Fabrication of Pilot Multi-Tube Fire-Tube Boiler Designed For Teaching and Learning Purposes in Mechanical Laboratory

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***Abstract* - The aim of this research is to design and fabricate pilot multi-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 fire 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. Stars and temperature of 111.4^{0}C. It can be used for domestic and industrial purposes.**

***Keywords*: Diesel fired burner, pure mild steel, sake of efficiency Domestic and Industrial purposes.**

I. INTRODUCTION

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.

The basic operation of steam turbines employs two concepts, which may be used either separately or together. In an impulse turbine the steam is expanded through nozzles so that it reaches a high velocity. The high-velocity, low-pressure jet of steam is then directed against the blades of a spinning wheel, where the steam's kinetic energy is extracted while performing work. Only low-velocity, low-pressure steam leaves the turbine.

In a reaction turbine the steam expands through a series of stages, each of which has a ring of curved stationary blades and a ring of curved rotating blades. In the rotating section the steam expands partially while providing a reactive force in the tangential direction to turn the turbine wheel. The stationary sections can allow for some expansion (and increase in kinetic energy) but are used mainly to redirect the steam for entry into the next rotating set of blades.

In most modern large steam turbines, the high-pressure steam is first expanded through a series of impulse stages sets of nozzles that immediately lower the high initial pressure so that the turbine casing does not have to withstand the high pressures produced in the boiler. This is then followed by many subsequent impulse or reaction stages (20 or more), in each of which the steam continues to expand.

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The first reaction-type turbine was built by Hero of Alexandria in the 1st century AD. In his aeolipile, steam was fed into a sphere that rotated as steam expanded through two tangentially mounted nozzles. No useful work was produced by the aeolipile. Not until the 19th century were attempts made to utilize steam turbines for practical purposes. In 1837 a rotating steam chamber with exhaust nozzles was built to drive cotton gins and circular saws. A single-stage impulse turbine was designed by the Swedish engineer Carl Gustaf de Laval in 1882. A later American design had multiple impulse wheels mounted on the same shaft with nozzle sections located between each wheel. Subsequent advances in the design of steam turbines and boilers allowed for higher pressures and temperatures. These advances led to the huge and efficient modern machines, which are capable of converting more than 40 percent of the energy available in the fuel into useful work.

Watt is credited as being the first inventor to separate the steam engine, and the boiler, into two separate units in the latter part of the 18th Century. In these early times, the primary use of the boiler was to generate steam for steam driven engines.

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 fire-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 'water-back' configurations, owes its heritage to these early multi-tube boilers and their application in ships constructed on Scotland's River Clyde.

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 water-tube 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).

During this period, variations in steam engine efficiency made it difficult to assign a qualified rating (i.e. Pounds per Hour (PPH)) to the amount of steam required to drive a 1 horsepower steam engine. Tests, conducted in 1876, determined approximately 30 pounds of steam per hour was required to produce 1 horsepower of mechanical work. In 1889, the American Society of Mechanical Engineers (ASME) standardized the term "Boiler Horsepower" as being based on a conventional steam engine evaporation rate of 30 pounds of steam per hour (PPH), at 70 PSIG pressure, and a feed water temperature of 100° F. This definition was subsequently modified to: Boiler Horsepower - the unit of capacity expressed as the equivalent evaporation of 34.5 pounds of water per hour, from and at 212° F (33,475 Btu/hr.).

Also, it was determined that for the steel fire-tube boilers of the day, which utilized brick set bases incorporating large amounts of refractory, and generally coal fired, 10 square feet of fireside heating surface was necessary for a steam engine to generate I mechanical horsepower. As a result it became an industry standard practice to rale lire-tube boilers in Boiler Horsepower, and to base this rating on fire-side heating surface (1 Bhp per 10 square feet of fire-side heating surface).

Competition between fire-tube boiler manufacturers eventually forced improvements in boiler design and fuel burning equipment. This, together with a broad shift towards liquid and gaseous fuel utilization, resulted in cleaner and more reliable combustion and improved heat transfer within the boiler. Progressive reduction in the fire-side heating surface required, per Boiler Horsepower, was therefore consistent with these advancements. By the I960's, the 10 square feet of fire-side heating surface per Boiler Horsepower criterion decreased to 5 square feel of fireside heating surface per Boiler Horsepower - an axiom which is commonly cited today, particularly in the United States.

