Full Paper

THE EVALUATION OF THE POWER OUTPUT OF A LOCALLY-DEVELOPED MICRO THERMAL POWER PLANT IN NIGERIA

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ABSTRACT

The erratic supply of electricity has been a fundamental problem confronting industrial development in Nigeria. Hence, the development of off-grid indigenous thermal power plant using local content approach has become necessary. In this study, a new prototype thermal power plant was developed, installed, and evaluated by considering three independent factors, biomass utility (20, 25, 30 kg), steam inlet pressure (5, 7.5, 10 bar), and steam flow-rate (120, 195, 270 cm^3/sec). The Box-Behnken design tool of Design Expert 12.1 was adopted to generate seventeen runs of experiment. The experimental data were optimized using Response Surface Methodology and validated using Desirability contour plots. The results showed that the thermal plant generated electrical power of 1.2 kW with thermal efficiency of 51.25%. The experimental results and predicted Response Surface Methodology plots postulate run 9 as the optimum, with corresponding factors and responses of 25 kg, 10 bar, and 270 cms^{-1} producing 245.5 V and 4.72 A for biomass utility, steam inlet pressure, flow-rate and voltage and current, respectively. The desirability model was used to validates Response Surface Methodology plots having resultant variables of 25.04 kg, 10 bar, and 270 cm^3/sec; 244.90 V and 4.60 A for biomass utility, steam inlet pressure, and steam flow rate; voltage and current, respectively at the desirability of 1.0. Thus, the study establishes the objective of developing micro and off-grid thermal power plant in Nigeria for small and medium-scales industries.

Keywords: *Power generation, Steam turbine unit, Biomass fired boiler, thermal power plant, and Local content.*

1. INTRODUCTION

Power generation has been a major challenge hindering the industrialization of underdeveloped African nations including Nigeria. Unfortunately, Nigeria is the largest holder of proven natural gas reserve in Africa and ninth among its world producer and supplier, yet she still suffers under-utilization of her Ore for power generation. This is due to the lack of adequate technical knowledge and facilities needed for power generation. IEA and World Bank, (2017); Arolowo *et al*, (2019) reported that about 58% and 39% of Nigerian pollution in urban and rural areas have access to partial steady electricity supply, respectively, while about 80% of these population still need to fallback to diesel or petrol generator. The unstable power supply has been the major challenged confronting socio-economic growth in Nigeria, likewise the emancipation of small and medium-scale entrepreneur across sub-Sahara Africa. Therefore there is need for the development of an indigenous off-grid mini thermal power plant using local content approach. Other challenges confronting the power sector are power value chain losses, limited transmission coverage across the nation, fuel supply disruption due to violence of militant groups, and finally corruption and theft (Omontuemhen 2016). There is also problem with distribution of the inadequate power generated through the national grid. IEA and World Bank, (2017) reported the lower estimated power generation capacity for 190 Million people in Nigeria to be 4,000 MW which necessitates for economy losses of US$29.3 Billion yearly compare other developed nation in terms of amount of power available per head.

According to Patrick *et al.* (2015), thermal power plants are significant to most power generating stations. Before the popularization of renewable energy sources (such as wind energy, tidal energy, solar energy, and fuel cells), the renowned sources of power generation were through hydro-power and the thermal power stations. The hydropower stations were observed to be seasonal since they depend on natural water bodies whose volume and flow properties are seasonal (Alessandro *et al.* 2018 and Maryam *et al.* 2019). Hence, thermal power station remains the most reliable and dependable all year-round source of electrical power generation. There are two basic classifications of Thermal Power Plant (TPP) namely; continuous and batched TPP. In batched TPP the operating fluid is supplied in batches during operation while for continuous TPP the same operating fluid is recycled with optimum energy conservation. Generally, TPP consists of a steam boiler, steam turbine, feed pump, condenser, super-heater, and alternator. The boiler converts feed water to superheated steam through heat transfer by conduction, convection, and radiation (Morakinyo and Akanbi, 2019). This was achieved using different heat sources from the combustion of raw fuel such as: coal, biomass, briquettes, charcoal, diesel, natural gas, and other conventional sources such as nuclear reactions. Recently, solar photo-cells are used as thermal energy harvester to generate electricity (Suojanen, 2015). Also, solar thermal source is applicable in the generation of high temperature steam using the Rankine cycle.

