.1: Materials Used and Reasons

| Parts | Material formally used or preferred and reasons | Material used and reasons |
|---|---|---|
| Furnace | Aluminum: good conductivity, high corrosion resistance but high melting point. | Mild steel: affordable, available, weldable, malleable, strength, high conductivity, and corrosion resistance. |
| Fire-tubes | Copper; high thermal conductivity, better formability. | Mild steel: affordable, available, weldable, malleable, strength, high conductivity, and corrosion resistance. |
| Return chamber | Aluminum: good conductivity, high corrosion resistance but high melting point. | Mild steel: affordable, available, weldable, malleable, strength, high conductivity, and corrosion resistance. |
| Pressure vessel | Wrought iron; toughness, malleable, and ductile. | Steel: low cost of fabrication, stronger, quick weldability, cheaper and less labor. |
| Smoke sack | Copper: high thermal conductivity, better formability | Mild steel: affordable, available, weldable, malleable, strength, high conductivity, and corrosion resistance. |

## Design of Component Parts of the Water Tube Boiler

Having completed the material selection for the water-tube boiler, the design of the various parts of the boiler is typified by the following features;

- The volumetric boiler pressure vessel (tank or shell).
- The furnace.
- The water-tube.
- The return chamber.
- The smoke stack.
- Actual volumetric capacity of the boiler.
- Pressure gauge.
- Temperature gauge.
- Safety valve.

## Design of the Volumetric Boiler Pressure Vessel

The boiler volumetric tank measures the quantity of water delivered to it at a given time. It has a capacity of 292 liters and it is made of steel metal of 0.006 m thickness for pressure resistance, Ø0.62 m and length of 0.76 m three holes were bored on the surface of the tank for both steam outlet (Ø0), turbine outlet (Ø0.50 m) and exhaust or smokestack outlet (Ø0.05 m). A hole of Ø0.178m is also provided at one end of the longitudinal section of the tank for the cylindrical furnace placed inside it. Other dimensions are as follows;( (Baoyou, *et al.*, 2006).

Volumetric capacity of the drum (tank) = volume of cylinder + volume of hemisphere.

$$V = \pi r^2 \times L + \frac{2}{3}\pi r^3 \qquad --- 1$$

To know the maximum pressure and temperature of the boiler, using the hoop law; We know that, Tensile stress of a mild steel = 60 Mpa Ultimate tensile stress of a mild steel = 410Mpa.

Hoop stress of mild steel = 140Mpa Pressure of steam at 111.4$^o$C (p) = 1.5bar = 0.15Mpa

Thickness of pressure vessel (t) = 6mm Diameter of vessel (d) = 620mm

The hoop of stress of the steam

$$\sigma h = \frac{p \times d}{2t} \qquad --- 2$$

The estimated maximum pressure of the vessel

$$P_{max} = \frac{\sigma_{max} \times 2t}{620} \qquad ---3$$

**Design of the Furnace**

The furnace made of mild steel located at one end of the boiler connected to a heat supply (diesel burner located outside the boiler vessel) in this case by means of a flange with specifications stated above, serves as the central system for heat (hot gases) distribution to the water tubes. The furnace has a length of 0.40m, thickness 10mm and a diameter of 0.170m. Other dimensions are given below;

$$Volume\ of\ the\ furnace = \frac{\pi d^2}{4} \times L \qquad ---4$$

$$= \pi \cdot \frac{0.17^2}{4} \times 0.40$$

= 0.0091 $m^3$

**Design of the Water-Tubes**

The water-tubes made of mild steel is a total 15 in numbers and is sub-divided into three sections namely

- Furnace section = 5 water-tubes of length 0.30m and diameter 0.030m each.
- Return chamber section = 5 water-tubes of length 0.30m and diameter 0.030m each.
- The third pass section (section to the smokestack) – 5 water-tubes of length 0.50m and diameter 0.030m each.

Other dimensions are as shown;

Volume of the water-tubes in the furnace section

$$Volume\ of\ the\ furnace = \frac{\pi d^2}{4} \times L \qquad ---5$$

$$= \pi \cdot \frac{0.03^2}{4} \times 0.3$$

= 0.001061 $m^3$

Volume multiplied by the number of water-tubes on this section

Volume of water-tubes in the return chamber section

$$Volume\ of\ the\ furnace = \frac{\pi d^2}{4} \times L \qquad ---6$$

$$= \pi \cdot \frac{0.03^2}{4} \times 0.3$$

= 0.001061 m$^3$

Volume multiplied by the number of water-tubes on this section

Volume of water-tubes in the third passes section

Volume of water-tubes in the return chamber section

$$Volume\ of\ the\ furnace = \frac{\pi d^2}{4} \times L \qquad ---7$$

$$= \pi \cdot \frac{0.03^2}{4} \times 0.5$$

= 0.001767 m$^3$

Volume multiplied by the number of water-tubes on this section

**Design of the Return Chamber**

The return chamber made of mild steel which serves as an intermediary of heat transfer between the above mention sets of water-tubes has a length of 0.15m and diameter of 0.30m.