During the latter part of the 20 Century, many manufacturers of fire-tube boilers designed and marketed boilers with greater input capacity burners with requisite steam nozzle and safety valve(s) characteristics which therefore permitted operation at less than 5 square feet of fire-side heating surface per boiler horsepower with acceptable reliability and efficiency;

It was during this same period that certain jurisdictional mandates were promulgated that required licensed boiler operators for boilers in excess of a certain defined fire-side heating surface criterion. These limitations generally afforded opportunity to employ less than 5 square feet of fire-side heating surface per Bhp. This furthered development of fire-tube boiler designs specifically for particular jurisdictional requirements, again with acceptable reliability and efficiency.

Manufacturers of other boiler types, such as vertical, water-tube and cast iron sectional boilers, have used the Bhp output rating as a means of comparison with fire-tube boilers. They have not, typically, related Bhp output to a certain square feet of fire-side heating surface criterion, opting • generally to rate by net output generated by the boiler; steam boilers expressed in measurements of PPM, 34.5 pounds per Boiler Horsepower from and at 212° F, or millions of Btu/Hr (MBH), and hot water boilers expressed in measurements of 33,475 Btu/hr per Boiler Horsepower, or millions of Btu/Hr (MBH).

A. Basic Design Requirements Criteria which govern the design and manufacture of fire-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 jurisdictions having authority (JHA),
- 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

Fire-tube boiler manufacturers have established over the years that these criteria can be satisfied with varying fire-side heating surface specifications. Thus, the nominal 5 square feet of fire-side heating surface per boiler horsepower axiom is less important as a critical design consideration.

B. High-pressure

While the advances of 18th century, the call was for higher pressures; this was strongly resisted by Watt who used the monopoly his patent gave him to prevent others from building high-pressure engines and using them in vehicles. He mistrusted the materials' resistance and the boiler technology of the day.

The important advantages of high pressure were:

1) They could be made much smaller than previously for a given power output. There was thus the potential for steam engines to be developed that were small and powerful enough to propel themselves and other objects. As a result, steam power for transportation now became a practicality in the form of ships and land vehicles, which revolutionised cargo businesses, travel, military strategy, and essentially every aspect of society.
2) Because of their smaller size, they were much less expensive.
3) They did not require the significant quantities of condenser cooling water needed by atmospheric engines.
4) They could be designed to run at higher speeds, making them more suitable for powering machinery.

The Disadvantages were:

1) In the low pressure range they were less efficient than condensing engines, especially if steam was not used expansively.
2) They were more susceptible to boiler explosions.

The main difference between how high-pressure and low-pressure steam engines work is the source of the force that moves the piston. In Newcomen's and Watt's engines, it is the condensation of the steam that creates most of the pressure difference, causing atmospheric pressure (Newcomen) or low-pressure steam. (Watt) to push the piston; the internal pressures never greatly exceed atmospheric pressure. In a high-pressure engine, most of the pressure difference is provided by the high pressure steam from the boiler; the low pressure side of the piston may be at atmospheric pressure or, if it is connected to a condenser, this only provides a small proportion of the pressure difference.

C. Considerations for the Future

It is apparent that the powerful analytical tools available today will continue to be applied to improve fire-tube boiler

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design, as well as that of the fuel burning equipment. This will inevitably result in smaller, higher efficiency fire-tube boilers with lower pollutant emissions.
Combustion technology, with specific regard to NOx reduction, is rapidly approaching the point of diminishing returns. Should further emission reductions develop, one method of achieving compliance will be a significant increase in boiler efficiency, and thus reducing fuel input consumption. Combined with an obvious general tendency by end users, architects and engineers, to minimize the boiler room footprint in building construction, the resultant more compact and higher efficiency boilers, requiring lower heating surface per Boiler Horsepower, will be furthered. Albeit, the resulting improvements will remain predicated upon the particular fire-tube boiler system application requirements, materials and manufacturing limitations.

Manufacturers of fire-tube boilers, recognizing the benefit of enhanced design and materials technology, currently apply these resources to advance product design, performance and manufacturing competitiveness. Individually, and together with the US Department of Energy, programs have been initiated to further development of these, and other technologies, to meet with the ever increasing expectation of fire-tube boiler capabilities.

