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Development of a Mini Single-Tube Biomass Boiler

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Abstract

This paper reports the design and construction of a biomass boiler that can generate steam from locally available wood charcoal. Various parts of the boiler were designed using the ASME standard, and appropriate components for safety and measurement were selected. The boiler tube was a 58 liters capacity cylindrical vessel with hemispherical base with thickness of 6 mm, designed for maximum pressure of 15 bar. After construction, the designed boiler was tested by heating with wood charcoal with intention to identify the boiler response time. The new boiler performed satisfactorily.

Keywords: Charcoal; Boiler response time; Biomass.

1. Introduction

A Boiler is a closed vessel or an apparatus in which fluid (water) is heated to produce steam [1]. The steam generated by the boiler is used for three primary purposes, namely: Power generation, heating purposes and specific industrial processes. Development and utilization of steam generators date back to the late 17th century [2]. Currently, there are several boilers designs and classification. A good number of the different boiler types are discussed in the literature [3; 4]. The depletion of some energy sources and their adverse environmental effects has inspired recent research into developing biomass boilers [5]. Based on the form of energy source, there are different boilers categories, of which boilers that use fossil fuel is the most common [6; 7]. Biomass boilers are not very popular yet, but due to the high prospects, its patronage is rising. Currently, there are governmental policies that encourage its usage in certain countries [8].

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Although specific challenges such as fouling and long response time have limited the use of biomass boilers; there are fewer problems with the use of biomass for boiler fuels. First of all, energy storage is not a significant problem. Additionally, biomasses are available, cheap and easy to transport [9]. Despite the many positive sides, only a small proportion of world energy usage is biomass, estimated to be just thirteen per cent by [10]. There are, however, different types of biomass fuel: dung, municipal wastes, agro-waste and wood. The most common of which is wood.

Wood is widely consumed and produced globally for energy. As a biomass fuel, it is easy to process and used for energy generation [11; 12]. The energy value of wood ranges from about 8 to 21 MJ/Kg [12; 13; 14]. Wood could be burnt directly but can also be processed using other methods to produce heat. Being a newly introduced fuel, problems such as the frequency of supply and the optimum size of combustion chambers, discussed in the literature [9], are associated with burning wood for steam generation. Therefore, information that can contribute to the use of wood for boilers sustainably is being sought after.

In this work, a single vertical water-tube biomass boiler was designed and constructed from locally available materials. It was fired with wood charcoal and then the boiler response time was determined.

2. Materials and Methods

2.1. Material selection

The materials for this work were selected was based on the ASME standard for boiler design [15], cost and availability. Also, the temperature and strength were considered in selecting the material; this is in line with the recommendations for boiler designs [16]. Consequently, Dual phase DP 600 steel was used for the fabrication of the boiler shell while mild steel A36 was selected for the construction of the frame stand and other peripheral parts in the boiler. The mechanical and chemical properties of the selected steel are shown in Table 1 and Table 2, respectively.

Table 1: Mechanical Properties of DP 600 Steel

Property	**Value**	**Units**
Density	7594	kg/m^3
Young modulus	201.5	GPa
Thermal conductivity	34.8	W/m°C
Ultimate Tensile strength	564	MPa
Poisson ratio	0.4	N/A
Yield strength	400	MPa
Specific heat	520	J/(kg°C)

Table 2: Chemical Properties of DP 600 Steel

Element	**Symbol**	**Content**
Carbon,	C	0.06-0.15%
Copper	Cu	0.06%
Manganese	Mn	1.5-3%
Chromium	Cr	0.181%
Vanadium	V	0.044%
Silicon	Si	0.175%
Sulphur	S	≤0.050%

2.2. Design Considerations

i. The internal boiler shell

The dimension of the boiler pressure vessel were 310 mm diameter and 560 mm height, with hemispherical shape at the base and top.

According to the ASME standard, cylinder thickness is obtained using equation (1)

$$t = PD/(2 \times A.S + P) + 0.005D \qquad (1)$$

Where P is the design pressure (15 bar), D is the diameter of the cylinder (460mm), moreover, A.S = allowable stress which is obtained as;

$$Allowable\ stress = \frac{yield\ strength}{n} = \frac{400}{4} = 100 \text{ MPa}$$

Where yield strength of mild steel material is 2470bar

Where n is the factor of Safety (n).

$$t = \frac{15*10^5 \times 0.31}{2 \times 100*10^6 + 15*10^5} + 0.005 \times 0.31 = \frac{4.65*10^5}{2015*10^5} + 0.00155 = 0.003858 \text{ m} = 3.86\ mm$$

According to the ASME standards for designed thickness less than 6 mm, value of 6 mm should be used as the designed thickness; hence 6 mm was adopted for this work.