The volume of the return chamber

$$Volume\ of\ the\ furnace = \frac{\pi d^2}{4} \times L \qquad ---8$$

$$= \pi \cdot \frac{0.3^2}{4} \times 0.15$$

= 0.010603 m$^3$

**Design of the Smokestack (Exhaust)**

The smokestack made of mild steel used to transport the flue out of the system has a length of 0.20 m and diameter of 0.15 m (Cengel and Boles, 2006).

The volume of the smokestack

$$Volume\ of\ the\ furnace = \frac{\pi d^2}{4} \times L \qquad ---9$$

$$= \pi \cdot \frac{0.15^2}{4} \times 0.2$$

= 0.0035343 m$^3$

**Actual Volumetric Capacity of the Boiler**

Actual capacity (i.e. volume) of the boiler = volume of the drum - total volume of the inner compartment of the boiler.

Volumetric capacity of the drum = 292 liters

$$\begin{aligned} &Total\ volumetric\ capacity\ of\ the\ inner\ compartments \\ &\quad = volume\ of\ furnace + volume\ of\ water \\ &\quad - tubes\ on\ each\ sections \\ &\quad + volume\ of\ the\ return\ chamber \\ &\quad + volume\ of\ the\ smokestack \end{aligned}$$

= {0.0091 $m^3$ + (0.001061 $m^3$ + 0.001061 $m^3$ + 0.001767 $m^3$) + 0.010603 $m^3$ + 0.0035343 $m^3$}

= 0.0271263 $m^3$ Therefore,

Actual capacity of the boiler = 0.2918431$m^3$-0.0271263$m^3$ = 0.2647168m3 = 264.721iters

**Thermal Design Calculation**

The thermal design calculation involves the heat transfer from all heat sources located in the boiler as outlined:

- Furnace heat transfer calculation.
- Water-tubes heat transfer calculation
- Return chamber heat transfer calculation.
- Smokestack calculation.

**Furnace Calculation**

The sensible heat loss of flue gas at furnace exit =

$$= m \times Cp \times \Delta T \qquad --- 10$$

Where; m = mass of flue gas (kg)

Cp = specific heat of flue gas

T = (flue gas temperature - ambient temperature) in $^{o}$C

Theoretical air required from air fuel ratio

*Mass* of flue gas [mg (P)] = ma + mf

Heat loss = Mp x Cp x $\Delta$T

**Radiation heat transfer from furnace**

$$Q_{rad} = \varepsilon\sigma(T_h^4 - T_c^4)A_c \qquad ---11$$

Where; qrad = heat transfer per unit time (W)

$\sigma$ = Stefan Boltzmann const = 5.6703 x l0$^{-8}$ (w/m$^2$k$^4$)

$\varepsilon$ = emissivity of material (mild-steel) used = 0.32

Th, = hot body absolute temperature (K) = temperature of water = 565$^o$C = 838$^o$k

Tc = cold surroundings absolute temperature = temperature of furnace = 30$^o$C = 303$^o$k

Ac = area of the object (m$^2$)

d = l 70mm: Ac = 0.02271m$^2$

**Convective heat transfer from furnace**

$$Qconv = hc \times A \times (\Delta T) \qquad ---12$$

Where; hc - convective heat transfer coefficient (w/m2k) = 250w/m2k

d = heat transfer diameter (m) = 0.17m,

$$A = \frac{\pi d^2}{4} = 0.02271\, m^2$$

$\Delta T$ = (temperature of furnace - temperature of water) $^o$k

L = length of furnace = 40cm = 0.4m

**Conduction heat transfer from furnace**

$$Q_{cond} = \frac{K_c \times A \times \Delta T}{l} \qquad ---13$$

Where; Kc = thermal conductivity coefficient (w/mk) = 59w/mk

$l$ = length of furnace

Th - hot body absolute temperature

(K) = temperature of water

Tc = cold surroundings absolute temperature = temperature of furnace

Ac = area of the object (m$^2$)

**Efficiency of Furnace**

Thermal efficiency of the furnace by direct method;

Mf = fuel consumption or mass flow rate

$$Thermal\ efficiency\ of\ the\ furnace = \frac{\text{Heat output from the burner}}{\text{Heat in the fuel consumed (heat input)}} \times 100 \quad ---14$$