The turbine converts the thermal energy of the superheated steam from the boiler into kinetic energy through steam turbine and alternator. Steam turbine usually consists of the nozzle, drive shaft, seals, bearings, rotor, stator, inter-stage nozzles, wheel and casing. These working components are commonly found in most power generating stations. For instance, in the hydro-power stations, propeller-type water turbines or Pelton wheels are usually installed. Olukanni *et al*., 2016 reported that the Kanji dam in Nigeria has a power generating capacity of 760 MW, installed with twelve turbine -alternator units categorized into two types. The first category of ten in number was made of adjustable-blade propeller turbine type called the Kaplan turbine; while the second category of two utilizes a fixed-blade propeller turbine. Egbin thermal power station happened to be the largest power generating station in Nigeria, has an installed power generating capacity of 1320 MW (Adegboyega and Odeyemi, 2011). It is a gas-fired turbine of the Rateau-Curtis-type; a turbine that is driven using an impulse-reaction blade. The alternators synchronized with the turbine drive shaft through coupling to convert the kinetic energy transmitted from the steam turbine through the wheels into electrical energy (Adegboyega and Odeyemi, 2011).

In this study, a batched TPP was designed, fabricated, testing and evaluated. The performance characterization of the developed TPP was evaluated and optimized by employing Design Expert software to generate seventeen experimental runs using the Box-Behnken design. The analysis of variance (ANOVA) and Response Surface Methodology were used to determine the effect of the interaction of the (input) factors which were: steam inlet pressure, steam injection flow-rate and biomass utility) on the output measurable parameters (Electric current and Voltage) to estimate the power output of the turbine. The set of the best combination of the independent factors predicted by RSM was validated using desirability plots and models to establish the optimum operating parameters of this thermal power plant.

2. MATERIALS AND METHODS

In this study, the TPP developement involved designing, modeling, fabrication, and evaluation using the local content approach. An existing indigenous biomass-fired vertical boiler was used as steam generator. It has an operating temperature of 200 °C and steam pressure of 10 bar as reported by Morakinyo and Bamgboye (2017). The boiler was assembled inline with newly developed steam turbine and an eletric alternator.

The steam turbine design was carried out considering the enormous impact stress and centrifugal force delivered on the frictionless rotating blades through the nozzle connecting the steam-line to the boiler. The turbine developed in this study is an axial flow turbine of the Rateau-Curtis type, evaluated in the sub-critical conditions using superheated steam at pressure range of 5-10 bar. Its working components were fabricated, assembled and fastening together using appropriate fit and tolerance limits.

The description of the thermal plant assembly working components, specifications and the input parameters evaluated were shown in Table 1. The developed Steam Turbine Unit (STU) was installed and synchronized with an existing biomass-fired, fire-in-tube batch boiler of the Department of Food Science and Technology, Obafemi Awolowo University Ile-Ife (Morakinyo and Akanbi, 2021). The installed STU was coupled to a 5 kW single phase alternator in a single line pattern layout to form a prototype of an indigenous biomass fired thermal power plant (TPP) depicted as in Figure 1. The schematic diagram of the thermodynamic process is shown in Figure 2. Water is supplied into kettle of the boiler, heat is generated from the combusted biomass that transfer thermal energy to the boiler. Steam is generated and compressed to high pressure of 10 bar, before the main gate valve releases the steam from the chamber and then to the nozzle where the steam's high velocity is compromised for high pressure before imparting the turbine blade. The imparting force on the blade propels the turbine shaft which in turn drives the alternator to generate electricity.

A simple electrical circuit board was built with a switch, indicator lamp and socket, in order to enhance the measurement of the power output. The power output was determined in terms of voltage and current for different pressure and flow rate of superheated steam discharged for the boiler. The values of the current and voltage were measured using two multi-meter acting as an ammeter and voltmeter, respectively.

