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Design Analysis of a Miniature Steam Boiler for the Generation of Steam

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Abstract

Current research into renewable energy sources, energy efficiency techniques, and cutting-edge technologies is intense among governments, corporations, and the scientific community to meet the world's energy needs while mitigating the impact of human activities on the environment. A design analysis of a small steam boiler for steam generation was done in this work. Along with the creation of a conceptual design, specifications, and design considerations were produced. The permitted expansion stress range, minimum pipe wall thickness, cylindrical steam boiler characteristics, and minimum cylinder wall thickness were all established. The minimum thickness (t) of the cylindrical steam boiler was determined to be 2.0815 mm. Nonetheless, when a factor of safety of 1.5 and a 0.9 mm allowance for corrosion is incorporated, the actual thickness of the cylindrical vessel employed becomes 4.02 mm. The minimum wall thickness of the pipe was 1.5 mm. In addition, a design temperature of 426 °C and an ambient temperature of 32 °C were chosen. It was calculated that the allowable expansion stress range was 166.1 MPa. When the steam spring relief valve was calibrated, the force at which pressure was released was measured and the result was 312.4 N.

1.0. Introduction

As the world's energy needs and environmental concerns continue to rise, there is an increasing need for effective and sustainable energy solutions [1-4]. The world is at a turning point when energy demands are only going to increase due to the world's booming industrialization and ever-growing population [5]. Climate change has gotten worse as a result of this increase in energy use, which is mostly driven by conventional fossil fuels [6]. Increases in greenhouse gas emissions, especially carbon dioxide from burning fossil fuels, have had unfavorable effects on the environment, including rising global temperatures, an increase in the frequency and intensity of extreme weather, and damage to ecosystems [7]. The urgent need to stop these negative effects is causing a paradigm change in favor of low-carbon and sustainable energy sources. To solve the twin problems of meeting growing energy demands while reducing the effect of human activity on the climate, governments, businesses, and the scientific community are currently ardently investigating renewable energy sources, energy efficiency strategies, and cutting-edge technology [8-10]. The convergence of global energy dynamics worries about climate change, and the need to reduce emissions has emerged as a key area for international collaboration and coordinated efforts to create a future that is more robust and sustainable [11].

An enclosed vessel used to heat water is called a steam boiler. The heat can then be transferred to the final user using the steam that is under pressure [12-14]. The development of the plain-cylinder boiler resulted in the creation of the first boiler. Since then, several attempts have been made to alter the boiler only to better suit its intended use. In a review paper, [15] conducted a thorough investigation into the design and analysis of Lancashire boilers. A dry steam boiler with an electrically powered superheater was built [16]. To clarify the main components of a boiler, [17] projected the laboratory steam boiler developed from the basic physical geometry of a fire-tube boiler. A comprehensive dynamic model of a full-scale fire-tube boiler was created by [18] including constitutional equations in addition to mass, energy, and momentum balances. [19] research on the design, construction, and performance evaluation of an electric steam boiler. They aimed to improve an existing steam boiler through the incorporation of a heating element and a thermostat. However, in this present study, we conducted a design analysis of a miniature steam boiler for the generation of steam to create a small-scale steam boiler for laboratory demonstration and to act as a source of steam generation at the Igbinedion University Okada, College of Engineering laboratory.

2.0. Material and Methods

2.1. Conceptualization

Figure 1 illustrates the heat flow via the proposed steam boiler's circular wall structure. With this configuration, air circulating the cylindrical steam boiler's wall boundaries is sucked in by suction into the boiler's side entrance, where it enters the combustion chamber. The air surrounding the boiler is attracted into the combustion chamber because heated air rises since it is less dense than cold air. Additionally, the boiler's feed water receives energy from the hot air to boil. Red clay and wood sawdust are the materials utilized as insulators; nevertheless, in terms of the direction of hot air movement, sawdusts with lower thermal conductivity were employed initially. The second layer is similarly made of red clay, with insulation that is 25 mm thick.

