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DEVELOPMENTAL DESIGN OF A LABORATORY FIRE-TUBE STEAM BOILER

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ABSTRACT: This paper presents the design of a laboratory fire-tube steam boiler for eventual construction and use as a teaching aid and for research purposes. Thermodynamics, heat transfer and strength of materials analysis were conducted to estimate dimensions of parts and 3D modelling process was used to draft the working drawings of the steam boiler. Operational, dimensional, and thermodynamic details of designed steam boiler were determined. The working drawings of designed boiler are also presented. The design enables the availability of portable and affordable steam boilers for steam generation in school laboratories and to enhance research and students' learning process in areas of thermodynamics, heat transfer and energy studies
KEYWORDS: fire-tube; steam boiler; thermodynamics; 3D modelling; laboratory

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 boilers are closed vessels which are usually used to produce steam from water by combustion of fuel (Rajput, 2006). 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 fire-tube laboratory boiler that can be manufactured to meet the needs of schools for practical demonstrations and teaching aid.

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 (Lou Roussinos, 2010). Fire-tube boilers are safer to use, require less expertise, and operate under lower pressures than water-tube boilers. Thus, they are more suitable for small scale applications. Water-tube boilers on the other hand, have a higher rate of steam production and are easier to construct and transport (Rajput, 2006).

They 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). Science and engineering education is incomplete without practical demonstrations.

This study is aimed at the design of a laboratory fire-tube steam boiler for eventual construction and use as a teaching aid and for research purposes. A 3D model of the designed boiler with Autodesk 3ds Max Computer Aided Design (CAD) software technology for flexible sizing and standardizing of parts would also be conducted.

METHODOLOGY

The process of designing the laboratory fire-tube steam boiler involves developing a conceptual physical geometry, making necessary calculations from which dimensions and other deductions were made, and finally, developing a working drawing.

Conceptual physical geometry of the laboratory fire-tube steam boiler

The conceptual physical geometry of the laboratory fire-tube steam boiler was developed from the schematic diagram of a boiler shown in Figure 1 (Saidur et al., 2010; Ohijeagbon, 2012). The boiler consists fundamentally of the combustion and heating chambers and other parts such as: fire tubes, water container, steam trap, steam tap, exhaust pipe and boiler casing which are designed in the geometry of the laboratory fire-tube steam boiler.

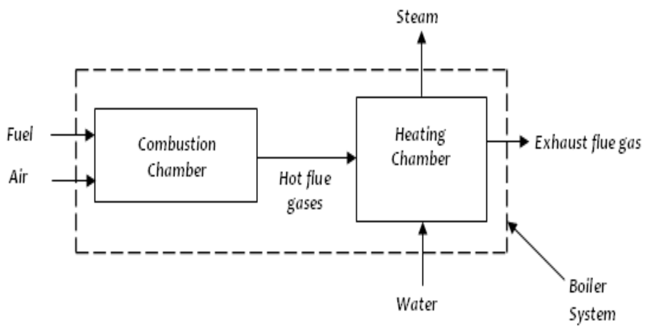

Figure 1: Schematic diagram of a steam boiler

Theoretical framework of the laboratory fire-tube steam boiler

For effective and efficient functioning of the boiler, important calculations to be carried out are enumerated as follows:

1. Operating temperature and pressure

The operating temperature and pressure of a boiler must be determined in order to make other important calculations required for effective functioning of the boiler.

2. Stresses in tubes and drums

Stresses are induced in different parts of an operating boiler by the temperatures and pressures of hot flue gases, feed water and steam respectively. The magnitudes of these stresses must be known so that the boiler will be operated under safe conditions.

3. Internal design pressure of a boiler is given by (Woodruff et al., 2004):

$$P = \frac{S_u \times t \times E}{R \times f_s} \quad (1)$$

where, P = internal design pressure on inside of drum or shell (N/m^2)
S_u = ultimate strength of plate (N/m^2)
t = thickness of plate (m)
R = inside radius of drum (m)
f_S = factor of safety (ultimate strength divided by allowable working stress)
E = efficiency of joints or tube ligaments (ultimate strength of joint or ligament divided by ultimate strength of plate)