Table 1: Description of the Designed Steam Turbine Unit (STU)

S/N	Description	Design Specification
1.	Turbine type	Rateau-Curtis
2.	Turbine flow type	Axial flow
3.	Steam boiler type	Batch
4.	Steam boiler outlet temperature	200 °C
5.	Boiler steam inlet pressure	10 bar
6.	Boiler steam inlet enthalpy (h_1)	2827.37 kJ/kg
7.	STU steam outlet temperature	133 °C
8.	STU steam outlet pressure	3 bar
9.	STU steam inlet enthalpy (h_2)	2163.47 kJ/kg
10.	Enthalpy change ($\Delta h = h_1 - h_2$)	663.9
11.	Specific heat capacity of Boiler steam	0.7760 kJ/kg K
12.	Steam inlet mass flow rate	0.2733 kg/s or 16.40 L/min
13.	Steam outlet mass flow rate	0.068 kg/s
14.	Design rotational speed	3600 rpm
15.	No of stages	3
16.	Fuel	Biomass (Wood)
17.	Alternator	5Kw

This indigenous prototype TPP was evaluated by considering three independent operational parameters or factors at three levels, namely biomass fuel (20, 25, 30 kg), steam inlet pressure (5, 7.5, 10 bar), and steam inlet flow rate (120, 195, 270 cm^3s^{-1}). For the experimental run, 20 kg of biomass was loaded inside the combustion chamber of the boiler and ignited. Heat generated from the boiler by combusting biomass was used to generate superheated steam at a pressure of 5 bar. At this pressure, the discharged gate valve of the boiler was opened to discharge steam at a flow rate of 120 cm^3s^{-1}. The steam is delivered into the STU through a converging nozzle having outlet daimeter