D. Scope of Research

The research work provides guidance on how to design a simple model fire-lube boiler for domestic and industrial use. This design guideline can assist upcoming engineers to understand the basic design of boiler and a suitable size, material and heat of combustion, The choice of fire-tube boiler and its design is crucial to give the best performance of boiler; good performance of boiler is influenced by maximum heat absorbed and minimum heat loss. The design of boiler may be influenced by factors including process requirements, economics, and safety. All the important parameters used in the guideline are explained in the definition section which helps the reader to understand the meaning of the parameters or term used

II. THE ORGAN OF BOILER

A boiler is a closed vessel in which steam is produced from water by combustion of fuel. 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).

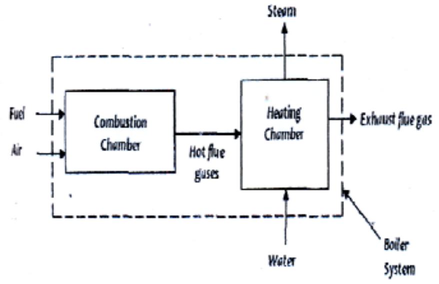

Fig 1: A schematic diagram of a steam boiler.

Boiler systems are classified in variety of ways. They can be classified;

- According to the end use, such as foe heating, power generation or process requirements.
- According to pressure, materials of construction, size tube contents (for example waterside or fireside), firing, heat source or circulation (for example, oil-fired, gas-fired, coal-fired, or solid fuel-fired).
- According to their method of fabrication.
- And boiler can be pack aged or field erected.

A. TYPES OF BOILERS

Fire Tube Boilers:

Fire tube boiler consists of boiler shell which is filled with water and perforated with tubes, there are different configurations of these tubes but horizontal configuration is the common one. Water is partially filled in the water tank and volume is left inside the tank to accommodate the steam. Long horizontal tubes arc called flues and these carry the hot combustion gases through the water tank and heating the water. The furnace is situated at one end of a fire tube which elongates the path of the hot gases, thus expanding the heating surface which can be further increased by making the gases reverse direction through a second tube or bundle of multiple tubes.
The water and steam in fire-tube boilers contained within a large diameter drum or shell, and such unit arc often referred to as 'shell type boiler'. Heat from the products of combustion is transferred to the boiler water by tubes and it goes out from the smokestack. Fire-tube boilers are approximated to 360psi of steam pressure. In case of fire-tube boiler the whole lank is under pressure so if tanks burst it creates a major explosion and if one need to increase the steam pressure of fire-tube boiler then it is necessary lo increase the thickness of the shell and material of tube sheet.

The water is confined by the outer shell of boiler. To avoid the need for a thick outer shell fire-tube boilers are used for lower pressure applications. Generally, he heat input capacities for fire-tube boilers are to 50mbtu per hour or less, but in recent years the size of fire-tube boilers has increased.
Fire-tube boilers are subdivided into three groups; horizontal return tubular (HRT) boilers typically have horizontal self-contained fire-tubes with a separate combustion chamber. Scotch, scotch marine, or shell boilers have the fire-tubes and combustion chamber housed within the same shell. Firebox boilers have a water-jacketed firebox and employ at most three passes of combustion gases.

Most modern fire-tube boilers have cylindrical outer shells with a small round combustion chamber located inside the bottom of the shell. Depending on the constructions details, these boilers have tubes configured in one, two, three or four pass arrangements, because the design of fire-tube boilers is simple, they are easy to construct in a shop and can be shipped fully assembled as a package unit. Fire-tube boilers typically have a lower initial cost, are more fuel efficient and are easier to operate.

Advantages of Fire-Tube Boilers;

i. Low cost.
ii. Fluctuations of steam demand can be met easily.
iii. It is compact in size.

B. Water-Tube Boilers;

In water-tube boilers the rack of tubes are positioned vertically in the firebox and through these tubes water flows which gets heated upon flowing 'through these tubes, these vertical pipes are called riser and these extends from the water drum which is at the bottom of the boiler to the stem headers which are at the top of the boilers. These typically surround the firebox in many layers like a dense forest. As steam bubbles form, they rise to the steam drum where the steam exist through the header.