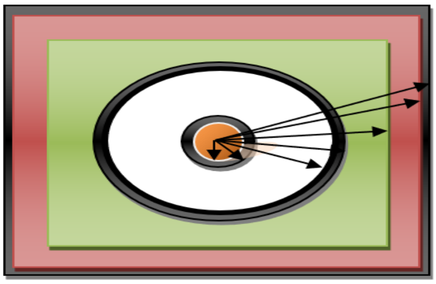

Figure 1: Heat flow through cylindrical wall arrangement

2.2. Design Consideration and Specification

One of the shaping techniques needed for the steam boiler's construction is bending. In essence, bending the metal to fit the drum is standard procedure. This is widely used for a variety of reasons, including cost savings and failure prevention if all angles need to be welded. Bending is the homogeneous stretching of metal, usually in the shape of a strip or flat sheet, as in this instance, around a straight axis perpendicular to the sheet's length-wise direction that is in the neutral plane. After the applied tension is removed, metal flow occurs within the metal's plastic range, resulting in a permanent bending strain. The bending's outside surface is under tension and its inner surface is in compression. The precise shape of the punch and die in the metal cannot be replicated by a simple bending movement. The plane area in bent metal where there are no strains at all is known as the neutral axis. Two main elements determine how severely a material may be bent:

i. The radius of the bend
ii. The thickness of the material

2.3. Determination of Minimum Wall Thickness of Cylinder

The longitudinal segment ABCD is where the cylinder fracture will happen. The resistive force in the plate section along AD and BC is depicted in Figure 2.

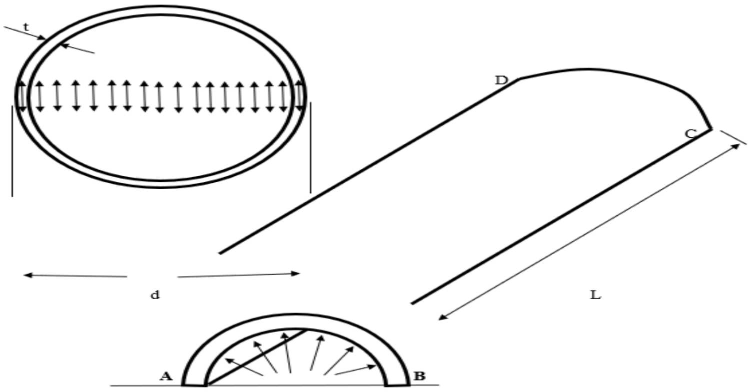

Figure 2: Resisting force

The internal bursting force is given by Equation (1).
Internal bursting force = resisting force offered by plate section along AD and BC

$$P \times d \times L = 2 \times t \times L \times SE \tag{1}$$

Thus,

$$t = \frac{\mathrm{pdL}}{2LSE} = \frac{\mathrm{pd}}{2SE} \tag{2}$$

$$\mathrm{t} = \frac{\mathrm{pd}}{2SE} \tag{3}$$

where,
SE = Circumferential or hoop stress for the material of the cylindrical shell
t = thickness of the cylindrical shell
L = length of the cylindrical
P = intensity of internal pressure

2.4. Determination of the Parameters of the Cylindrical Steam Boiler

The circumference of the cylinder is given by Equation (4) while the volume of the cylinder drum is given by Equation (5). Also, the total volume of the cylindrical drum is given by Equation (6).

$$C = \pi D \tag{4}$$

$$V = \pi r^2 H \tag{5}$$

$$V_T = \pi R^2 H - \pi r^2 H \tag{6}$$

Where;
D = Diameter of the cylinder
H = Height of the cylindrical drum
r = Radius of the cylinder

2.5. Selection of Steam Pipe for the Steam Boiler

The ASTM dimensions standards and material criteria were followed in the selection of all the pipes. Furthermore, all wall thicknesses and diameters meet all application codes when taking into account the two most widely used piping codes (B31.1 and B31.3, respectively). Power piping code B31.1 was taken into consideration for the design and, consequently, the pipe selection for this steam boiler design.

