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Development of a Steam Boiler for Domestic Use.

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ABSTRACT

Energy is vital to poverty eradication and security of any country. Uninterrupted energy supply is crucial for economic growth, which depends on the long-term availability of affordable, accessible, and environmentally friendly energy sources. The security, climate change, public health, and the standard of living of any nation is closely dependent on the per capita energy consumption. The global energy crisis is due to two reasons: the rapid population growth and the increase in the living standard of the whole societies. This focus is to develop a small-scale prototype of a steam boiler and conservation of energy, which can help in the national industrial revolution to boost its economy. Mild steel plates are the materials used for the development and fabrication of the steam boiler; while fiberglass was utilized on the boiler surface as the lagging materials to retain heat in the system. The properties of the steam in the boiler were measured using a temperature gauge, while the pressure within the boiler was taking with pressure relief valves. The flow of the steam and water in the boiler was regulated using gate valves, T-junction pipes, elbows, and straight mild steel plates. The boiler developed, finds its application in small-scale industries and thermo-fluid laboratories; and can generate steam ranging from one bar to 10 bars pressure. The design permits modifications for the production of superheated steam for power generation. Biogenic waste serves as materials to co-fire the boiler to reduce the ignition time and increase the rate of steam production. Palm kernel shells biomass waste is the source of heat energy for boiler development.

Keywords: Biomass, Combustion, Dryness fraction, Energy generated, Steam boiler, Stress

1.0 INTRODUCTION

Energy is essential for the modern industrial economy. Energy provides an ingredient for almost all human activities such as space/water heating, lighting, health, food production and storage, education, mineral extraction, industrial production, and transportation. Modern energy services are powerful engines of economic and social development. No nation can develop beyond a subsistence economy without ensuring at least minimum access to energy services for its population. Throughout the world, the energy resources available to citizens and their ability to pay largely determine their modes of life. Oil pricing and cost of renewable energy resources exploitation affect the economies of developing nations and essential in shaping them (Khurmi and Gupta, 2005).

The enormous energy crisis, which has engulfed Nigeria for almost two decades, has largely contributed to the incidence of poverty by paralyzing industrial and commercial activities. The Council for Renewable Energy of Nigeria estimates that power outages brought about a loss of 126 billion naira (US$ 984.38 million) annually. Apart from the huge income loss, it has also resulted in health hazards due to the exposure to carbon emissions caused by the constant use of 'backyard generators' in different households and business enterprises, unemployment, and high cost of living leading to a deterioration of living conditions (Oyedepo, 2012).

The authors focus on the conversion of this non-renewable energy that is non-toxic bio-gradable and non-bio-gradable solid energy gotten from items like palm kernel shells, irrelevant wasted pieces of woods, to steam energy which can be useful to both home and country in so many different ways. Water superheated to produce steam in power plants, and the pressurized steam drives turbines that produce an electrical current. The thermal energy steam energy of steam is thus converted to mechanical energy, which in turn is converted to from boiling or heating fluids like water. Steam is useful in various ways and finds applications in agricultural fields, power generation, water heaters in homes, and reciprocating engines. Steam in power generation, if adequately harnessed will boost industrial and economic growth (Sriveerakul et.al, 2006)

Inability to utilize and harness solar energy, wind energy, geothermal energy resources, and strategies that promote the utilization of cleaner, cost-effective alternatives like biomass or waste-based fuels to generate energy from steam are becoming more attractive. Nigeria's economic decline is a devastating and shocking wave to every immediate habitat. Energy generation from steam boilers can be a positive catalyst in the industry and economic development. The main purpose of this work is to produce steam for domestic use by harnessing, utilizing, and managing non-toxic biogenic and non-biogenic solid energy sources like palm kernel shells. The focus is to design and fabricate a prototype of a steam boiler producing less than or equal to 10 bar pressure (Sokan-Adeaga, 2015).

Biomass is solar energy stored in organic matter. Biomass is a renewable energy source because the growth of new plants and trees replenishes the supply. The use of biomass for energy causes no net increase in carbon dioxide emissions to the atmosphere. As trees and plants grow, they remove carbon from the atmosphere through photosynthesis; a process, which uses energy from the sun to convert carbon dioxide from, plants into carbohydrates (sugars, starches, and cellulose). When plants die, the process of decay releases the energy stored in carbohydrates and discharges carbon dioxide back into the atmosphere Biomass fuels are readily available throughout the world There is a need for deliberate policies to enhance the efficiency and sustainability of biomass energy in Nigeria and make clean commercial energy more accessible and relatively cheaper (Suleiman and Idris, 2016).