Water-tube in furnace can be arranged in many different configurations and they are often used to connect water drums at the bottom and water, and steam drum at the top, there exist a mono-tube boiler pump used to circulate water through a succession of coils, this type of boiler has very fast production of steam but has very less storage capacity. Water-tube boilers are preferred for high pressure application because of the high pressure steam/water is contained in smaller diameter pipes which withstand the high pressure.

Water tube boilers require less weight of metal for a given size, are less liable to explosion, produce higher pressure, are accessible and can respond quickly to change in steam demand. Tubes and drums of water-tube boilers are smaller than that of fire-tube boilers and due to smaller size of drum, higher pressure can be used easily in water-tube.

Advantages of Water-Tube Boilers.

i. High pressure of the order of 140kg/cm^2 can be obtained.
ii. Heating surface is large; therefore steam can be generated easily,
iii. Large heating surface can be obtained by use of large number of tubes,
iv. iv. As a reason of high movement of water in the tubes the rate of heat transfer becomes large resulting into a greater efficiency.

III. DESIGN PROCEDURE OF THE BOILER

In the design of multitude fire boiler in this report, many things were considered when analyzing the system:

- Design specification
- Design consideration
- Detailed design
- Technological details.

A. Design Specification

The fire tube boiler consists of various components and it will be great importance to have a detailed specification before the design. The arrangement of the fire-tube boiler is illustrated below.

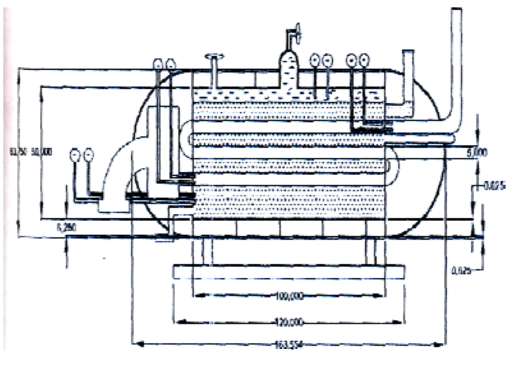

Fig 2: Dimensioned diagrams of the three pass fire-tube boiler

The diesel burner used to heat up the furnace of the fire-tube has the following specifications:

- Mass firing rate = 2.5 - 5kg/hr
- Orifice diameter for exit (d) = Ø0.0005m
- 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 (d_0) = Ø0.017 x 2m
- Inner diameter of circular flange (dj) = Ø0.013 x 2m
- Number of opening for bolts and nuts of flange = 4 openings
- Diameter of the bolts and nuts used (d_b) = Ø00.014m

The furnace which is located inside the boiler pressure vessel (shell) and situated at one end of 5 section of longitudinal fire-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 fire-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 fire-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 fire-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 fire-tubes
ii. A furnace
iii. Two return chamber
iv. Smoke stack.

B. Design Consideration for Material Selection.

For an intelligent design to be done, the knowledge of the materials available as well as the properties they posses are very important For the selection of the proper material to be used for the design of the fire-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 fire-tube boiler were thus selected and tabulated below;

TABLE 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.

C. Detailed Design

Having completed the material selection for the fire-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 lire-tube.
- The return chamber.
- The smoke stack.
- Actual volumetric capacity of the boiler.
- Pressure gauge.
- Temperature gauge.
- Safety valve.
- Thermal stresses and creep analysis.

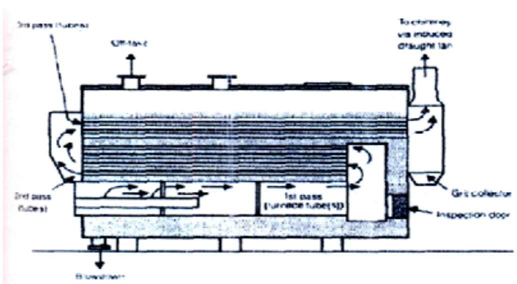

Fig 3: Schemetic diagrams of the three pass fire-tube boiler

D. 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 0.006m thickness for pressure resistance, Ø0.62m and length of 0.76m three holes were bored on the surface of the tank for both steam outlet (Ø0.50m), turbine outlet (Ø0.50m) and exhaust or smokestack outlet (Ø0.05m). 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;

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

$$= \pi r^2 \times L + \frac{2}{3}\pi r^3 \quad (1)$$

To know the maximum pressure and temperature of the boiler, using the hoop law;