4. Maximum allowable working pressure for pipes (Woodruff et al., 2004)

$$t_w = \frac{Pd}{2S_aE + 0.8P} + c \quad (2)$$

where, S_a = allowable stress (N/m^2)
t_w = minimum wall thickness (m)
P = design pressure (N/m^2)
d = tube outer diameter (m)
E = ligament efficiency
C = corrosion allowance

5. Minimum required wall thickness

The minimum required wall thickness of a boiler is a value beyond which the boiler wall cannot be easily damaged by the operating pressure in a boiler. The formula is given as (Woodruff et al., 2004):

$$t = \frac{PR}{SE - 0.6P} \quad (3)$$

where, t = minimum required wall thickness (m)
P = internal design pressure (N/m^2)
S = allowable stress of material at design temperature (N/m^2)
E = efficiency of weld joints or of ligaments between openings
R = inside radius of drum (m)

6. Efficiency of a joint or tube ligament

This is generally found by dividing the strength of the section in question by the strength of the solid plate. In the case of a drum that is drilled for tubes that are parallel to the axis, the efficiency of the ligament can be calculated as (Woodruff et al., 2004):

$$\frac{P - d}{P} \quad (4)$$

where, P = pitch of the tube hole (m)
r = radius of the tube hole (m)

7. Heating surface of a boiler

The heating surface of a boiler refers to the areas that are in contact with heated gases on one side and water on the other side. It is usually expressed in square feet (Woodruff et al., 2004).

8. Rated horsepower of a boiler

This depends on the type of boiler and the number of square feet of heating surfaces it has. It is calculated by dividing the square feet of heating surfaces by a factor corresponding to the type of boiler in question (Woodruff et al., 2004).

9. Boiler horsepower and steam generation

Boiler horsepower (BHP) refers to a steam capacity of 34.5 mm/s of steam at atmospheric pressure with feed water at 212°C. The formula for converting BHP to steam generation is given as (Ganapathy, 1994):

$$W = \frac{33{,}475 \times BHP}{\Delta h} \quad (5)$$

where, W = steam flow (m/s)
Δh = enthalpy absorbed by steam/water, expressed as:

$$\Delta h = (h_s - h_{fw}) + BD \times (h_f - h_{fw}) \quad (6)$$

where, h_S = enthalpy of saturated steam at operating steam pressure (kJ/kg)
h_f = enthalpy of saturated liquid (kJ/kg)
h_{fw} = enthalpy of feed water (kJ/kg)
BD = blowdown fraction

10. Water required for cooling gas streams

It is important to know the quantity of water required for cooling flue gas streams so that maximum heat is absorbed from the flue gases, hence increasing the efficiency of the steam boiler. The formula for obtaining the appropriate quantity of water is given as (Ganapathy, 1994):

$$q = 5.39 \times 10^{-4} \times (t_1 - t_2) \times \frac{W}{1090 + 0.45 \times (t_2 - 150)} \quad (7)$$

where, q = water required (litres/s)
t_1, t_2 = initial and final gas temperatures (°C)
W = gas flow entering the cooler (m/s)

11. Velocity of fluid inside tubes, pipes or cylindrical ducts

It is important to know the velocity of fluid flow in a boiler so as to control or determine other conditions of the boiler's operation. The formula is given as (Ganapathy, 1994):

$$V = 0.05 \times W \times \frac{v}{d_i^2} \quad (8)$$

where, V = Velocity (m/s)
W = flow (m/s)
v = specific volume of the liquid (m^3/kg)
d_i = inner diameter of pipe (mm)

12. Stoichiometric and actual air-fuel ratio

Complete combustion of a hydrocarbon with atmospheric air is written as (Ohijeagbon, 2011),

$$C_xH_y + a(O_2 + \frac{0.79}{0.21}N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + \frac{a0.79}{0.21}N_2 \quad (9)$$

where x,y and a are constant coefficients that characterises the hydrocarbon and combustion process. By balancing the number of atoms of O, this shows that

$$a = x + \frac{y}{4} \quad (10)$$

The stoichiometric air-fuel ratio (AFR_{st}) (by mass) is then given by

$$AFR_{st} = \frac{a(MW_{O_2} + {}^{0.79}/_{0.21} MW_{N_2})}{MW_{fuel}} \quad (11)$$

where, MW_{O_2} = mass weight of oxygen, O_2
MW_{N_2} = mass weight of nitrogen, N_2
MW_{fuel} = mass weight of fuel, C_xH_y

The actual air-fuel ratio (AAF) is given by (Ohijeagbon, 2011),

$$AAF = (1 + EA) \times AFR_{st} \quad (12)$$

in which, EA = excess air
The recommended excess air level for single fuel oil burners is 20% (Ohijeagbon, 2011).