Volume of boiler pressure vessel

The volume of the cylindrical section of the boiler pressure vessel is calculated using equation (2).

$$V_{Boiler} = \pi r^2 h \quad (2)$$

The volume of the vessel calcualted with equation (1) is given as 42 dm^3. While volume of one hemisphere is calculated using equation (3):

Where, r = 155 mm and h = 560 mm; are the radius and height, respectively.

$$V_{Boiler} = 3.142 \times 155^2 \times 560 = 42{,}000{,}000 mm^3 = 42\ dm^3$$

The volume of the hemispherical cap at the top and base is computed as;

$$V_s = \frac{2}{3}\pi r^3$$

$$V_s = \frac{2}{3} * \frac{22}{7} * 155^3 = 7{,}804{,}404\ mm^3 = 7.8\ dm^3 \quad (3)$$

The total volume of the boiler = volume of cylinder + volume of spherical heads

$Total\ Volume_{boiler} = 42 + 2 * 7.8 = 57.6\ dm^3$ = 58 litres

i. External vessel of boiler

This is the part that covers the entire boiler, housing the boiler pressure vessel. It was designed to have a conical top for easy movement of effluent gasses through the exhaust stack after combustion.

A plate of 460 mm diameter and length 715mm was used. The shell volume of the boiler tube is determined as;

$$V_{cylinder} = \pi r^2 h = 119\ dm^3 \quad (4)$$

Where V is the volume of the cylinder, r is the inner radius in mm (230mm), h is the height of the shell (715mm).

The diameter of the cone is the same as that of the inner boiler tube. The volume of the cone is calculated using equation 5. "r" is the radius of the cone which is the same as that of the vessel (230 mm). h_c is the height of the cone which was taken as 280 mm.

$$V_{cone} = \frac{1}{3}\pi r^2 h_c \quad (5)$$

Where, $\pi = 3.142, r = 230mm, h = 280mm, V_{cone}$ =0.015513 $m^3 = 15.51\ dm^3$

The total volume of the combustion chamber

$$V_{total} = V_{cylinder} + V_{conical} = 134354538.33 mm^3 = 134\ dm^3 \quad (6)$$

ii. Heat Losses using Rock Wool as Lagging Material

Rock wool was selected as lagging material due to it's capable of preventing heat loss for a long time without deformation and availability. It has a thermal conductivity of 0.045 W/mk. Diameter of the boiler vessel is given as 460 mm while a thickness of 6 mm was chosen for lagging. This results in an external plate covering of diameter 472 mm. It is expected that the inside temperature would be maintained at about 202℃, noting that the pressure is 15 bar while the outside temperature is assumed to be 30℃, being the average atmospheric temperature in the area. The heat loss through a cylindrical wall is calculated using equation 13, as obtained in the literature [19; 20]

$$Q = (2\pi L(t\_1 - t\_3))/(In(r\_2/r\_1)/k\_A \ + In(r\_3/r\_2)/k \tag{7}$$

Neglecting the resistance offered by mild steel, the heat transfer rate across the tube results in equation 8.

$$Q = (2\pi L(t\_1 - t\_3))/((In(r\_3/r\_2))/k\_B) \tag{8}$$

$$r1 = 460/2 = 130mm\ or\ 0.13m \tag{9}$$

$$r2 = 472/2 = 236mm\ or\ 0.236m \tag{11}$$

$$r_3 = r_1 + r_2 = 130 + 236 = 366mm\ or\ 0.366m \tag{12}$$

$$Q = (2 \times 3.142 \times 0.28(202 - 30))/(In(0.236/0.230)/0.045) = 528.830\ W/Sec \tag{13}$$

iii. Nozzle design Calculation

To increase the velocity of the steam output to a value of a proposed turbine blade rotation, the convergent nozzle was selected. The flow of steam through the nozzle is assumed to be compressible and adiabatic.

(a) The velocity of the steam flowing through the nozzle

The design pressure (P_1) of the boiler is $1.5 \times 10^6\ N/mm^2$. The adiabatic constant for superheated steam is 1.4, an exit pressure (P_2) of $1.4 \times 10^6\ N/mm^2$ was selected (as suitable for a locally developed turbine application). The density of steam (ρ_1) at the operating pressure of 15 bars is $7.596\ kg/mm^3$ (from steam tables). As derived in the literature [17; 18], the steam exit velocity v_2 was determined using equation (14).