2.6. Determination of Minimum Wall Thickness of Pipe

The minimum wall thickness of the pipe is determined using equations (7) and (8).

$$t_m = \frac{pD}{2(SE+Py)} + A \tag{7}$$

$$t_m = \frac{pD+2SEA+2yPA}{2(SE+Py-P)} + A \tag{8}$$

where,

t_m = Minimum wall thickness (mm)

P = Internal design pressure (kPa)

D = Outer diameter of pipe as given in tables of standard and specification (mm)

d = Inside diameter of pipe (mm)

SE = Maximum allowance stress for materials and joint efficiency at design temperature (kPa)

A = additional thickness to provide for threading, grooving, corrosion, erosion, mechanical strength, etc. (mm)

y = Coefficient

2.7. Determination of Allowable Expansion Stress Range

For the B31.1 codes to be effectively utilized, Equation (9) should be satisfied;

$$S_A = f\,(1.25S_c + 0.25S_h) \tag{9}$$

where,

S_A = Allowable expansion stress range,

S_c = Allowable stress for piping material at cold conditions which include cryogenic services, or ambient installation temperature for elevated temperature service,

S_h= Allowable stress for piping material at the hot operating temperature which would be the design temperature for elevated temperature service or ambient for cold or cryogenic services, and

f = A factor depending on the number of heating cycles that the pipe will undergo in its life.

However, the stress range factor is used mainly to account for fatigue as shown in Equation (10)

$$f = 6 / N^{0.2} \tag{10}$$

where,

N = Equivalent number of full displacement cycles. But, if f > 1.0. Then S_c and S_h shall be limited to 138 MPa.

2.8. Calibration of Spring Relief Valve of Steam

The pressure relief valve is determined using Equation (11).

$$\text{Pressure (P)} = \frac{Force(F)}{Area(A)} \tag{11}$$

2.9. Heat Transfer Analysis

The conduction of heat in the solids is partly due to the impact of adjacent molecules that vibrate internal radiation. The heat will now flow from the hotter end to the coldest end. The greater the temperature difference, the faster the heat will flow. The quantity of heat flow is given by Equation (12). Convection occurs when a solid surface is in contact with a fluid of a different temperature from the surface, and it can be evaluated using Equation (13). When an object gives off some radiation, then the energy stored in the object must decrease by the amount of energy given off by the radiation. The total radioactive flux throughout the hemisphere from the black surface of area "Ay" and the absolute temperature T is given by the Stefan- Boltzmann law as shown in Equation (14).

$$Q = \frac{KADT}{DX} \tag{12}$$

$$Q = hA_1(T_2 - T_1) \tag{13}$$

$$Q_y = A_yT^4 \tag{14}$$

where,
Q = The rate of heat flows in KW
K = Thermal conductivity of the material (W/mk)
DT = Temperature difference between the surfaces of metal
DX = Thickness of the material (m)
A = Area of the section at the right angle
A_1 = Area of surfaces not perpendicular to the direction of heat flow
h = Coefficient of corrective heat transfer
$T_2 – T_1$ = Temperature difference
Q_y =Heat flux, energy per Time.
A_y =Area of heat flux intensity.
σ =Stefan Boltzmann constant (5.67 x 10-8) 10/m2 (K4)
T=Absolute Temperature.

2.10. Determination of the Calorific Value of the Wood Waste for Combustion

Equation (15) [20] was utilized in the bomb calorimeter experiment to quantify the gross heat of combustion, and as a result, the calorific value for burning the wood waste was found. The calorimeter and the surrounding water absorbed the heat that the fuel released during combustion.

$$Cv\ (kJ/kg) == \frac{C\Delta T-(e_1+e_2+e_3)}{m} \tag{15}$$

where,
Cv = Calorific value of fuel in kJ/kg
△T = Change in temperature, m
m = Mass of samples (g)
C = Heat capacity of bomb calorimeter
e1, e2, e3 = Corrections for the formation of nitric acid, sulphuric acid, and fuse wire.