13. Mass flow rate of material streams in boiler

$$\dot{m}_a + \dot{m}_f = \dot{m}_p \quad (13)$$

$$\dot{m}_p = \dot{m}_g \quad (14)$$

$$\dot{m}_w = \dot{m}_s \quad (15)$$

where, $\dot{m}_a$ = mass flow rate of air
$\dot{m}_f$ = mass flow rate of fuel
$\dot{m}_p$ = mass flow rate of hot products
$\dot{m}_g$ = mass flow rate of flue gas
$\dot{m}_w$ = mass flow rate of water
$\dot{m}_s$ = mass flow rate of steam
Hence,

$$\dot{m}(kg/s) = q_m(litres/hr) \times SG/3600 \quad (16)$$

where, $\dot{m}$ = mass rate of substance
q_m = rate of material stream
SG = specific gravity of substance

14. Combustion temperature

The temperature of combustion in a boiler furnace is given as (Ohijeagbon, 2011),

$$T_c = T_{ca} + \frac{h_f}{[c_{pp} \times (1 + AAF)]} \quad (17)$$

where, T_c = combustion temperature
T_{ca} = temperature of the combustion air before entering the burner
h_r = heat of reaction = lower heating value (LHV)
c_{pp} = specific heat of fuel at temperature of products of combustion

15. Enthalpy of hot products

The enthalpy of hot products is given as (Ohijeagbon, 2011),

$$h_p = \frac{m_f h_f + m_a h_a}{m_p} \quad (18)$$

16. Temperature of exhaust flue gases

The temperature of exhaust flue gases was estimated from the values of the hot product and exhaust flue gas temperatures given by Ohijeagbon (2012),

17. Enthalpy of exhaust flue gases

Enthalpies of most gases used in combustion calculations can be curve-fitted by the simple second order equation (Kitto and Stultz, 2005):

$$h = aT^2 + bT + c \quad (19)$$

where, h = enthalpy in Btu/lb
T = temperature in degrees, ^{0}F
a, b and c are coefficients with the following values for T {0-500 ^{0}F (260 ^{0}C)} given as:
a = 1.683x10-5; b = 0.233; c = -18.03

18. Entropy of exhaust flue gases

The entropy of exhaust flue gases is given as (Ohijeagbon, 2011),

$$s_g = c_p \ln \frac{T_g}{T_{0a}} \quad (20)$$

At $T_a = 200K, s_a = 1.29559 kJ/kgK$ (Cengel& Boles, 2006)
where, T_g = temperature of exhaust flue gases
c_p = the average of c_p of air and exhaust flue gases

19. Entropy of hot products (Ohijeagbon, 2012)

$$s_p = \frac{h_p}{T_p} \qquad (21)$$

where, T_p = temperature of the hot products (^0C)

20. Entropy of combustion fuel gas (Ohijeagbon, 2012)

$$s_f = \frac{h_p}{T_f} \qquad (22)$$

where, T_f = combustion fuel temperature (^0C)

21. Rate of heat transfer (conduction and convection) (DOE Fundamentals Handbook, 1992)

$$\dot{Q} = \frac{T_a - T_b}{1/h_1A + \Delta x/kA + 1/h_2A} \qquad (23)$$

$$\dot{Q} = U_o A \Delta T_{overall} \qquad (24)$$

where, $\dot{Q}$ = rate of heat transfer (kJ/hr)
T_a = temperature of flue gas (°C)
T_b = temperature of water (°C)
h = convective heat transfer coefficient (W/m^2K)
k = thermal conductivity (W/m K)
Δx = thickness of tube wall (m)
A = cross sectional area for heat transfer (m^2)
U_o= overall heat transfer coefficient (W/m^2 K)
ΔT = temperature change (°C)

22. Heat energy

The heat energy is given by (DOE Fundamentals Handbook, 1992)

$$q = mC_p\Delta T \qquad (25)$$

where, q = heat energy (kJ)
C_p = specific heat capacity (J/kg °C)
ΔT = temperature change (°C)

23. Boiler efficiency

Boiler efficiency varies with different types of fuel. It is important to determine this value so as to know what to expect from boiler operation.
For fuel oils (Ganapathy, 1994),

$$\eta_{LHV}, \% = 99.0 - (0.001383 + 0.0203 \times EA) \times \Delta T \qquad (26)$$

where, EA = excess air factor
ΔT = difference between exit gas and ambient air temperatures
These and other necessary calculations are further discussed and implemented in the design chapter.