Rusinowski and Stanek, (2010) described the development hybrid model of a boiler with the application of both analytical modeling and artificial intelligence. The analytical part of the model includes the balance equations. The empirical models express the dependence of the flue gas temperature and the mass fraction of the non-combustibles in solid combustion products on the operating parameters of a boiler. Big boilers' energy efficiency is usually determined with the application of the indirect method. Flue gas losses and non-combustible losses have a significant influence on the boiler's efficiency. The estimate of losses requires the knowledge of the influence of the operating parameters on the flue gas temperature and the content of combustible particles in the solid combustion products. The basic parameters influencing the energy efficiency of the boiler are a specific amount and the temperature of flue gases as well as a specific amount of solid combustion products and their composition (the mass fraction of non-combustibles). The specific amount of flue gases and solid combustion products can be determined using stoichiometry calculations. Substrates of the combustion process and measurement results of O2 and CO content in flue gases determine flue gas temperature and the mass fraction of the combustibles, the combustion, and the heat transfer processes within the boiler (Nieminen and Kivela, 1998).

Neuman et.al (1994) proposed the modification of an extreme control system with combustion optimization, which ensures minimal NO2 and CO levels in flue gases lying below emission limits, with minimal power losses. They concluded that the main functions of an engineering simulator consists of the check controller ranges, actions and down limits, new control strategies test implementation, and transferring DCS engineering from the simulator work directly to the control system. They presented an update of the model of a drum pulverized-coal fired steam boiler including the turbine effects and special extreme combustion control. The authors described the creation of the last version of the model for a fossil power plant.

A boiler is an enclosed vessel that provides a means for combustion and transfers heat to water until it becomes hot water or steam. The hot water or steam under pressure is then usable for transferring the heat to a process. When water is boiled into steam its volume increases about 1,600 times, producing a force that is almost as explosive as gunpowder. These make the boiler extremely dangerous equipment, which should handle carefully. Hot gases of combustion are on the heating surface of the boiler while water is on the other side. The larger the heating surface a boiler has, the more efficient it becomes. Boilers are also called Steam generators; apparatus designed to convert a liquid to vapor. In conventional steam power plants, the boiler consists of a furnace in which fuels are burnt, surfaces that transmit heat from the combustion products to the water, and a space where steam forms and collected (Skodras et.al, 2002).

Rusinowski and Stanek (2010) modeled a steam boiler system using hybrid automata. They proposed the description of an industrial boiler, which consists of a water tank, four pumps, a sensor that measures the pumping rates, the water level, the evacuation rate of steam, and the operational status of the components. A controller regulates the complete system operation, problem specification, and verification of the design efficiency and safety of the boiler.

A conventional boiler has a furnace that burns fossil fuel or, in some installations, waste fuels. A nuclear reactor can also serve as a source of heat for generating steam under pressure. Modern boilers are made of alloy steel to withstand high pressures and extremely high temperatures. The parts of the boiler are the feedwater system, steam system, and fuel system.

2. MATERIALS AND METHOD

The materials employed in the construction of the boiler were readily available and locally sourced. Mechanical properties such as toughness, durability, flexibility, and availability were of prime importance for material selection. The materials use for the boiler development are mild steel, fiberglass, gate valves, pressure gauge, pressure relief valve, temperature gauge, and hose. Table 1 shows the material description and specification.