2.11. Determination of Percentage Moisture Content

The moisture content of each wood waste sample was calculated using Equation (16) based on the weight change after oven drying.

$$Mc = \frac{\Delta W}{W} \times 100\% \tag{16}$$

where,
MC = Moisture content,
△W = Change in weight of sample
W = Original weight of sample

2.12. Determination of Steam Boiler Efficiency

Equation (17) provides the steam boiler efficiency, which is the ratio of heat used in steam generation to the heat provided by fuel.

$$\eta = \frac{M_a(h-h_f)}{Cv} \qquad (17)$$

where,

η = Steam boiler efficiency
Ma = Mass of water actually evaporated into steam per kg of fuel at the working pressure
h = Specific enthalpy of steam
hf= Specific enthalpy of feed water
Cv = calorific value of fuel

2.13. Material Specification

Table 1 shows the material specification.

Table 1: Material specification

S/N	*Specification*	*Basis*	*Justification*	*Quantification*
1	The outer rectangular covering box is mild steel	To make it rigid	To withstand high pressure	400 mm x 400 mm x 400 mm
2	The inner cylindrical drum is high-carbon steel	To heat up fast	High thermal heating	$\emptyset 310\ mm$
3	The boiler should have wood sawdust insulation	Low thermal conductivity	Retention of more heat within the compartment	N/A
4	The frame supporting the boiler is mild steel	To make it rigid	To withstand high pressure	N/A
5	Steam pipes are Carbon steel designed to ASME B16.9 A106	High tensile strength	Creep resistance at high temperature	$\emptyset 15\ mm$
6	Chimney pipe is galvanized steel	To heat up faster	Thermal capacity	$\emptyset 50\ mm$
7	Ball valves are cast iron	To withstand high pressure	High strength	N/A
8	The frame support is provided with two rollers	To carry the weight of the boiler	Easy movement of the boiler from one location to another	N/A
9	Thermometer	Temperature measurement	To measure temperature ranges of 0^0 C -650 ^{0}C	One (1) piece
10	Barometer	Pressure gauge	To measure pressure range of 1bar – 18bar	One (1) piece
11	Pressure relief valve	For safety of the boiler and boiler operator	Relief pressure at 10 bar	One (1) piece

2.14. Machine Configuration

Figures 3 and 4 show the working drawing and isometric view of the miniature steam boiler for the generation of steam. Figure 5 shows a picture of the developed miniature steam boiler for the generation of steam.