Determination of dimensions and 3D modelling process for the steam boiler

The size of a boiler determines other characteristics, such as temperature and pressure design limits. Therefore, in the design of a boiler, the first stage is to determine the size of the boiler, which is based on the intended use of the boiler. Since the boiler of interest is a laboratory fire-tube steam boiler, it will be relatively smaller in comparison with industrial boilers. Therefore, the design temperatures and pressures of operation will be within the operating capacity of the boiler. All other calculations are derived from the size and load of the boiler. The overall boiler dimensions are stated as: length (1 m), width (0.5 m) and height (0.5 m) respectively.
The required working drawings of the laboratory fire-tube steam boiler were derived from the application of the dimensions and calculations made, as the final stage of the design process. After the development of the working drawings, the laboratory fire-tube boiler will be modeled using Computer Aided Design (CAD) Technology. The software used in this project is Autodesk 3ds Max which is three-dimensional (3D) design software. It is preferred over other software because it provides comprehensive, integrated 3D modelling for designers, and is very flexible, and therefore aids exhaustive design and 3D modelling and speeds up the production process (Murdock, 2007).

RESULTS OF DESIGN ANALYSIS

A summary of the basic details and operational data of the designed steam boiler are presented in Table 1. Specifications for the fuel used for combustion are presented in Table 2. Also, a summary of the dimensional analysis is presented in Table 3.

Operational details of designed steam boiler

Determined operational details of the designed steam boiler are presented in Table 1.

Table 1: Summary of details and operational data of steam boiler

S/No	Details	Description/Values
1	Orientation	Horizontal
2	Type of tube	Fire 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 fire tubes	3 (3 passes each)
9	Operating feed water temperature	80 °C
10	Operating steam temperature	151.8 °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 A36
17	Material used for boiler insulation	Brick

Specification of diesel fuel

Every fuel has a unique composition and energy content described by its fuel specifications presented in Table 2. Knowing the fuel specifications is essential for determining various combustion parameters (Ohijeagbon, 2012).

Table 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)]	0.100

Source: Ohijeagbon (2012)

Dimensional details of designed steam boiler

Determined dimensional details of the designed steam boiler are presented in Table 3.

Table 3: Summary of dimensional details

S/No	Details	Description/Values
1	Diameter of boiler shell	0.5m
2	Length of boiler shell	1m
3	Thickness of insulation	0.0625m
4	Diameter of fire-tubes	0.035m
5	Length of fire-tubes	0.6m
6	Thickness of fire-tubes	2.5mm
7	Thickness of boiler shell	6.25mm
8	Volume of fuel tank	$0.027m^3$

Thermodynamic details of designed steam boiler

Determined thermodynamic details of the designed steam boiler are presented in Table 4.

Table 4: Thermodynamic properties of material streams of the boiler

Substances	Mass flow rate (kg/s)	Temperature (°C)	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 flue gas, m_g	2.4192	150.10	225.77	2.0449

Working drawings of designed boiler

Determined parameters obtained in the design analysis were used to draft the working drawings of the boiler. The whole boiler was modelled in three-dimensional details using Autodesk 3ds Max. This presented a more detailed view of the different parts of the boiler and enables better visualization of what the fabricated product will look like.