Table 1: Steam Boiler Material description and specification

S/N	Part/ Component Description	Quantity	Material	Function
1	Surface cover (6 mm x 0.0012 mm)	4	Mild steel plate	Used in the boiler unit construction
2	Fibreglass	I roll	Reinforced glass	For boiler insulation
3	Boiler cover	1	Mild steel plate	For fabrication of boiler surface covering
4	Semi-circular fuel system cover	1	Mild steel plate	For fabrication of semi-circular surface covering
5	Rectangular fuel system cover	3	Mild steel plate	For fabrication rectangular covering
6	Chimney pipe	1	Mild steel plate	For exhaust pipe construction
7	Bolts and nuts	12	Mild steel	For fasten f boiler parts
8	Pressure gauge (Max. pressure relief of 16 bar)	1	Stainless steel	To determine the amount of steam pressure leaving the boiler
9	Pressure relief valve (Max. pressure relief of 10 bar)	1	Cupper	To determine the amount of steam pressure leaving the boiler
10	Temperature gauge (Max. temp scale of 300 ℃)	1	Stainless steel	Ensure boiler constant for a steam pressure of 10 bar
11	T-junction pipe	3	Galvanised	Pipe Joining
12	Gate valve	5	Mild steel	For fluid flow control
13	Elbow pipe	4	Galvanised	Pipe Joining
14	Straight pipe	8	Mild steel	Fluid transfer medium
15	Union pipe	4	Galvanised	Pipe Joining
16	Rollers	4	Rubber	Movement of boiler platform
17	Hose		Fabric rubber	Fabric rubber

a. Boiler Design

The steam boiler design involves various criteria used for heat applications in units, which operate under high pressure at a very high temperature. Thus, the boiler design is for cost-effectiveness, flexibility in fabrication, ease of maintenance, and capacity to withstand the high pressure and temperature.

i. Determination of the minimum thickness for the Boilers mild steel plate

The minimum thickness of a boiler is read from table 3 given with the relationship between the boiler thickness and boiler diameter, the minimum thickness for this particular boiler design is taken to be 6 mm since the boiler diameter is less than 0.9 m that is 0.15 m and therefore it is a thin shell type.

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Table 3: Minimum thickness of a boiler with respect to its diameter

Boiler diameter (m)	Minimum plate thickness(t)
≤ 0.9 m	6 mm
0.9 m ≤ 1.35 m	7.5 mm
1.35 m ≤1.8 m	9 mm
>1.8 m	12mm

Source: (Khurmi and Gupta, 2005)

ii. Determination of Stresses in the Thin Pressure Vessel Due to an Internal Pressure

The induced stress in a thin cylindrical shell is analyzed based on the following assumptions: neglecting the effect of the curvature of the cylinder wall; uniformly distribution of the tensile stresses are over the section of the walls, and neglecting the effect of the restraining action of the heads at the end of the pressure vessel.

Internal pressure exerted on thin cylindrical shell causes to fail along the longitudinal section (Circumferential or hoop stress) splitting the cylinder into two troughs, and across the transverse section (Longitudinal stress) splitting the cylinder into two cylindrical shells.

iii. Circumferential or Hoop Stress

For a thin cylindrical shell subjected to an internal pressure shown in figure 1, tensile (circumferential or hoop stress) stress acts in a direction tangential to the circumference of the longitudinal section (or on the cylindrical walls).

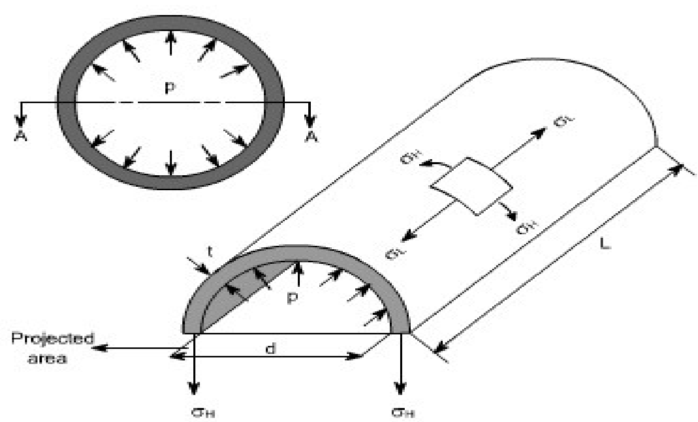

Figure 1: Circumferential or Hoop Stress Acting on a Pressure Vessel

Khurmi and Gupta (2005) gave equations 1 to 3 for circumferential stress respectively.

Force acting on the longitudinal section of the shell, F_L = intensity of pressure × projected area

$$F_L = p \times d \times l \quad (1)$$

And the total resisting force acting on the cylinder walls, F_R

$$F_R = \sigma_{t1} \times 2t \times l \quad (.2)$$

Equating equations (1) and (2)

$$\sigma_{t1} \times 2t \times l = p \times d \times l \quad \text{or} \quad \sigma_{t1} = \frac{p \times d}{2t} \quad \text{or} \quad t = \frac{p \times d}{\sigma_{t1}} \quad (3)$$

Where d is the internal diameter of the cylindrical shell, l is the length of the cylindrical shell, t is the thickness of the cylindrical shell, and $\sigma_{t1}$is the circumferential or hoop stress for the material of the cylindrical shell.

iv. Longitudinal Stress

Furthermore, Khurmi and Gupta (2005) gave equations 4 to 7 for longitudinal Stress deriving with figure 2.