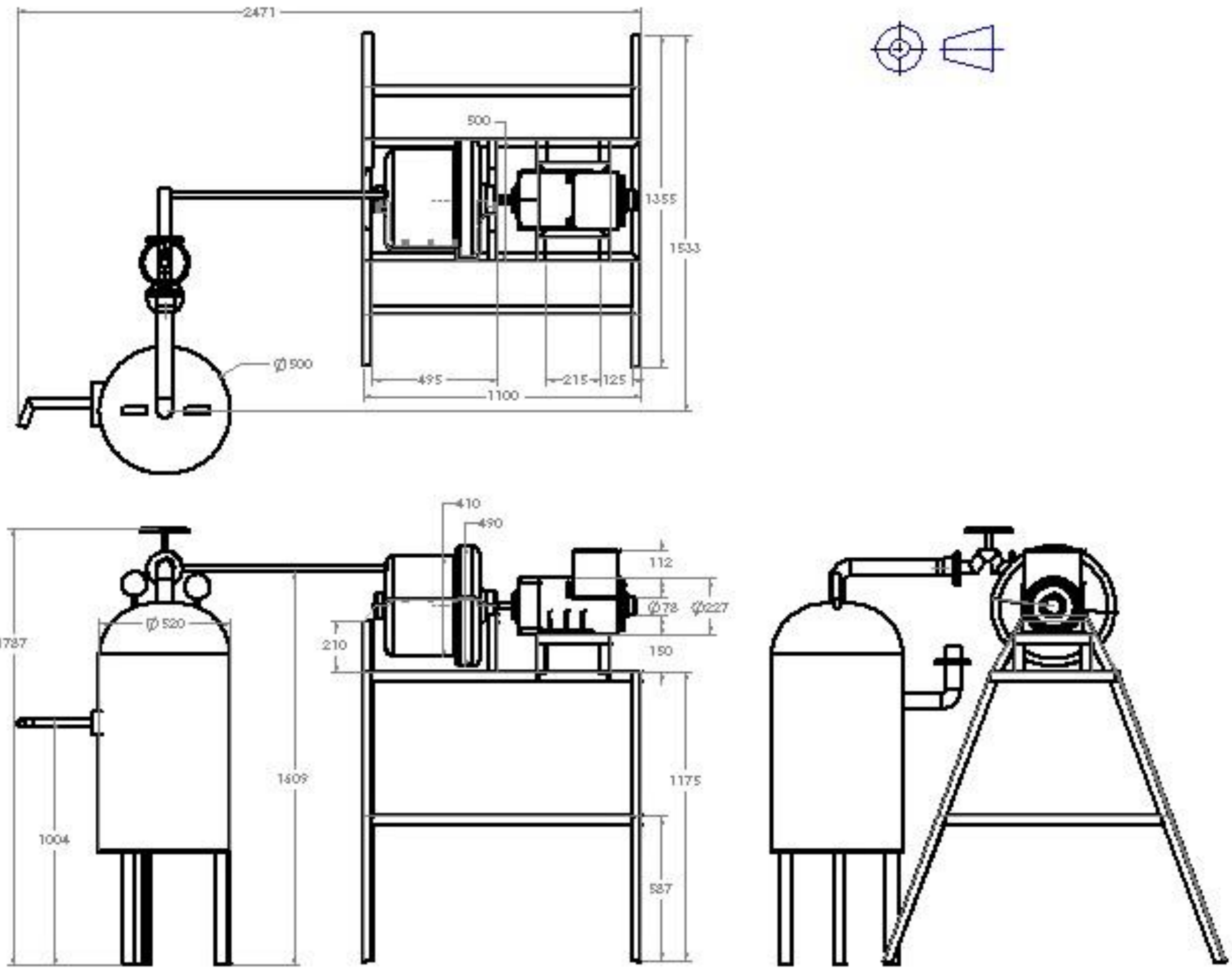

Figure 1: Orthogonal view of the thermal power plant

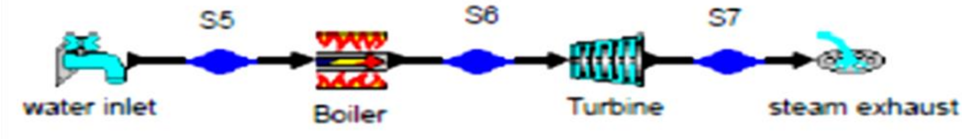

Figure 2: Schematic diagram for thermodynamic section

of 9.0 mm. The altenator was propelled by the STU and the values of voltage and current output were taken. The same procedures were observed for 25 kg and 30 kg of biomass loading with corresponding steam pressure attainment levels of 7.5 and 10 bar, and likewise at discharge steam flow rate of 195 and 270 cm^3/sec, respectively. The corresponding power output in terms of voltage and current generated was measured and likewise the thermal efficiency.

The result obtained was analysed using the Design Expert optimization tool, the regresssion model equation for both current and voltage were obtained in terms of the input parameters. The 2D and 3D surface contour plots wwer used to visualize effect of the interactions of the input parameters on the output while the desirability overlay plot shows the optimized response values for each output.

3. Design of Experiment and Statistical Analysis

The Box-Behnken rotatable design of Design-Expert 12.1.0 (Stat-Ease, Inc., 2019) software was employed to generate the design of the experiment of seventeen runs to establish the optimum run. The design of the experiment involved the selection of three independent factors at three levels of factorial design of the second-order polynomial model as shown in Table 2. The interaction of each factor was evaluated at a low, center, and high levels as shown in Table 3. The independent factors were steam inlet pressure, steam injection flow rate, and biomass utility. The dependent response was voltage and current output. A second-order polynomial regression model describing the quadratic surfaces for the interaction of factors and responses was shown in Equation 1. The experimental data obtained were optimized using Response Surface Methodology contours. The analysis of Variance (ANOVA) also was determined to confirm the adequacy of the fitted model and the level of significance of interaction among the factors at $p \leq 0.05$. The reliability of the regression model was validated using a coefficient of determination (R^2), coefficient of correlation (R), and Lack of Fit test. The optimum run of RSM was validated using Desirability plots.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^3 \quad (1)$$

where Y= Predicted response; β_0 = intercept coefficient (offset); β_1, β_2 and β_3 = linear terms (first order); β_{11}, β_{22} and β_{33} = quadratic terms (second order); β_{12}, β_{13} and β_{23} = interaction terms; X_1, X_2 and X_3 = un-coded independent factor.