Heat output from burner = 55kw

$$Heat\ in\ the\ fuel\ consumed = \frac{\text{GCV of diesel } \left(\frac{\text{kJ}}{\text{kg}}\right)}{\text{fuel consumption rate } \left(\frac{\text{kg}}{\text{hr}}\right)} \times 100 \quad ---15$$

**Radiation heat transfer from furnace to the Return Chamber Section**

$$Q_{rad} = \varepsilon\sigma(T_h^4 - T_c^4)A_c \quad ---16$$

Where; qrad = heat transfer per unit time (W)

**Convective heat transfer from furnace to the Return Chamber Section**

$$Qconv = hc \times A \times (\Delta T) \quad ---17$$

Where; hc - convective heat transfer coefficient (w/m2k) = 250w/m2k

d = heat transfer diameter (m) = 0.17m,

$$A = \frac{\pi d^2}{4} = 0.02271\ m^2$$

$\Delta T$ = (temperature of furnace - temperature of water) $^o$k

L = length of furnace = 40cm = 0.4m

**Conduction heat transfer from furnace to the Return Chamber Section**

$$Q_{cond} = \frac{K_c \times A \times \Delta T}{l} \quad ---18$$

Where; Kc = thermal conductivity coefficient (w/mk) = 59w/mk

d = heat transfer diameter (m) 0.03 = d x 5 = 0.15m, $A = \frac{\pi d^2}{4}$ = 0.017671m2

ΔT = (temperature of furnace - temperature of water) °k

L = length of furnace 0.3 = Lx5 = 1.5m

$$Q_{cond} = \frac{59 \times 0.0177 \times 535}{1.5} = 371.87\text{w}$$

**Return Chamber Heat Transfer Calculation**

**Radiation Heat Transfer**

$$Q_{rad} = \varepsilon\sigma(T_h^4 - T_c^4)A_c \quad ---19$$

Where; qrad = heat transfer per unit time (W)

**Convective Heat Transfer**

$$Q_{conv} = hc \times A \times (\Delta T) \qquad --- 20$$

Where; hc - convective heat transfer coefficient (w/m2k) = 250w/m2k

**Conduction Heat Transfer**

$$Q_{cond} = \frac{K_c \times A \times \Delta T}{l} \qquad --- 21$$

Where; Kc = thermal conductivity coefficient (w/mk)

**Amount of Steam Generated**

The amount of steam generated is calculated from the formula below;

$$M_s = \frac{q_t}{h_e}$$

Where: Ms - mass of steam (kg/h)

qt = calculated total heat transfer (kw)

he = evaporation energy of steam (kj/kg)

From steam table; under saturated steam of Psat at 111.4$^o$C

**Boiler Efficiency**

This is also known as 'input - output method' (Cengel and Boles, 2006) due to the fact that it needs only the useful output (steam) and the heat input (i.e. fuel) for evaluating the efficiency. This efficiency can be evaluated using the formula;

$$Boiler\ Efficiency = \frac{heat\ output}{heat\ input} \times 100$$

$$= \frac{37.93}{55} \times 100$$

$$= 68.96\%$$

$$\approx 69\%$$

**Construction of the Water Tube Boiler**

A horizontal steam and water drum which is supported by a steel structure at a certain height and is independent of brick works. A bundle of steel tubes were connected to the uptake header (water box) by a short tube and the rear end is connected to the down take header (water box) by a long tube. In between the headers, a number of small-diameter steel tubes are fitted at angle of 5° to 15° with the horizontal to promote the water circulation. These steel tubes are arranged in the combustion chamber in a zigzag way so that more surface area of the tube is exposed to hot gases. The combustion chamber is the space above the grate, below the front end of the drum where combustion of fuel takes place. This chamber enclosed by brickwork and is lined from inside by fire bricks. Doors are provided to give access for cleaning, inspection and repairing. The combustion chamber is divided into three separate compartments above the furnace is the hottest and the last chamber is of lowest temperature. This makes the path of hot gases longer before leaving the boiler through the chimney. The super heater is placed between the drum and water tubes. Dampers are provided at the rear end of the chamber to regulate the fresh air supply for maintaining proper combustion of fuel. The safety and control devices are also provided (Kitto and Stuitz, 2005).