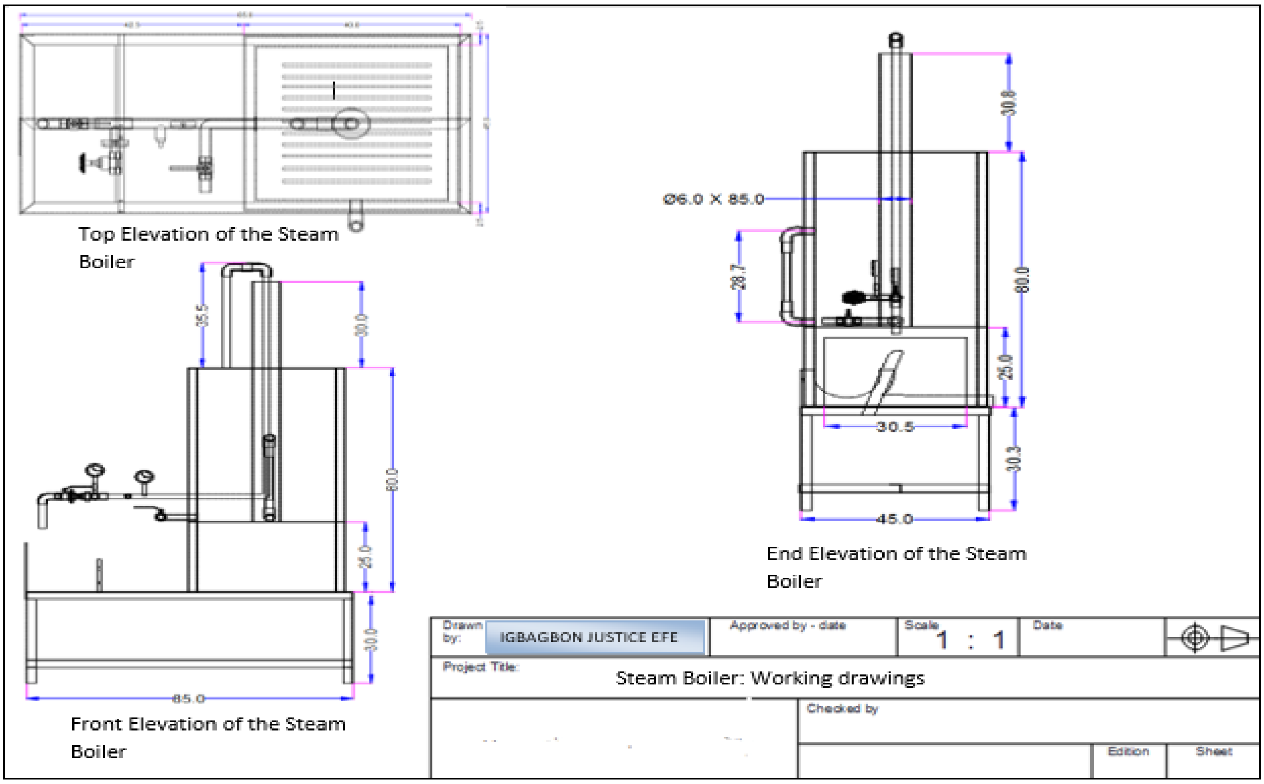

Figure 3: Working drawing of the miniature steam boiler for generation of steam

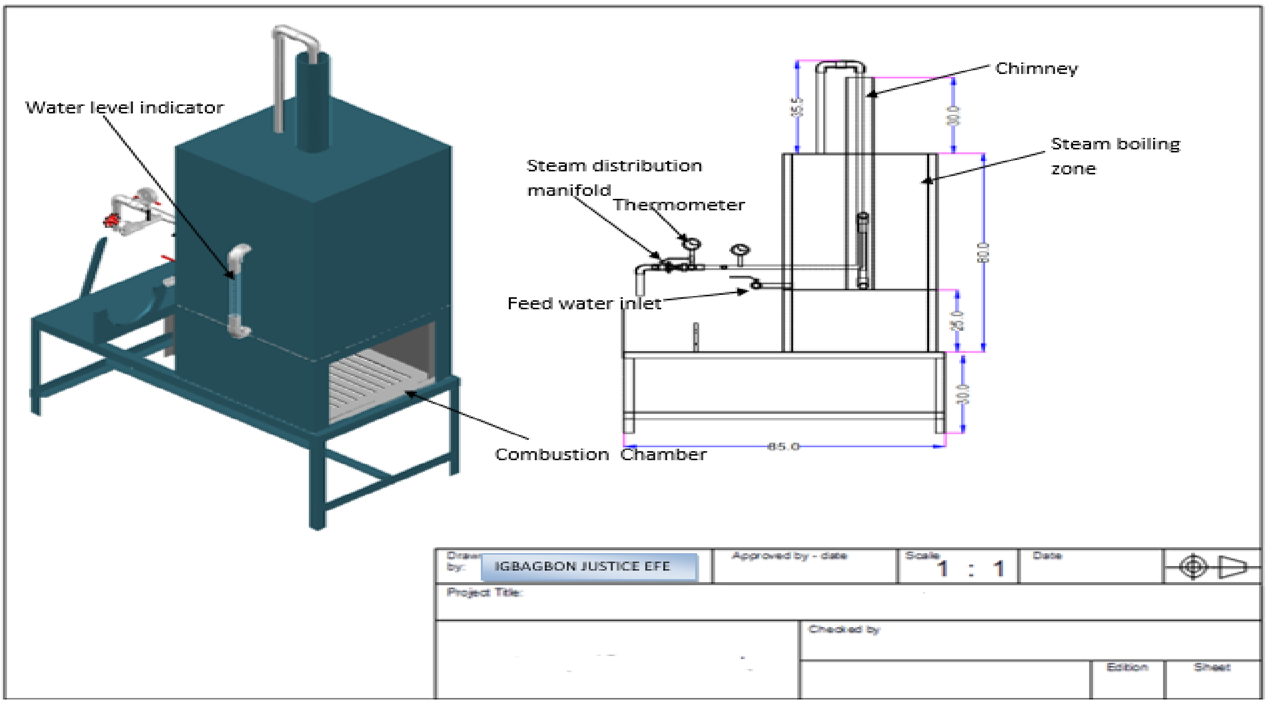

Figure 4: Isometric view of the miniature steam boiler for generation of steam

Figure 5: Picture of the developed miniature steam boiler for the generation of steam

3.0. Results and Discussion

The fundamental objective of the steam boiler's conceptual design was to provide a functional boiler that was inexpensive, safe, simple to maintain, and practical. To accomplish the design objective, we created the main boiler components, which include the cylindrical vessel. The minimum thickness (t) of the cylindrical steam boiler was determined to be 2.0815 mm. Nonetheless, to guarantee end-user safety and increase the cylindrical vessel's usable life, a factor of safety of 1.5 was used. Furthermore, when a 0.9 mm allowance for corrosion is incorporated, the actual thickness of the cylindrical vessel employed becomes 4.02 mm. Phase-by-phase nominal diameter-designated pipe diameters are offered. Each pipework component is built by ASTM specifications for dimensions, needs, and material specifications. The design and/or pipe selection in this study made use of every size and wall thickness that complied with code B31.1. For the design and/or pipe selection in this inquiry, power piping code B31.1 was utilized. According to ASME B16.9 A106, carbon steel is commonly used for steam system pipes.

Furthermore, for a seamless, longitudinally welded, spirally welded, straight pipe operating below the creep range and under internal pressure, the minimum pipe wall thickness needed for design pressure and temperature did not go above what was allowed for the different materials as recommended in the B31.1 code's acceptable stress table for power piping and the B31.3 code's admissible stress table for process piping, including consideration for mechanical strength. Equations (7) and (8) were used to determine the pipe's minimum wall thickness and the result obtained was 1.5 mm and this was in line with the research work of [15, 17]. To account for fatigue, the stress range factor was incorporated in determining the allowed expansion stress range. Moreover, a design temperature of 426 ⁰C and an ambient temperature of 32 ⁰C were selected because the pipe will be constructed using carbon steel that meets ASTM A106 grade seamless specifications. A computed acceptable expansion stress range of 166.1 MPa was determined. The force at which pressure is released was measured during the calibration of the steam spring relief valve, and 312.4 N was the result. Table 2 displays the findings of the experimental test evaluation conducted on the successfully designed steam boiler utilizing a 2 kg sample of Ekki (*Lophira alata*) wood waste.