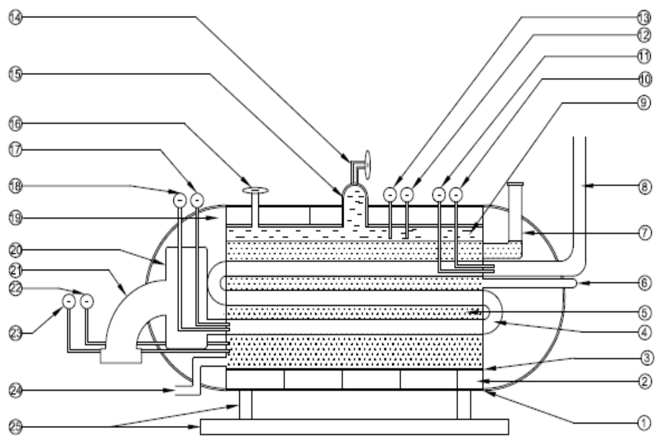

Figure 2: Cross-sectional view of the steam boiler

Figure 2 shows the cross-sectional view of the steam boiler with all the parts identified. The list of parts of the steam boiler is presented in Table 5. Figure 3 shows the major dimensions of the steam, Figure 4 gives the isometric view of fire-tubes showing the path travelled by flue gases, Figure 5 represent the cut-away image showing boiler wall, and Figure 6 is the isometric view of the steam boiler.

Table 5: List of parts of the fire tube steam boiler

S/No	PARTS	S/No	PARTS
1	Boiler casing	14	Steam tap
2	Brick lining	15	steam dome
3	Boiler shell	16	Safety valve
4	Fire-tube	17	Flue gas temperature gauge
5	Water	18	Flue gas pressure gauge
6	Water return tube	19	Boiler access door
7	Water level indicator	20	Combustion chamber
8	Exhaust pipe	21	Burner
9	steam	22	Feed water temperature gauge
10	Exhaust gas temperature gauge	23	Feed water pressure gauge
11	Exhaust gas pressure gauge	24	Feed water inlet
12	Steam temperature gauge	25	Boiler supports
13	Steam pressure gauge		