$$V\_2 = \surd(2\gamma/(\gamma - 1) \times P\_1/\rho\_1 \ \times 1 - (P\_2/P\_1)\text{^}((\gamma - 1)/\gamma)) \tag{14}$$

$$V_2 = \sqrt{\frac{2\times1.4}{1.4-1} \times \frac{1.5\times10^6}{7.596} \times 1 - \left(\frac{1.4\times10^6}{1.5\times10^6}\right)^{\frac{1.4-1}{1.4}}} = 115.429\ m/s$$

(b) The Area of the Exit Nozzle (A_2)

For suitable turbine application, the mass flow rate of the steam flowing through the pipe is assumed as $0.25 m^3/s$. Equation (16) as adopted from the literature [19] governs the mass flow rate and nozzle area of the boiler, and was therefore used to determine the area of the nozzle.

$$\dot{m} = A\_2 \left(\sqrt{}(2\gamma/(\gamma-1)\ P\_1\ \rho\_1\ [(P\_2/P\_1)\hat{}(2/\gamma) - (P\_2/P\_1)\hat{}((\gamma+1)/\gamma)\ ]\ )\right) \tag{15}$$

$$A\_2 = \dot{m}/((\sqrt{}(2\gamma/(\gamma-1)\ P\_1\ \rho\_1\ [(P\_2/P\_1)\hat{}(2/\gamma) - (P\_2/P\_1)\hat{}((\gamma+1)/\gamma)\ ]\ ))\ ) \tag{16}$$

$$A_2 = \frac{0.25}{\left(\sqrt{\frac{2\times1.4}{1.4-1}\times15\times10^5\times7.596\left[\left(\frac{14.5}{15}\right)^{\frac{2}{1.4}}-\left(\frac{14.5}{15}\right)^{\frac{1.4+1}{1.4}}\right]}\right)} = \frac{0.25}{855.8456} = 2.9212\times10^4 m^2$$

(c) The diameter of the Nozzle d_2

$$A_2 = \pi {r_2}^2 \tag{18}$$

$$r\_2 = \sqrt{}(A\_2/\pi) = \sqrt{\frac{2.9212\times10^{-4}}{3.142}} = 9.6422\times10^{-3} m$$

$$d_2 = 2r_2 = 2\times9.6422\times10^{-3} = 0.01928\ m\ or\ 19.28\ mm$$

2.3. Selection of Measurement component

The pressure gauge: A 10-bar bourdon pressure gauge in Figure 1 was selected as it meets the design requirements, which measures the exit pressure of steam.

Figure 1: Bourdon Pressure Gauge

Gate valve: the gate valve controls the flow of steam out of the turbine. It is a 2" brass stopcock gate valve shown in Figure 2. Its cost, fitting capability, availability and corrosion resistance influenced the selection.

Figure 2: Selected Stopcock Gate Valve

Pressure relief valve: A safety valve to control or limit the pressure in the system to the designed operating pressure of 15 bars was selected. It is shown in Figure 3.

Figure 2: Selected Pressure Safety Valve

2.4. Engineering Drawings of the Designed Boiler

Figure 4 is the two-dimensional view of a boiler in an AutoCAD environment. Figure 5 and 6 show the exploded and assembly view, respectively, of the designed boiler.