We know that,

Tensile stress of a mild steel = 60Mpa Ultimate tensile stress of a mild steel = 410Mpa

Hoop stress of mild steel = 140Mpa Pressure of steam at 111.4^0C (p) = 1.5bar = 0.15Mpa

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

The hoop of stress of the steam

$$\sigma h = \frac{p \times d}{2t} \quad (2)$$

The estimated maximum pressure of the vessel

$$P_{max} = \frac{\sigma_{max} \times 2t}{620} \quad (3)$$

E. 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 fire 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

$$= \frac{\pi d^2}{4} \times L = \pi\, 0.17^2 / 4 \times 0.40 \quad \textbf{(4)}$$

F. Design of The Fire-Tubes

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

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

Other dimensions are as shown;

Volume of the fire-tubes in the furnace section

$$= \frac{\pi d^2}{4} \times L = \frac{\pi (0.03)^2}{4} \times 0.3 \quad (5)$$

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

Volume of fire-tubes in the return chamber section

$$= \frac{\pi d^2}{4} \times L = \frac{\pi (0.03)^2}{4} \times 0.3 \quad (6)$$

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

Volume of fire-tubes in the third passes section

$$= \frac{\pi d^2}{4} \times L = \frac{\pi (0.03)^2}{4} \times 0.5 \quad (7)$$

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

G. 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 fire-tubes has a length of 0.15m and diameter of 0.30m. The volume of the return chamber

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$$= \frac{\pi d^2}{4} \times L = \frac{\pi(0.3)^2}{4} \times 0.15 \quad (8)$$

H. Design of The Smokestack (Exhaust)

The smokestack made of mild steel used to transport the flue out of the system has a length of 0,20m and diameter of 0. 15m, The volume of the smokestack

$$= \frac{\pi d^2}{4} \times L = \frac{\pi(0.15)^2}{4} \times 0.20 \quad (9)$$

I. 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 dram = 292 liters (10)

Total volumetric capacity of the inner compartments = volume of furnace + volume of fire-tubes on each sections + volume of the return chamber + volume of the smokestack = {0.0091m + (0.001061m^3 + 0.001061m^3 4 0.001767m^3) + 0.010603m^3 + 0.0035343m^3} = 0.0271263m^{3}Therefore,

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

$$Q = -K_{12}\frac{T_2 - T_1}{X_{12}} = -K_{23}\frac{T_3 - T_2}{X_{32}} = -K_{34}\frac{T_4 - T_3}{X_{43}} \quad (11)$$

$= (T_2 - T_1) - (T_3 - T_2) - (T_4 - T_3) = (T_4 - T_1)$ For the complete wall as a whole;

$Q = -U(T_4 - T_1)$

Where, U is the overall heat transfer coefficient of the wall

T is the temperatures of inner and outer wall

$$\frac{1}{U} = \frac{X_{12}}{K_{12}} + \frac{X_{23}}{K_{23}} + \frac{X_{34}}{K_{34}} \quad (12)$$

Therefore, $\frac{1}{U} = \frac{X_{12}}{K_{12}} + \frac{X_{23}}{K_{23}} + \frac{X_{34}}{K_{34}}$ (13)

J. Modes of Heat Transfer in Fire Tube Boiler

The importance of heat transfer in boiler design is self-evident. In conventional 3 pass fire tube and 4 pass fire tube boilers, only a smaller portion of total heat is transferred in the furnance as it has as much as 90% and more heat transfer surfaces in the tubes. The radiation in the tubes is almost non existent compared to convection, while in the furnance, the radiation can be even smaller then convection, as the test boilers demonstrated. This is in total contradiction to water-tube boilers where convection represents less than 20% of total amount of heat exchange in furnance can be as high as 80%. Hot water test boilers showed additionally that the percentage of surfaces in tubes could be close to that found in the furnance. The industrial-sized steam test boiler has as low as 2.3 times more area in the tubes then in the rest of the boiler. Furthermore it was proved that the convection in the furnance of fire-tube boilers can be made even higher than the radiation.