Table 2: Results of experimental test evaluation

S/N	Mass of Wood Waste (kg)	Pressure (Bar)	Temperature (⁰C)
1	2.00	11.50	215.00
2	2.15	12.31	215.00
3	2.20	12.61	215.03
4	2.30	13.20	215.04
5	2.40	13.75	215.02
6	2.55	14.62	215.03
7	2.68	15.41	215.01
8	2.70	15.51	215.00
9	2.85	16.39	215.02
10	2.90	16.63	215.01
∑	24.73	141.93	2150.16
Mean	2.473	14.193	215.016
Variance	0.095846	3.183312	0.000204
Standard Deviation	0.309589	1.784184	0.014298

With the Lophira alata wood sample, a minimum percentage moisture content of 6.95% was obtained. According to [21-23], relatively low moisture content promotes thermochemical conversion, since excessive moisture content lowers conversion system efficiency and, consequently, lowers the energy available from wood wastes during combustion since heat would be needed to evaporate them. Additionally, the calorific value of 19.99 MJ/kg was obtained for Lophira alata, indicating good energy content; this result is consistent with the research work of [21].

Steam is generated at an average pressure and temperature of 14.193 bar and 215.016 ⁰C, respectively, according to data collected for the pressure and temperature after ten (10) test sessions, as shown in Table 2 and Figure 6. This value was higher than the steam pressure of 1.5 bar and a steam temperature of 111.40 °C reported by [14]. These readings were below the permitted expansion stress range of 166.1 MPa and the design temperature of 426 ⁰Cand this was an indication of a good design. The mass of wood waste, pressure, and temperature all had low standard deviations (SD) as shown in Table 2, which suggests that the data are more reliably clustered around the mean. Although the mean indicates the value at the center of the distribution, it does not show the distance between the data points and the center. Greater standard deviation values indicate that more data points deviate from the mean. Smaller values show that the dataset's values are often consistent—the data points cluster closer to the mean.

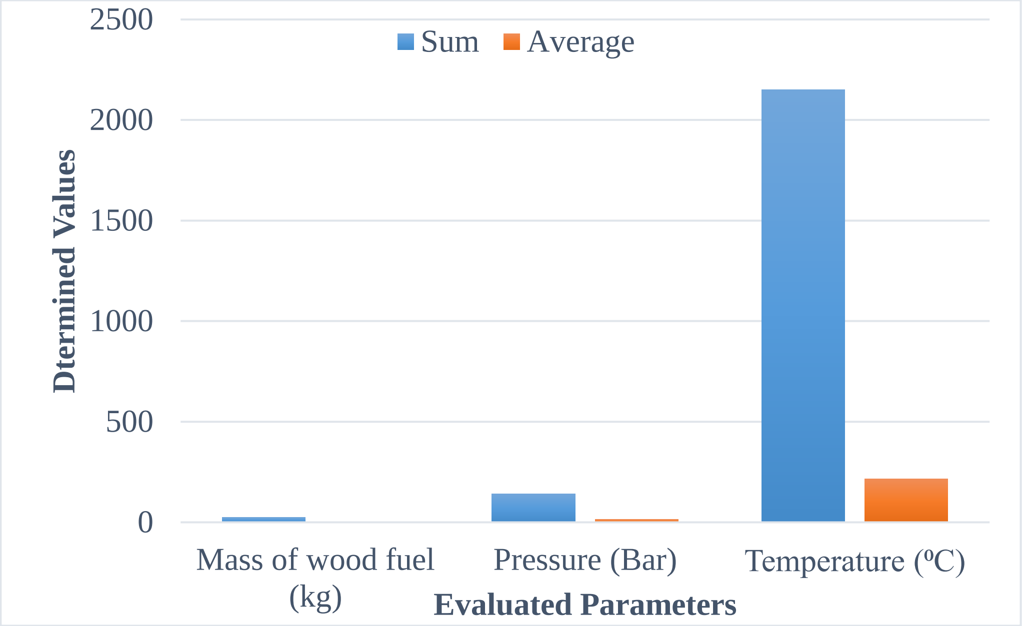

Figure 6: Evaluation of sum and average wood waste, pressure and temperature

Besides, it was found that variations in the fraction of wood waste generated more steam, which was reflected in an increase in pressure. The temperature difference was, however, essentially insignificant. Above and beyond, the boiler's efficiency was determined to be 90.33% based on the collected data and this was higher than the boiler efficiency of 69% reported by [14].