## Operation of the Water Tube Boiler

The water in Babcock and Wilcox boilers pumped by a feed pump and it enters the drum through the feed check valve up to the prespecified level so that the headers and tubes are always flooded. When the combustion takes place above the grate, the products of hot gases come out and rush through each compartment of the combustion chamber. Hence, the rear part of the tubes has lowest temperature and the front part of the tubes as highest temperature. Due to continuous heat supply, some of the water gets vaporized into steam inside the tubes and mixture of water and steam enters the boiler drum through the uptake header. The cold water from the boiler drum comes down through the uptake header and enters the lower end of the water tubes for getting heated further. This natural circulation is called thermosiphon system (Baoyou, *et al.*, 2006).

The steam generated gets collected in the steam space above water space in the boiler drum. In order to remove all water particles from the steam, it is finally through the superheating. The superheated steam is then available for use.

## RESULTS AND DISCUSSION

The fabricated water tube boiler was tested to evaluate its performances, efficiency and determine its evaporation ratio. The purpose of the performance test is to determine the actual performance and efficiency of the oiler and compare it with design values or norms. It is an indicator for tracking day-to-day and season-to-season variations in boiler efficiency and energy efficiency improvements.

When the burner is turned on and ignition occurs which produces the required water in the furnace inside the furnace, a hot flue gas is produced which is forced through the water tubes (by the he p of blower in the burner) and heat is thus transferred into the water which in turn results in production of the required steam that may be used for industrial purposes.

### Result

The result in this case is a torque produced at a steam pressure of 1.5bar and a steam temperature of 111.4$^{o}$C also raising the temperature of the water from 30$^{o}$C to a generated steam quantity of 61.34kg/hr, with a diesel quantity of 5.2Htres/hr. The efficiency of the burner after getting an adequate combustion air/fuel ratio and heat delivery from the burner resulted into 64.3%. The efficiency of the boiler was also calculated to be 69%. The detailed description of other parts are shown in table 4.1.

Table 4.1: Summary of details and operational data of steam boiler

| S/N | DETAILS | DESCRIPTION OF VALUES |
|---|---|---|
| **1** | Orientation | Horizontal |
| **2** | Type of tube | Water tube |
| **3** | Type of firing | Internally fired |
| **4** | Type of circulation | Natural circulation |
| **5** | Type of pressure | Low pressure |
| **6** | Stationary or portable | Stationary |
| **7** | Single or multi – tube | Multi tube |
| **8** | Number of water tubes | 3 |
| **9** | Operating feed water temperature | 80$^{o}$C |
| **10** | Operating steam temperature | 151.8$^{o}$C |

| | | |
|---|---|---|
| **11** | Operating steam pressure | 500 kN/m$^2$ (5 bar) |
| **12** | Combustion fuel | Diesel |
| **13** | Operating steam capacity | 5.65 tons/hr |
| **14** | Firing rate | 483.84 kg/hr |
| **15** | Boiler capacity | 18.87 GJ/hr |
| **16** | Material used for boiler shell | Mild steel A 36 |
| **17** | Materials used for boiler insulation | Brick |

**Discussion of the Results**

Good boiler design practices must take into account the operation of the boiler and not simply the heat transfer, parameters that a good boiler design addresses include;

a. Ample furnace volume must be included to absorb a significant portion of Radiative heat transfer and allow the low NOx burner designs to function.
b. Optimized pressure drop across the boiler convective passes, the pressure drop determines the fan size required for the boiler application.
c. Ample steam storage and steam height. The volume of steam and distance from the steam nozzle to the normal water level determine to a very large extent the steam quality and the amount of water that will be carried over into the system. Boiler design and optimization programs have been written to determine the performance of water-tube boilers. These programs can be applied to analyze a wide variety of the boiler scenarios for many different boiler applications extending from simple gas water systems to complex waste heat applications.

In-flame gas temperature data for lire-tube boilers has been obtained. The data follows expected trends and has been very useful in the validation of predictive optimization models. This data is compared to predicted results from computational fluid dynamic combustion models and good agreement has been found. This data is used to optimize furnace and heat transfer surfaces for typical water-tube boilers. Gas temperatures measured at the entrance to the convective tube surfaces provided excellent data that validated the heat transfer sub-models augmented surface tubes have proven to be a valuable resource in the design of water-tube boilers for many special applications. The advantages of thee augmented tube are that it allows the designer to include larger steam storage

and steam height resulting in higher steam quality and rapid load swing handling ability. Using the augmented tube also allows the designer to have a lower overall pressure drop with a boiler efficiency that is still over 81%. The augmented tube boiler may be used to reduce the boiler shell diameter and still maintain standard steam volumes, steam heights, and boiler efficiency.
The following are the features of the fabricated water tube boiler that makes it more advantageous than others:

1. Generation of steam is much quicker due to small ratio of water content to steam content. This also helps in reaching the steaming temperature in short time.
2. Its evaporative capacity is considerably larger and the steam pressure range is also high-200 bar.
3. Heating surfaces are more effective as the hot gases travel at right angles to the direction of water flow.
4. The combustion efficiency is higher because complete combustion of fuel is possible as the combustion space is much larger.
5. The thermal stresses in the boiler parts are less as different parts of the boiler remain at uniform temperature due to quick circulation of water.
6. The boiler can be easily transported and erected as its different parts can be separated.
7. Damage due to the bursting of water tube is less serious. Therefore, water tube boilers are sometimes called safety boilers.
8. All parts of the water tube boilers are easily accessible for cleaning, inspecting and repairing.
9. The water tube boiler's furnace area can be easily altered to meet the fuel requirements **diesel fuel**

## Diesel Fuel Specifications

Every fuel has a unique composition and energy content described by its fuel specifications presented in Table 4.2. Knowing the fuel specifications is essential for determining various combustion parameters.

Table 4.2: Fuel specifications for diesel

| Property | Value |
|---|---|
| **% Carbon (C )** | 85.54 |
| **% Hydrogen (H)** | 12.46 |
| **HHV (Gross heating value) kJ/kg** | 45, 482.52 |
| **LHV (Net Heating Value) kJ/kg** | 42, 790.21 |
| **$CO_2$ max** | 15.60 |
| **% Sulphur (S)** | 1.60 |
| **% Moisture (M)** | 0 |
| **% $O_2$ [100 – (C+H+S+M)]** | 0 |

**Dimensional details of Designed Steam Boiler**

Determined dimensional details of the designed steam boiler are presented in Table 4.3.

Table 4.3: Summary of dimensional details

| S/N | Details | Description/value |
|---|---|---|
| **1** | Diameter of boiler shell | 0.5 m |
| **2** | Length of boiler shell | 1 m |
| **3** | Thickness of insulation | 0.0625 m |
| **4** | Diameter of water tubes | 0.035 m |
| **5** | Length of water tubes | 0.6 m |
| **6** | Thickness of water tubes | 2.5 m |
| **7** | Thickness of boiler shell | 6.25 mm |
| **8** | Volume of fuel tank | 0.027 $m^3$ |

**Thermodynamic details of Designed Steam Boiler**

Determined thermodynamic details of the designed steam boiler are presented in Table 4.4.

Table 4.4: Thermodynamic properties of material streams of the boiler

| Substances | Mass flow rate (kg/s) | Temperature (ºC) | Enthalpy (kJ/kg) | Entropy (kJ/kgk) |
|---|---|---|---|---|
| **Air $m_a$** | 2.2848 | 40.00 | 313.26 | 1.7446 |
| **Fuel $m_f$** | 0.1344 | 1, 051.31 | 42, 790.21 | 2.0185 |

| | | | | |
|---|---|---|---|---|
| **Hot products $m_p$** | 2.4192 | 186.67 | 2, 673.09 | 4.0922 |
| **Feed water $m_w$** | 1.5692 | 80.00 | 334.90 | 1.0750 |
| **Steam, $m_s$** | 1.5692 | 151.80 | 2, 749.00 | 6.8220 |
| **Exhaust fuel gas $m_g$** | 2.4192 | 150.10 | 225.77 | 2.0449 |

## Conclusion

The water tube boiler designed was projected from the conceptual physical geometry tube boilers which elucidated the primary units making up a boiler. Thermodynamics, heat transfer and strength of materials analysis subjected to temperature and pressure variations were conducted in the theoretical framework of the laboratory fire-tube steam boiler. Conclusively, a simple laboratory water tube steam boiler is herein presented for fabrication, testing and further improvement. Production of a simple steam boiler of this sort will enable the availability of portable and affordable steam boilers for steam generation processes, especially in school laboratories. The availability of steam boilers in school laboratories will enhance students' learning process, especially in the area of thermodynamics, heat transfer and energy studies.

## Recommendation

Having achieved the set objectives of this work, the following recommendations are therefore made from the work:

i. Safety. The boiler is safe under operating conditions.
ii. Accessibility. The various parts of the boiler are accessible for repair and maintenance.
iii. Capacity. The boiler should is capable of supplying steam according to the requirements.
iv. Efficiency. To permit efficient operation, the boiler should be able to absorb a maximum amount of heat produced due to burning of fuel in the furnace.
v. It is simple in construction and its maintenance cost is low.
vi. Its initial cost is low.
vii. The boiler has joints exposed to flames.

Although the objective of this work was achieved, there is need to modify the already existing work in order to achieve higher efficiency:

i. Other pre-heater devices should be applied.
ii. Feed water pump should be applied for higher efficiency.

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