The number of boiler tubes is limited by burner fan capability to overcome internal pressure loss. By that fact, the general direction in designing fire-tube boilers is given; namely to install only as many tubes as are necessary. This requires the exact analytical assessment of heat transfer in particular boiler sections to which this research work was devoted. Thus, by proper design of the boiler (for which the in-deep knowledge of heat transfer is of primary importance), as demonstrated in this work, a sizable intensification of heat transfer and noticeable savings in boiler manufacturing cost can be achieved. We can identify three modes of heat transfer;

1. Conduction
2. Convection
3. Radiation

However, they have part to play in the boiler. Though conduction is not considered in simple boiler calculation.

K. Heat Transfer By Convection In Boilers

Convection in boilers takes place simultaneously with radiation. In tubes of fire-tube boilers more than 90% of heat exchange takes place by convection, while in the furnaces the radiant part is greater than in tubes. Calculation of convection is conducted by standard equations for flows in straight tubes and channels it is also true for the boiler furnaces, whether they are circular or rectangular in cross-section. This picture totally changes when gas flow directly hits the surface involved in convection, such as in the case of the rear of the furnace. The rate of convection is much higher in these cases and cannot be assessed by classical equations for straight flow in tubes and channels. Tests showed much lower gas exit temperatures from the furnace than had been calculated which was found to be attributable to lack of taking into account the heat transfer from impinging jet of the flue-gases. Also test shows an overall improvement in heat transfer in boilers with use of cylinder of high temperature and
corrosion resistant material (to have less scaling of surfaces by unburned fuel sulfur, less soot, while also affecting radiation and convection).

Heat transfer by convection relies on the bulk movement of a heated fluid in relation to a surface. It features strongly in the design of plant items such as super-heaters and re-heaters, where there is gas-to-metal and metal -to-steam convective heat transfers.

$Q_{conv} = h\,(T_h - T_c)\,A_c$ .... (i)

TABLE 3: COMBUSTION TEMPERATURES, SPECIFIC HEAT CAPACITY AND FLUE-GAS ENTHALPY AT THAT TEMPERATURE.

COMBUSTION TEMPERATURE OF DIESEL OIL	ENTHALPY (H) DIESEL FUEL	DENSITY OF DIESEL	SPECIFIC HEAT CAPACITY (C_P) OF DIESEL	SPECIFIC HEAT CAPACITY(C_P) OF AIR
540 – 650^{0}C	44500kj/kg	840kg/m^3	1.75kj/kg^{0}C	1.006kj/kg^{0}C

Burner Heat Transfer Rate Per Unit Time

A burner that should be able to fire a boiler to generate 80kg/hr, assuming that the water will be heated from ambient condition that is temperature of 30^{0}C to a temperature of 111.4^{0}C at 1.5bar.

Quantity of heat energy needed to generate this quantity of steam is given by

$Q = M_s h_f g$

Where, M_s = mass of steam produced per second

Hf_g = Enthalpy of vaporization of water

M_s = 80/3600 = 0.0222kg|s

From steam table hf_g of water at 111.4^{0}C and 1.5bar is equal to 222 x 10^{3}j/kg Therefore; Q = MS hf_g

Fuel Consumption Rate of The Burner

Power output = fuel consumption x calorific value of fuel

$P_b = M_f$ x CV (15)

Where, P_0 = power output

Cv = calorific value of fuel

Given that calorific value of diesel is 45500kj/kg

∴ Fuel consumption or mass flow rate of fuel (M_f)

Mass flow rate = Volumetric flow rate x Density

Mf = Q_f x P_f

$$\therefore\ Q_f = \frac{M_f}{P_f} \quad (16)$$

Where P_f = density of diesel = 840kg|m^3

Thermal Design Calculation

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

Fire Tubes Heat Transfer Calculation

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

Furnace Calculation

The sensible heat loss of flue gas at furnace exit =

m x C_p x ΔT (17)

Where; m = mass of flue gas (kg)

C_p = specific heat of flue gas

T = (flue gas temperature - ambient temperature) in ^{0}C

Theoretical air required from air fuel ratio

Mass of flue gas [m_g ($_P$)] = $m_a + m_f$

Heat loss = M_p x C_p x ΔT

Radiation heat transfer from furnace

$Q_{rad} = \varepsilon\sigma (T_h^4 - T_c^4) A_c$ (18)

Where; q_{rad} = heat transfer per unit time (W)

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

ε = emissivity of material (mild-steel) used = 0.32

T_h, = hot body absolute temperature (K) = temperature of water = 565^{0}C = 838^{0}k