Table 2: Independent variables for Design of Experiment with coded levels

S/No	Independent variables	Symbol	Unit	Coded levels		
				-1	0	+1
1	Steam inlet pressure	A	Bar	5	7.5	10
2	Steam injection flow rate	B	cm^3/s	120	195	270
3	Biomass utility	C	Kg	20	25	30

4. RESULTS AND DISCUSSIONS

The overall result obtained from the evaluation of the TPP's power output and thermal efficiency was 1.2 kW and 51.25% respectively. The peak power (P) generated was calculated using equation (2), while the thermal efficiency of the newly developed power plant was determined using equation (3).

$$P_{gen} = I \times V$$
$$= 4.72A \times 245.5V = 1158.76W = 1.2kW \quad (2)$$
$$\eta = \frac{Power\ output}{Power\ input} \times 100\% \quad (3)$$

According to Rasul and Tapenden (2006), the thermal efficiency of an un-insulated boiler, furnace, and heated pressure vessel (steam turbine) can be determined by adopting the ASME power test code, PTC 4.1, which estimated multiplying factor of 0.6934 - 0.7046 by the power input. Rasul *et al.* (2006) deduced the mathematical expression for the thermal efficiency of an un-insulated heated pressure vessel as depicted in equation (4). This same trend of thermal efficiency was reported by Ibrahim *et al.* (2016).

$$\eta = \frac{Power\ output}{0.6934 \times Power\ input} \times 100\% + 9.65\% \quad (4)$$
$$\eta = \frac{Utilized\ steam\ power\ for\ electricity + unutilized\ steam\ at\ outlet}{0.6934 \times Steam\ power\ input} \times 100\% + 9.65\%$$

In this present work, the utilized steam power is equivalent to the electric power output (i.e. 1.2 kW), while the unutilized saturated steam at exhaust has temperature, pressure and flow rate of 110 °C, 3 bar, and 0.068 kgs^{-1} respectively.

Unutilized thermal energy per unit seconds

$$= (\dot{m}\Delta h)out = 0.068\ kg/s \times 663.9\ kJ/kg = 45.15\ kJ/s$$

Steam power input at temperature, pressure, and flow rate values are 200 °C, 10 bars, and 0.2773 kgs^{-1}, respectively.

Supplied thermal energy per unit seconds

$$= (\dot{m}\Delta h)in = 0.2733 kg/s \times 663.9\ kJ/kg = 181.44\ kJ/s$$
$$\eta = \frac{1.2kW + 45.15\ kJ/s}{0.6934 \times 181.44\ kJ/s} \times 100\% + 9.65\% = 46.49\%$$

The overall thermal efficiency of the plant here is 46.49% at optimum steam inlet pressure and isentropic compression efficient nozzle. However, the major reasons for low power output and thermal efficiency may be due to the automatic voltage regulator (AVR) of the fairly-used alternator installed (Hoque, 2014) and likewise error in the angle of contact between the nozzle and the rotor blade. Other visible contributing factors were steam leakages in-between the rotor casing and its cover, un-insulated steam pipeline, and turbine casing. More importantly, in this study, the exhaust steam from the turbine was not recycled back to the boiler to conserve heat loss.

Adegboyega and Odeyemi, (2011) analyzed the performance of the Egbin power plant in Nigeria and reported the average thermal efficiency to be 33.95%. Their report shows a lower efficiency which fall below the standard value of 40-45%, due to poor maintenance, incessant breakdown, delaying in the overhauling of major units, obsolescent technology, instability of the national grid system and interruption in gas supply. Considering the results in Table 2, as the steam inlet pressure increased from 5 -10 bar, the steam inlet flow rate increased from 120 – 270 cm^3/s. Consequentially, the peak voltage attained was 245.5 V, while the least voltage value was 175 V. Furthermore, the electrical current generated for the peak and least voltages were 4.72 A and 1.78 A, respectively.

4.1. Voltage Value Generated

In Table 3, the experimental run that generated optimum voltage value of 245.5 V was found to be the 9th run with corresponding independent factors of 25 kg, 10 bar, and 270 cm^3s^{-1} for biomass utility, steam inlet pressure, and steam inlet flow-rate, respectively. This indicates that for the optimum performance of this indigenous developed thermal plant, the optimum independent parameters that must be utilized are 25 kg, 10 bar, and 270 cm^3s^{-1}, for the biomass utility, steam inlet pressure, and the steam injection flow-rate respectively, that will generate optimum voltage and current. In Table 3, it can be deduced that as the superheated steam pressure increased from 5-10 bar, the voltage output increased from 174.5-245.5V.