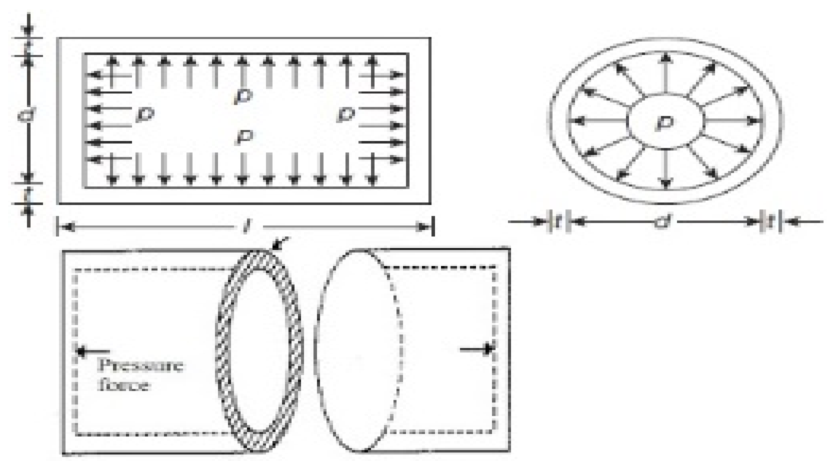

Figure 2: Longitudinal Stress

For longitudinal stress, σ_{t2}

The total force acting on the shell $= p \times \frac{\pi}{4}(d)^2$ (4)

And total resisting force $= \sigma_{t2 \times \pi\, d.t}$ (5)

Combining equations (4) and (5), we have

$$\sigma_{t2 \times \pi\, d.t = p \times \frac{\pi}{4}(d)^2} \quad (6)$$

$\sigma_{t2} = \frac{p \times d}{4t}$ or $t = \frac{p \times d}{4\,\sigma_{t2}}$ (7)

v. Boiler Dimensioning

Area of the vessel, $A_v = \frac{\pi(d)^2}{4}$ (8)

V_{sa} = Volume of steam allowance = Area of steam allowance in the vessel × height of steam allowance in the vessel

V_w = Area of water in the vessel × height of maximum water level = $A_v \times h_{wmax}$ (9)

V_b = Area of the vessel × height of boiler = $A_v \times h_b$ (10)

vi. Evaluation of Steam Properties

Using data from steam tables, the dryness fraction is computed using the specific volume of wet steam as follows:

Specific volume, $V_1 = x \times V_g + (1\text{-}x)\, V_f = \frac{Volume\ of\ the\ vessel}{mass\ of\ mixture}$ (11)

Where, x *is the* Dryness fraction,

V_g, *is the* Specific volume of saturated steam,

V_f, *is the* Specific volume of saturated water,

Where specific volume, $V_{sp} = \frac{Volume\ of\ the\ vessel}{mass\ of\ mixture}$ (12)

Mass of the mixture, M_m = mass of steam + mass of water (13)

Where the mass of steam, $M_s = \rho_1 \times V_{st}$ (14)

Mass of water, $M_w = \rho_w \times V_w$ (15)

where, ρ_w = Density of water $(kg/m^3) = 1000\ kg/m^3$

V_w = Volume of water in the vessel (m^3)

If the rate of heat flux released, $\dot{Q} = \dot{m} \times \Delta H = \frac{H_c \times m_p}{t}$ (16)

Where H_c = Calorific value of palm kernel shell in kJ/kg

m_p = Mass of palm kernel shell used to fire the boiler = 5 kg

t = Time taken for the water to produce steam at 10 bar pressure = 30 minutes

b. Fabrication of Steam Boiler System

This boiler has a diameter of 155.57 mm and a length of 1203.9 mm and was fabricated to a volumetric capacity of 0.0913 m^3 using a 6mm thick mild steel because of its strength to withstand pressure and its cost effectiveness. The boiler is portable as it occupies little space enabling its movement from place to place for foundry operations. The schematic diagram and exploded diagrams are shown in figures 3, and 4 respectively. The fabrication of the steam boiler system involves the following procedures:

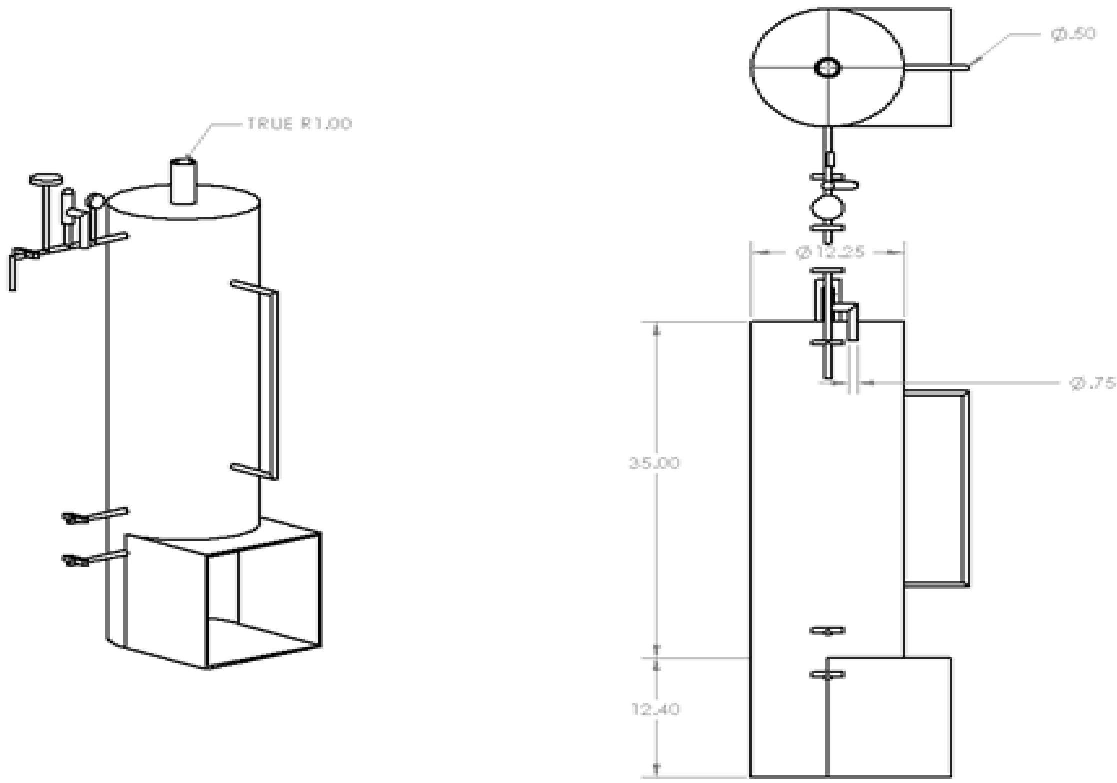

Figure 3: Schematic Diagram of Steam Boiler

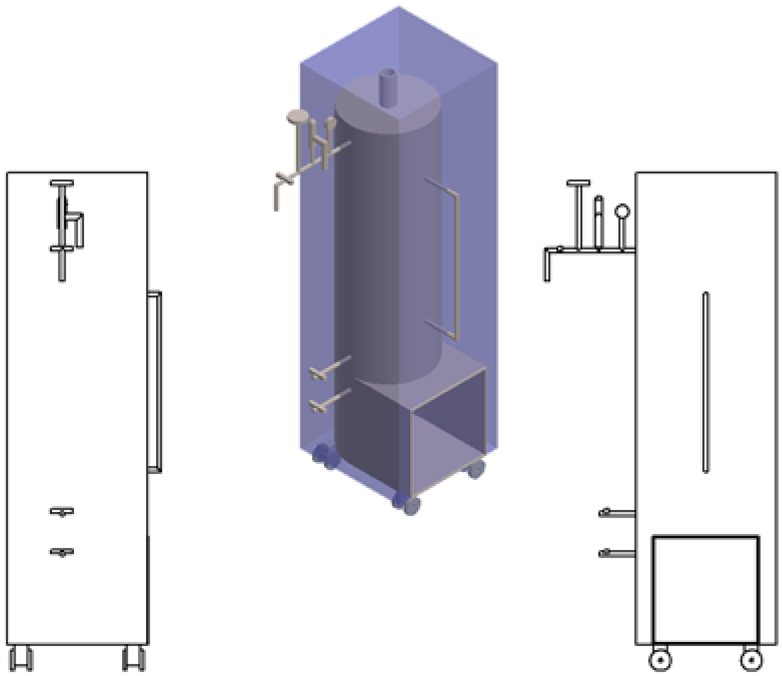

Figure 4: Steam Boiler Exploded and Simulated View

i. Construction of the Boiler Unit

The mild steel sheets were cut to155.57 mm diameter and 1203.9 mm in length. The sheet was then rolled using a rolling machine. Using the Orlikhon electrode the rolled sheets were welded to the bottom and top of the hollow cylinder to form the boiler. Two separate sheets of mild steel were drilled in the middle according to its design and welded with the use of. A separate mild steel pipe of 50.8 mm diameters was placed in the drilled middle of the boiler and welded with the use of Orlikhon Electrode to form the chimney. Five different holes of 12.6mm in diameter were drilled at different areas of the Boiler surface according to the design for the water level indicator, the water inlet, the steam outlet, and the service unit. The chimney and boiler unit fabrication is shown in figure 5.

ii. Construction of Water Level Indicator

Using a pipe range two-gate valves were threaded at two different threaded areas for an efficient grip. Unions and two 90-degree elbows galvanized pipes were also threaded with pipe range for an efficient grip. Hose for indicating the water level was connected and clipped with stainless steel.

iii. Installation of Measuring Instrument

The instruments listed and used in the design and fabrication of the Steam Boiler are the temperature gauge, pressure gauge, and pressure relief valve. These instruments were arranged and installed in the design to monitor steam in the Boiler. These instruments were threaded with pipe range and there