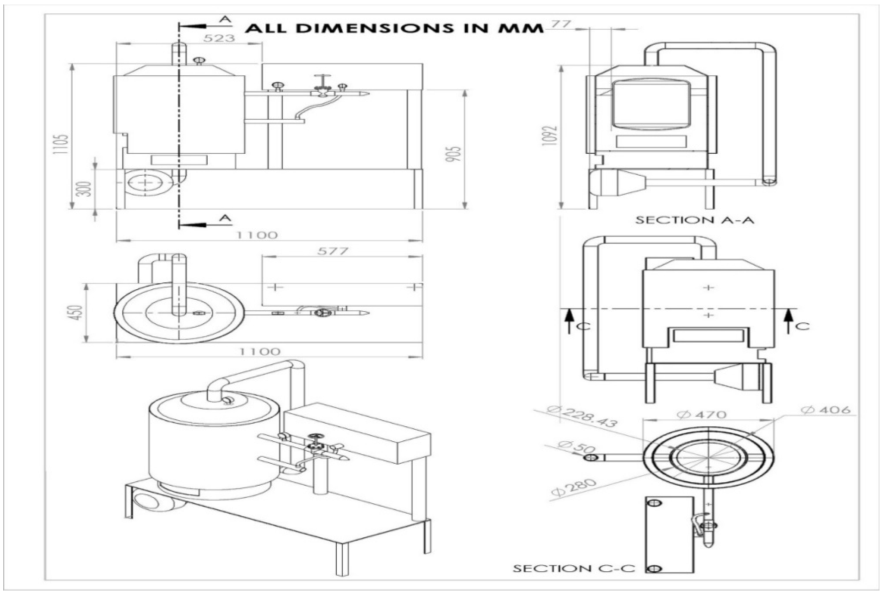

Figure 4: The two-dimensional view of the boiler

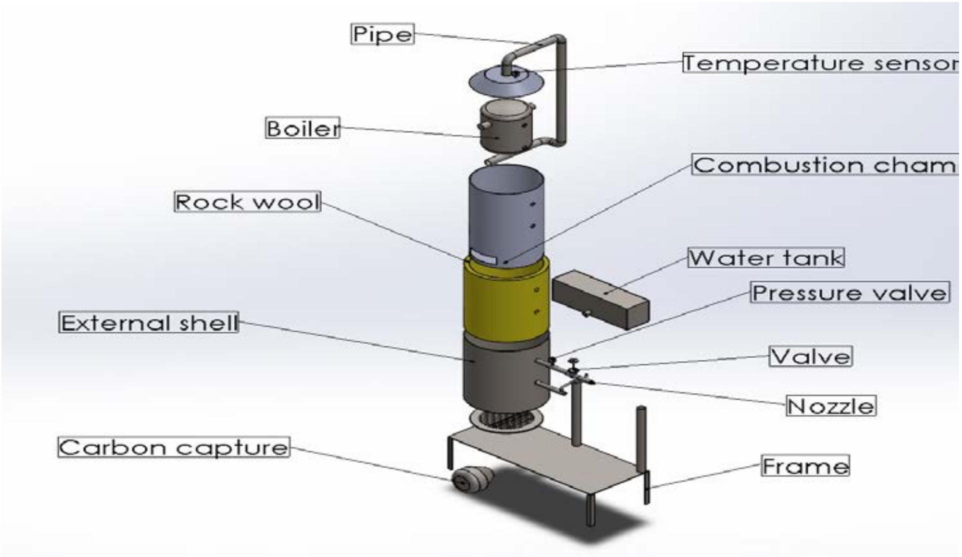

Figure 5: Exploded View the boiler

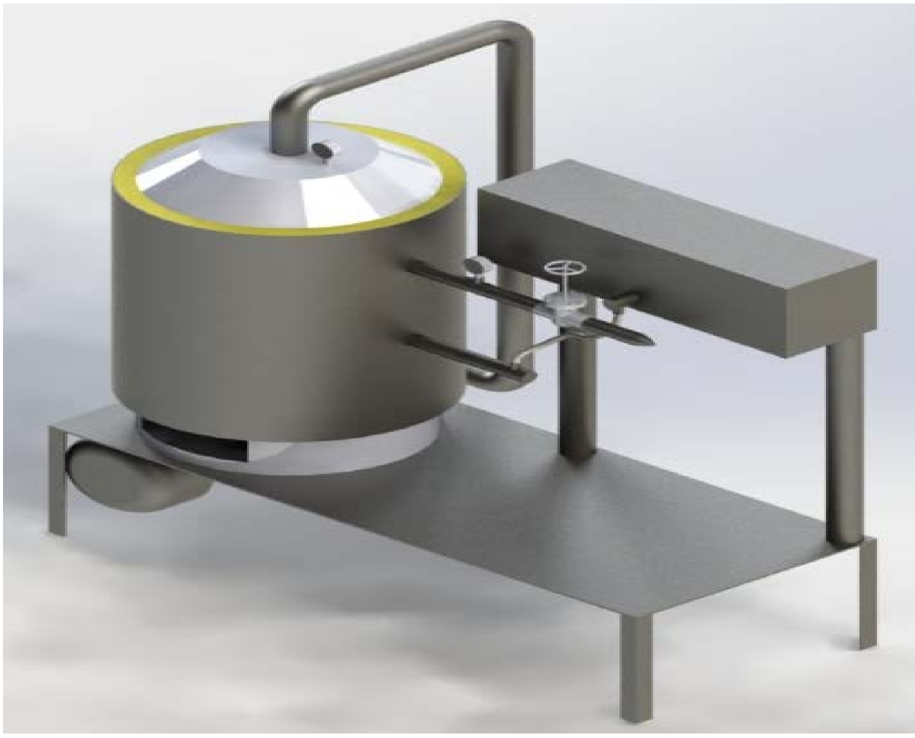

Figure 6: Assembly View of the boiler

Fabrication and testing of the Boiler

The fabricated boiler was carried out in-line with the ASME standards for boiler design. The fabricated boiler is shown in Figure 7. The boiler was constructed based on the following dimensions.