Similar trend had been reported by Rout *et al.*, (2013), they observed that increase in the superheated steam temperature enhanced the output power and thermal efficiency of a steam turbine power plant. They also reported that the steam quality at the turbine's exhaust increases relatively to the voltage and current output. However, the results of the ANOVA in Table 4 showed that the quadratic regression modeling equation and model terms were significant at the level of $p \leq 0.05$ for all responses. Furthermore, in Table 4, all other independent factors such as steam inlet pressure and flow-rate contributed significantly to the increase or decrease of the voltage generated except biomass utility. The biomass utility has no significant effect on the voltage increase because the discharge of the superheated steam into the turbine was done at the point when the predetermined pressure was attained at the end of combustion of the loaded biomass.

Table 3 Result of Box Behnken Design of Experimental Runs

Run	A: Biomass Utility (kg)	B: Steam Inlet Pressure (Bar)	C: Steam Injection Flow-rate (cm^3s^{-1})	Voltage (Volts)	Current (Amp)
1	30	7.5	270	237.2	3.70
2	25	5	270	190.8	2.26
3	20	7.5	120	218.6	2.87
4	30	5	195	188.2	2.17
5	20	10	195	240.1	3.93
6	25	7.5	195	226.9	3.36
7	25	7.5	195	221.7	3.19
8	20	7.5	270	234.0	3.67
9	25	10	270	245.5	4.72
10	25	10	120	216.8	2.58
11	20	5	195	187.9	2.03
12	25	7.5	195	226.8	3.31
13	25	5	120	175.4	1.78
14	25	7.5	195	221.5	3.15
15	30	7.5	120	218.2	2.93
16	30	10	195	237.0	3.65
17	25	7.5	195	220.7	2.98

Table 4 ANOVA of Quadratic model and Regression Coefficients for Responses.

Source	Df	Voltage			Current		
		Standard Error	Coeff. Estimate	P-value	Standard Error	Coeff. Estimate	P-value
Model	9	1.27	223.52	< 0.0001	0.0819	3.20	< 0.0001
A	1	1.00	0.0000	1.0000	0.0648	-0.0062	0.9258
B	1	1.00	24.64	< 0.0001	0.0648	0.8300	< 0.0001
C	1	1.00	9.81	< 0.0001	0.0648	0.5237	< 0.0001
AB	1	1.42	-0.8500	0.5675	0.0916	-0.1050	0.2893
AC	1	1.42	0.9000	0.5455	0.0916	-0.0075	0.9370
BC	1	1.42	3.32	0.0513	0.0916	0.4150	0.0027
A^2	1	1.38	4.83	0.0101	0.0893	0.1022	0.2897
B^2	1	1.38	-15.05	< 0.0001	0.0893	-0.3553	0.0053
C^2	1	1.38	-1.35	0.3617	0.0893	-0.0077	0.9333
R^2			0.9917		0.9746		
R			0.9958		0.9872		
Adj. R^2			0.9810		0.9419		
F value			92.91		29.81		
Lack of fit			18.68		0.1462		
CV%			1.30		5.96		
Adeq. Precision			31.7018		19.2706		

A, B and C are the biomass utility, steam inlet pressure, and steam injection flow-rate respectively at linear terms (first-order), A^2, B^2, and C^2 are quadratic terms (second-order), AB, AC, and BC: interaction terms