were all linked with six 12.6mm diameter mild steel straight pipes, three T-junction 12.6mm diameter mild steel pipes, two 12.6mm diameter galvanized union pipes, four galvanized nuts, one 90 degrees elbow pipe, two $3\frac{1}{4}$ $inch$ diameter mild steel pipe and one $3\frac{1}{4}$ $inch$ diameter mild steel elbow pipe. The instrumentation section was installed at the steam outlet to monitor the flow of steam i.e. its temperature, pressure, and irrelevant pressures generated. Figure 6 shows the boiler designed and fabricated at Afe Babalola University, Ado-Ekiti, Nigeria.

3.0 RESULTS AND DISCUSSION

a. Stress Results

Using $t = 6$ mm, $d = 311.15\ m,$ and $P = 10\ bar \approx 1$ N/mm^2 for the design parameters of the steam boiler, both hoop stress, and longitudinal stress:

$$\sigma_{t1} = \frac{1 \times 311.15}{2\,(6)}$$

$$\sigma_{t1} = \frac{311.15}{12}$$

$$\sigma_{t1} = 25.9\ Mpa$$

The longitudinal stress is half of the circumferential or hoop stress, hence stress acting in the steam boiler (pressure vessel) was designed using the maximum stress i.e. hoop stress.

b. Steam Boiler Dimensions

Where, d = diameter of the vessel = 0.311 m

Where, the height of the vessel, h = 1.203 m

$$A = \frac{3.142(0.311)^2}{4} = 0.0759\ m^2$$

Area of water in the vessel = $A_w = A_1 = 0.0759\ m^2$

∴ Volume of the vessel, V = (0.0759)(1.203) = 0.0913 m^3

Table 4 shows the result of the dimension for the construction of the steam boiler

Table 4: Steam Boiler Dimensions

Diameter, d (m)	Height, h (m)	Area, A (m^2)	Volume, V (m^3)
0.311	1.213	0.0759	0.913

c. Steam properties for boiler construction

Table 5 shows the result of the steam properties for boiler construction.