T_c = cold surroundings absolute temperature = temperature of furnace = 30^{0}C = 303^{0}k

A_c = area of the object (m^2)

d = l 70mm: A_c = 0.02271m^2

Convective heat transfer from furnace

$Q_{conv} = h_c$ x A x (ΔT) (19)

Where; h_c - convective heat transfer coefficient (w/m^{2}k) = 250w/m^{2}k

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

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

ΔT = (temperature of furnace - temperature of water) ^{0}k

L = length of furnace = 40cm = 0.4m

Conduction heat transfer from furnace

$$Q_{cond} = \frac{kc \times A \times (\Delta T)}{l} \quad (20)$$

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

L = length of furnace

T_h - hot body absolute temperature

(K) = temperature of water

T_c = cold surroundings absolute temperature = temperature of furnace

A_c = area of the object (m^2)

Efficiency of furnace

Thermal efficiency of the furnace by direct method;

M_f = fuel consumption or mass flow rate

Thermal efficiency of the furnace =

$$\frac{\text{Heat output from the burner}}{\text{Heat in the fuel consumed (heat input)}} \times 100$$

Heat output from burner = 55kw

Heat in the fuel consumed =

$$\frac{\text{GCV of diesel}\left(\frac{\text{kj}}{\text{kg}}\right)}{\text{fuel consumption rate}\left(\frac{\text{kg}}{\text{h}}\right)}$$

Fire-tube heat transfer at the following sections:

a. Furnace section to return chamber.

b. Return chamber to 2nd pass tubes

c. 2nd pass tubes to smokestack.

Radiative Heat Transfer in The Furnace To The Return Chamber Section

$Q_{rad} = \varepsilon\sigma (T_h^4 - T_c^4) A_c$ (22)

Where; q_{rad} = heat transfer per unit time (W)

Convective heat transfer

$Q_{conv} = h_c$ x A x (ΔT) (23)

Where; h_c = convective heat transfer coefficient (w/m^{2}k)

Conduction heat transfer

$$Q_{cond} = \frac{kc \times A \times (\Delta T)}{l} \quad (24)$$

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

d = heat transfer diameter (m) 0.03 = d x 5 = 0.15m, A = $\pi d2/4$ = 0.017671m^2

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

L = length of furnace 0.3 = Lx5 = 1.5m

$$Q_{cond} = \frac{59 \times 0.0177 \times (535)}{1.5}$$

= 37I.87w

Return Chamber Heat Transfer Calculation

Radiative heat transfer

$Q_{rad} = \varepsilon\sigma (T_h^4 - T_c^4) A_c$ (25)

Where; q_{rad} = heat transfer per unit time (W)

Convective Heat Transfer

$Q_{conv} = h_c$ x A x (ΔT) (26)

Where; h_c = convective heat transfer coefficient (w/m^{2}k)

Conduction heat transfer

$$Q_{cond} = \frac{kc \times A \times (\Delta T)}{l} \quad (27)$$

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

Heat Transfer By The Fire Tubes From Return Chamber 1(2nd Pass) To Return Chamber 2 (3rd Pass)

Radiative heat transfer

$Q_{rad} = \varepsilon\sigma (T_h^4 - T_c^4) A_c$ (28)

Where; q_{rad} = heat transfer per unit time (W)

Convective heat transfer

$Q_{conv} = h_c$ x A x (ΔT) (29)

Where; h_c = convective heat transfer coefficient (w/m^{2}k)

Conduction heat transfer

$$Q_{cond} = \frac{kc \times A \times (\Delta T)}{l} \quad (30)$$

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

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Heat Transfer By The Fire Tubes From Return Chamber 2(3rd Pass) To The Smoke Stack

Radiative heat transfer

$$Q_{rad} = \varepsilon\sigma\,(T_h^4 - T_c^4)\,A_c \qquad (31)$$

Where; q_{rad} = heat transfer per unit time (W)

Convective heat transfer

$$Q_{conv} = h_c \times A \times (\Delta T) \qquad (32)$$

Where; h_c = convective heat transfer coefficient (w/m^{2}k)

Conduction heat transfer

$$Q_{cond} = \frac{kc \times A \times (\Delta T)}{l} \qquad (33)$$

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

Smoke Stack Heat Loss Calculation

Radiation heat loss

$$Q_{rad} = \varepsilon\sigma\,(T_h^4 - T_c^4)\,A_c \qquad (34)$$

Where; q_{rad} = heat transfer per unit time (W)