The volume of the external shell = 118841437mm^3

The volume of the conical cover of the shell = 15513101.33mm^3

The total volume of the combustion chamber = 134354538mm^3

The total volume of the boiler = 24874166.67mm^3 = 25 Litres

The thickness of the shell = 6mm

The velocity of steam flowing through the nozzle = 115m/s

The diameter of the exit nozzle = 19.28mm

Diameter of the cylinder = 520mm

Height of the cylinder = 675mm

The thickness of lagging material= 25.4mm

Figure 7: The fabricated boiler

TESTING

The test procedure of the fabricated boiler involves the following process: Firstly, 11 litres of water was supplied into the boiler. The combustion chamber of the boiler was then loaded with a 2.5 kg of wood charcoal obtained at the Effurun market, in Delta State. It was heated with the burning charcoal, and then the corresponding temperature and pressure were measured over the heating period. After the first mass of charcoal was supplied, a total of 2.5 Kg was added gradually as the heating progressed. The internal temperature of the boiler was observed with a thermometer attached to the conical head of the boiler and recorded at 10 minutes' interval while the external surface temperature of the boiler was assessed via physical touch. Also, the time pressure was first released via the relief valve was noted and identified as the boiler response time, as this is the time that the pressure reached the operating pressure of the boiler.

3. Results and Discussions

The boiler was heated for 2 hours. The temperature of the outer boiler surface was about that of the environment when observed via physical touch. The measured temperature of the heating area inside the boiler observed on ten munites intervals is shown in Figure 8. The last mass of charcoal fire started dying out after about 135 minutes of heating.

As shown in Figure 8, the temperature rose gradually from 150^0C after 10 minutes of heating to a maximum temperature of 400^0C, after 2 hours of heating. As a result, the temperature dropped steadily after it reached its peak of 400^0C at 120 minutes. The first pressure relief occurred at 110 minutes of heating, indicating that the pressure of steam inside the boiler vessel was about 10 bars. As at that time, the temperature of heating around the shell was about 350^0C.

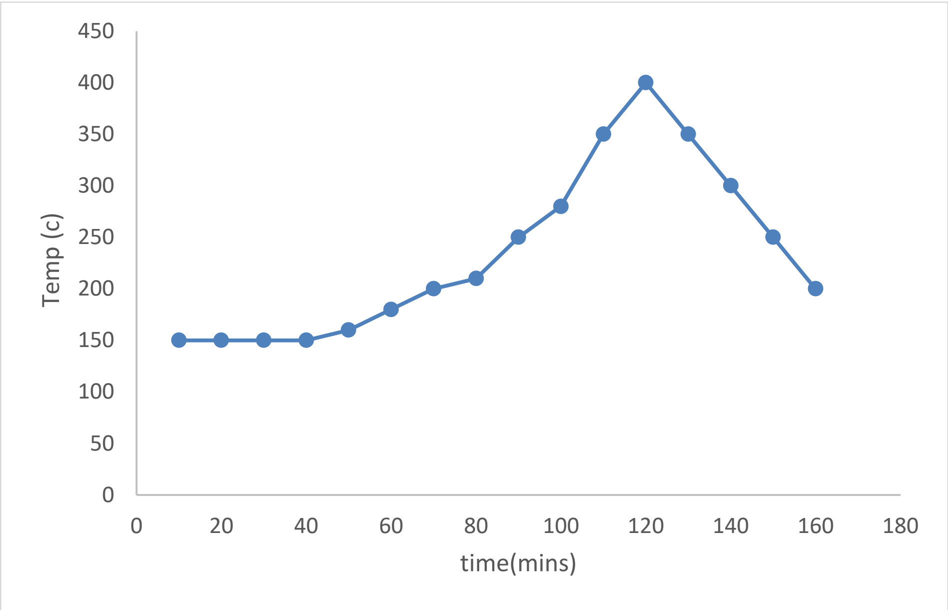

Figure 8: Graph of Temperature against Time

4. Conclusion and recommendation

4.1. Conclusion

A miniature boiler was developed. The design and construction details were presented. The boiler was fired with wood charcoal. Although the response time was low, steam was generated. Steam pressure measured was up to 10 bar which is its operational pressure. The developed boiler can be used safely, as the temperature of the outer shell does not differ much from that of that of ambient and the safety relief valve was found effective. Ultimately, the boiler can be scaled up for industrial application. It is however recommended that a super-effluent carbon capture device should be incorporated into the system to help trap the emission of effluent gases.

4.2. Recommendation

It is recommended that a super-effluent carbon capture device should be incorporated in the system to help trap the emission of effluent gases. Also, it is important that the exhaust gasses from the boiler be analyzed to ascertain its constituent.

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