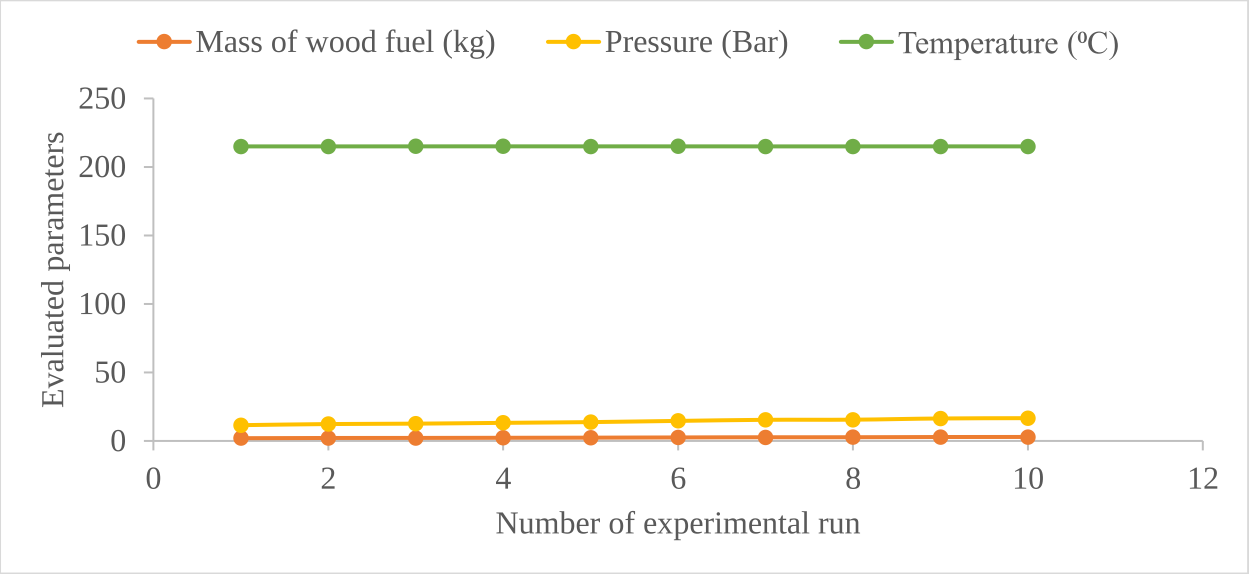

Figure 7: Evaluation of variation wood waste on pressure and temperature of steam

4.0. Conclusion

A small steam boiler was effectively designed in this study. In this setup, air that is blowing past the walls of the cylindrical steam boiler is drawn in by suction and sent into the boiler's side entrance, where it is released into the combustion chamber. The minimum thickness (t) of the cylindrical steam boiler was determined to be 2.0815 mm. Nonetheless, to guarantee end-user safety and increase the cylindrical vessel's usable life, a factor of safety of 1.5 was used. When a 0.9 mm allowance for corrosion is incorporated, the actual thickness of the cylindrical vessel employed becomes 4.02 mm. In addition, since ASTM A106-grade seamless carbon steel will be used in the construction of the pipe, a design temperature of 426 °C and an ambient temperature of 32 °C were chosen. It was calculated that the allowable expansion stress range was 166.1 MPa. When the steam spring relief valve was calibrated, the force at which pressure was released was measured and the result was 312.4 N. These measurements were below the allowable expansion stress range of 166.1 MPa and the design temperature of 426 °C. Steam is generated at an average pressure and temperature of 14.193 bar and 215.016 °C. When the designed miniature steam boiler was tested, higher efficiency was obtained when compared with the already existing one. Therefore, it can be deduced that the designed miniature steam boiler for the generation of steam can be operated with optimum efficiency when compared with the existing one.

Declaration of Competing Interest

The authors declare no competing financial interests or personal relationships that could have appeared to impact the work reported in this paper.

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