Convective heat loss

$$Q_{conv} = h_c \times A \times (\Delta T) \qquad (35)$$

Where; h_c = convective heat transfer coefficient (w/m^{2}k)

Conduction heat loss

$$Q_{cond} = \frac{kc \times A \times (\Delta T)}{l} \qquad (36)$$

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

Amount of Steam Generated

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

$$M_s = \frac{qt}{he} \qquad (37)$$

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

q_t = calculated total heat transfer (kw)

h_e = evaporation energy of steam (kj/kg)

From steam table; under saturated steam of P_{sat} at 111.4^{0}C

Boiler Efficiency

Basically boiler efficiency can be tested by the following methods;

1. **The direct method;** where the energy gain of the working fluid (water and steam) is compared with the content of the boiler fuel.
2. **The indirect method;** where the efficiency is the difference between the losses and the input.

In working out the efficiency of our boiler we will be applying the direct method.

Direct Method

This is also known as 'input - output method' 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;

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

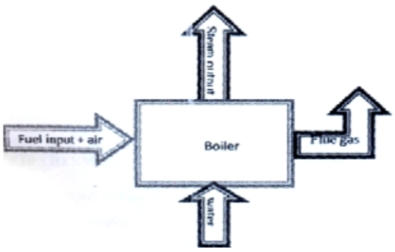

Fig 4: Input and Output

$$\text{Boiler Efficiency} = \frac{37.93 \times 100}{55}$$

$$= 68.96\%$$

$$\sim= 69\%$$

IV. TEST AND RESULT

The fabricated fire 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.

Test

When the burner is turned on and ignition occurs which produces the required fire in the furnace inside the furnace, a hot flue gas is produced which is forced through the fire-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^{0}C also raising the temperature of the water from 30^{0}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%.

V. CONCLUSION

The following conclusions can be drawn from the data and research that has been mentioned in this paper. 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. Dimensions of major and secondary parts were estimated from computations from the theoretical framework and 3D modelling process for the steam boiler was then carried out to present various working drawings of the steam boiler for possible construction.

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 NO_x 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 fire-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 fired systems to complex waste heat applications.

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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 fire-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 fire-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.

Conclusively, a simple laboratory lire-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

I am recommending this research work to any other research institute, students and public to serve as a basis for further research and improvements on fire-tube boiler design. We also recommend that other per-heater devices and feed water pump should be applied for higher efficiency.

APPENDIX I

Fig 6: The fabricated fire-tub boiler

Fig 7: Side view of the Boiler

Fig 8: Plan of the Boiler

APPENDIX II

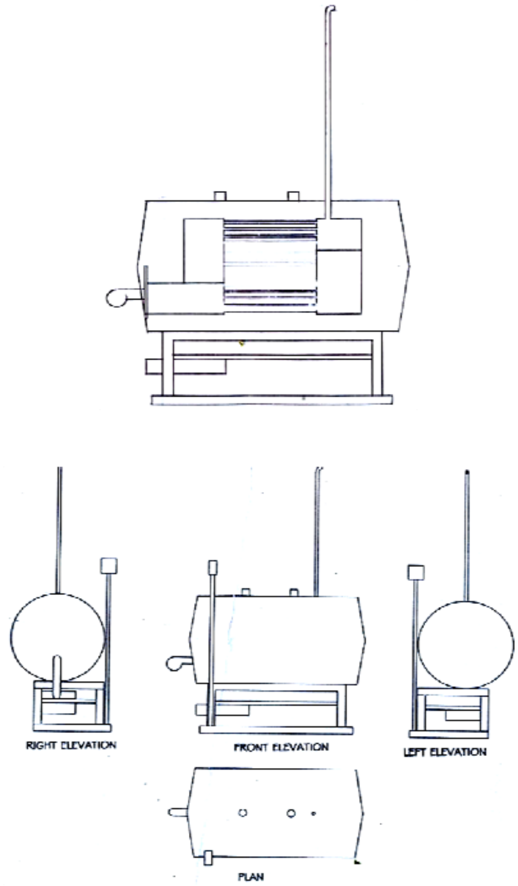

Fig 9: Difference technical views of the Boiler

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