Table 5: Steam properties for boiler construction

$\rho_1(kg/m^3)$	$h_o(kJ/kg)$	$h_i(kJ/kg)$	$\Delta H(kJ/kg)$	m(kg/s)	Q (kJ/s)	x
5.147	780.319	117.288	662.439	0.0585	38.74	0.0050726

Maximum height of water level, $h_{max} = = h_1 - h_2 = 1.225 - 0.401 = 0.802$ m

The volume of water in the vessel $V_w = (0.0759)(0.802) = 0.6087\ m^3$

$M_w = (1000)(0.6087) = 608.7\ kg$

M_m, mass of mixture = $608.7 + 0.1564 = 608.85\ kg$

Specific volume of wet steam, $V_1 = \frac{V_2}{m_3} = \frac{0.0913}{608.85}$

Recall, the specific volume of wet steam, $V_{sp} = x \times V_g + (1\text{-}x)\ V_f$

$V_g = 0.194\ kg/m^3$ and $V_f = 0.001127\ kg/m^3$

Then, $0.000149 = x \times 0.194 + (1-x)0.001127 = 0.001127 + 0.194x - 0.001127x$

$0.000149 - 0.001127 = x\ (0.1928)$

$-0.000978 = x(0.1928)$

$\therefore x = \frac{-0.000978}{0.1928} = -0.0050726$

$\therefore$ x $= /-0.0050726/ = 0.0050726$

Where Enthalpy of saturated steam at 10 bar pressure at the steam outlet = h_o

$$h_o = h_{fo} + x(h_{fgo}) \quad (4.8)$$

Where $h_{fo} = 762.6\ kJ/kg$

$h_{fgo} = h_{go} - h_{fo} = 2776.2 - 762.6 = 2013.6\ kJ/kg$

$\therefore\ h_o = 762.6 + 0.0050726(2013.6) = 780.319\ kJ/kg$

$\Delta H = h_o - h_i$

Where, h_i = Enthalpy of water at the boiler inlet = $h_{fi} + x(h_{fgii})$ (5.0)

$h_{fi} = 104.9\ kJ/kg$

$h_{fgi} = h_{gi} - h_{fi} = 2547.2 - 104.9 = 2442.3\ kJ/kg$

$h_i = 104.9 + 0.0050726(\ 2442.3\ ) = 117.288\ kJ/kg$

$\Delta H = 780.319 - 117.88 = 662.439\ \ kJ/kg$

$\dot{Q}\ = 38.74\ kJ/s\ =\ \dot{m}\ \times\ 662.439\ \ kJ/kg$

$\rho_1 =$ Density of steam at 10bar pressure = 5.147 kg/m^3

Where Area of steam allowance in the vessel, $A_{sa} =\ A_1$ = 0.0759 m^2

And the height of steam allowance in the vessel, $\mathrm{h_{sa}} = \frac{1}{3} \times 1.203 = 0.401$ m

mass of steam, M_s = (5.147)(0.0304) = 0.1564 kg

$\dot{Q} = \frac{13{,}945\ \times 5}{30\ \times 60} = 38.74\ kJ/s$

$\dot{m} = \frac{38.74}{662.439} = 0.0585\ \ kg/s$

Figures 6 show the chimney and the boiler unit while figure7 depict the final picture of the assembled steam boiler.

Figure 6: The chimney and the boiler unit

Figure 7: Assembled Steam Boiler

The result of the steam generated by the steam boiler gives a dryness fraction in steam energy. The magnitude of dryness fraction is very essential in steam generation. Also, the steam generated dryness fraction is essential for the computation of enthalpy and entropy of the boiler system, which are useful parameters for evaluating the internal energy of the boiler as well as its gravimetric flow rate. Steam dryness is important because it has a direct effect on the total amount of transferable energy contained within the steam boiler. These factors affect the heating efficiency, quality of steam within the boiler, and power generation. Dryness fraction helps in determining whether the blade of a turbine in a power generating station will undergo cavitation or rusting, which can degrade the strength of the turbine blade and consequently reduce its overall efficiency for power generation. A high percentage of wet steam can spoil the food kept for preservation.

4. Conclusion

Developing countries, particularly Nigeria have raw materials waiting for harnessing to boost science and technology. In situations where job opportunities are scarce and most businesses at the brink of shutting down, it is necessary to revive and improve the power generation. The boiler developed will increase the science and technological aspect by not depending on the old ways of developing and operating boilers. This research reveals that, given the right working environment and necessary support, locally sourced raw materials are good for efficient design of boilers and serve as the basis upon which small and medium scale industries in Nigeria can thrive in terms of power generation, food processing, and preservation. Because the materials used are locally sourced, machine components and spare parts are cheap thus the developed boiler will be cost-effective.

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