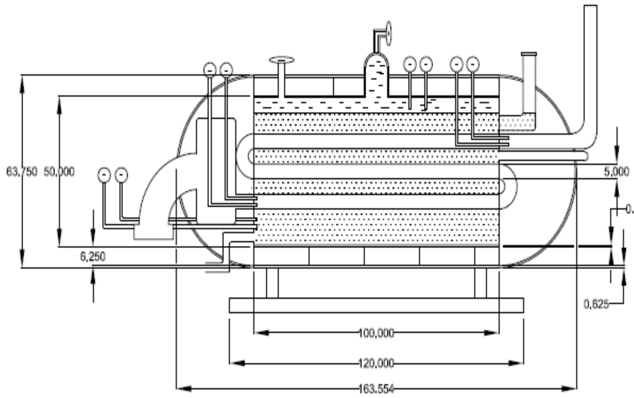

Figure 3: Major dimensions of the steam boiler

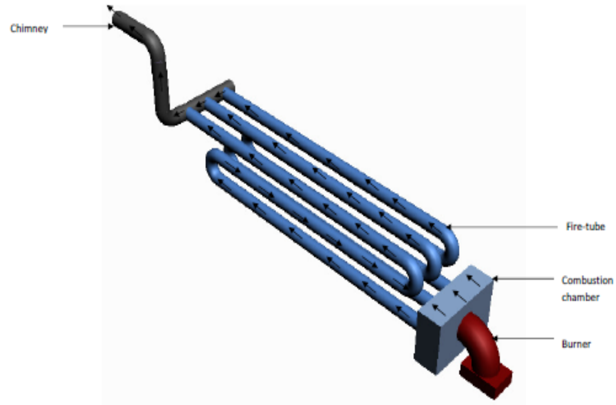

Figure 4: Isometric view of fire-tubes showing the path traveled by flue gases

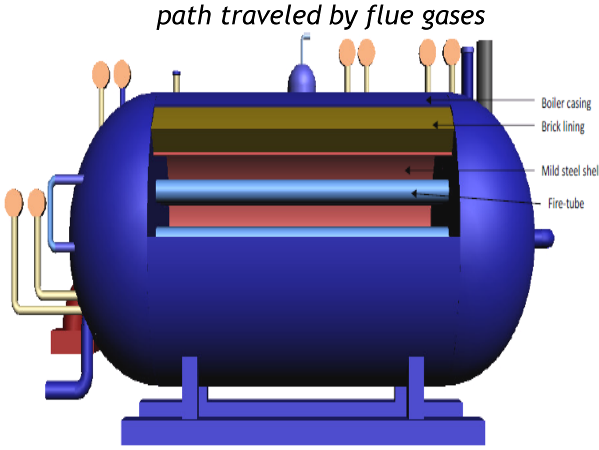

Figure 5: Cut-away image showing boiler wall layers

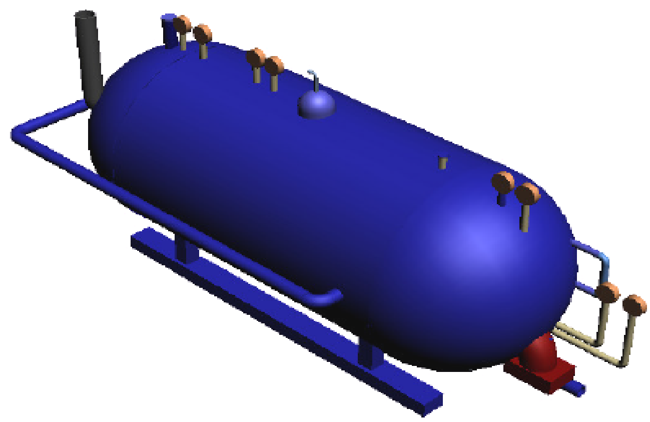

Figure 6: Isometric view of the steam boiler

CONCLUSIONS

The laboratory steam boiler designed was projected from the conceptual physical geometry of fire-tube boiler 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. 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. Conclusively, a simple laboratory fire-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.

REFERENCES

[1.] Adeyinka A. A., "Current Problems of Educational Development in Nigeria", [online], Available: https://www.unilorin.edu.ng/journals/education/ pdf, Accessed: October 30, 2010, 1992.

[2.] Boiler Fuels and Emissions, "Continuing Education for Engineers", PDH engineer. Com [online], Available From the World Wide Web: http://www.pdhengineer.com/pages/M3004.htm. Accessed: November 26, 2009.

[3.] 3. Cengel, Y. A. and Boles, M. A., "Thermodynamics: An Engineering" Approach, 5th Edition, McGraw Hill, 2006.

[4.] DOE (Department of Energy) Fundamentals Handbook, "Thermodynamics, heat transfer, and fluid flow" U.S. Department of Energy, Washington, D.C. [Online].

[5.] Available: www.hss.doe.gov/nuclearsafety/techstds/docs/handbook/h1012v1.pdf. Accessed: September 7, 2010, 1992.

[6.] Ganapathy, V., "Steam Plant Calculations Manual", 2nd Edition, Marcel Dekker Inc., 1994.

[7.] Kitto, J. B. and Stultz, S. C., "Steam: Its Generation and Use", 41st Edition, The Babcock and Wilcox Company, Barberton, Ohio, U.S.A, 2005.

[8.] Lou Roussinos, P. E., "Boiler Design and Efficiency" [online], Available: http://www.forestprod.org/drying06williamson.pdf, Accessed: September 1, 2010.

[9.] Murdock, K. L., "3ds max 9 Bible, Wiley Publishing Inc. Indianapolis, Indiana, 2007.

[10.] Ohijeagbon, I.O., "Life Cycle Energetic Studies of Steam Boilers Operation in a Nigerian Beverage Industry", Postdata Report for Doctor of Philosophy Degree, LAUTECH, Ogbomoso, Nigeria, 2011.

[11.] Ohijeagbon, I. O., "Life Cycle Energetic Analysis of Steam Boilers Operation in Selected Production Industries", Doctor of Philosophy Dissertation, Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria, 2012.

[12.] Rajput R.K., "Thermal Engineering", Laxmi Publications (P) Ltd., New Delhi, 2006.

[13.] Rawson W.R., "Boiler. The Encyclopedia of Earth", [online], Available: http://www.eoearth.org/article/Boiler, Accessed: November 1, 2010, 2008.

[14.] Saidur, R., Ahamed, J. U. and Masjuki, H. H., "Energy, Exergy and Economic Analysis of Industrial Boilers", Energy Policy, Vol. 38, pp2188-2197, 2010.

[15.] Woodruff E.B., Lammers H.B. and Lammers T.F., "Steam Plant Operation", 8th Edition. The McGraw-Hill Companies, Available: www.digitalengineeringlibrary.com, Accessed: September 7, 2010, 2004

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