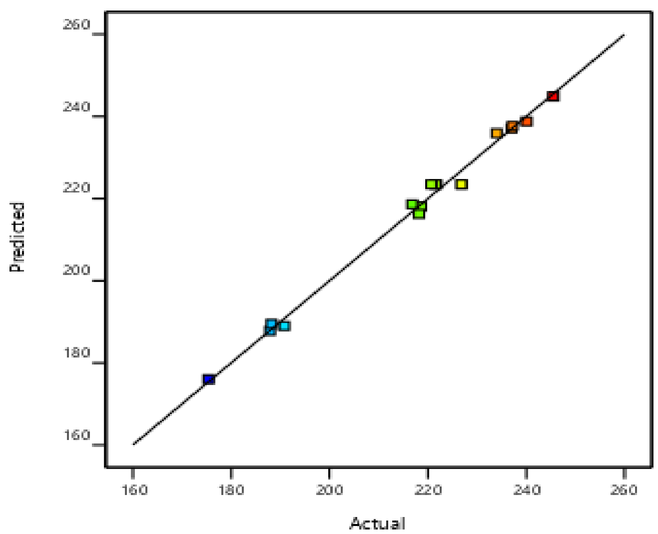

Figure 3: Plot of the predicted voltage against actual voltage

More importantly, at the attainment of each set of steam inlet pressure, the corresponding steam flow-rate was measured, while the energy source had been cut-off before discharging the superheated steam through the gate valve to propel the turbine. Hence, the kinetic energy attained at the nozzle outlet propels the STU rotor, i.e. the potential energy in the boiler steam was been converted to kinetic energy at the nozzle. In Table 4, the coefficient of determination (R^2) was 0.9917, this implies a high level of correlation among the independent factors and implies that this model could explain 99.17% of the experimental data. The coefficient of correlation (R) was analyzed to be 0.9958. This shows that the actual (experimental) voltage efficiently correlates to the predicted values obtained at 99.58%. This high level of correlation was demonstrated graphically in Figure 3 which shows a straight line of best fit or the predicted values against actual value. Hence, an adequate precision of 31.70 was obtained, indicating a greater signal to noise ratio, greater than 4, this shows the desirability level for the voltage output regression model depicted in equation 5.

$$Y = 223.52 + 0.00A + 24.64B + 9.81C - 0.85AB + 0.90AC + 3.32BC + 4.83A^2 - 15.05B^2 - 1.35C^2 \quad (5)$$

where, Y =Voltage, 223.52 = intercept coefficient (offset); A, B and C are the biomass utility, steam inlet pressure, and steam injection flow-rate respectively at linear terms (first-order), A^2, B^2, and C^2 are quadratic terms (second-order), AB, AC, and BC: interaction terms.

In Figure 4 of Response Surface plots of 2D, the predicted optimum voltage value was 245.5 V at the point when yellow color was turning to red. This optimum voltage value occurred at corresponding values of steam inlet pressure and biomass utility of 10 bar and 25 kg, respectively. The linearity of biomass coordinates to the biomass input values shows that increase in the biomass quantity after 25 kg does not affect the increase in the voltage values, this also clearly demonstrated in Figure 4. Apparently, at the point of superheated steam discharged from the boiler, the combustion of biomass added no more pressure to the steam chamber since its loading was terminated earlier. Furthermore, Figure 4 explained the interaction between factors A and B as biomass utility and steam inlet pressure, respectively to be insignificant to the value of voltage, having a P-value of 0.5675 and an F-value of 0.3599 in Table 4. The same trend was observed in the interaction of AC (Interaction between biomass utility and steam injection flow rate) in Table 4. In contrast to the interaction AB (Interaction between biomass utility and steam inlet pressure) and AC (Interaction between biomass utility and steam injection flow rate), the interaction BC (steam inlet pressure and steam injection flow rate) is highly significant to the voltage output having $p \leq 0.05$.

Figure 4 of Response Surface plots of 2D, established the optimum predicted biomass utility value to be 25 kg with a corresponding optimum steam inlet pressure of 10 bar as pressure increased from 8 – 10 bar. Furthermore, in Figure 5, the predicted optimum voltage values generated were tending to 240 V as the steam inlet flow-rate increased from 120 to 270 cm^3s^{-1} with a corresponding increase in the biomass utility from 20 to 30 kg. In Figure 5, the interaction of BC factors on voltage value was validated by showing a tremendous increase in the voltage values as steam inlet pressure increase from 120 - 270 cm^3s^{-1}. Figures 5 and 6 clearly showed that at lower values of steam flow rate of 120 cm^3s^{-1}, the voltage values appear to be zero. However, as the flow rate increases from 220 to 240 cm^3s^{-1} the voltage output becomes significant. As the flow rate increases beyond, 240 cm^3s^{-1} at pressure greater than 9 bar in Figure 5, the voltage tends towards the predicted value of 245.5 V.

4.2. Electric Current Value Generated

In Table 3, the optimum current value generated was found to be 4.72 A, which occurred at 9th run with corresponding independent factors of 25 kg, 10 bar, and 270 cm^3s^{-1} for biomass utility, steam inlet pressure, and steam inlet flow-rate, respectively. Furthermore, it was observed that as steam inlet pressure increases from 5 to 10 bar with a corresponding increase in the steam inlet flow-rate, the current value increases from 1.78 - 4.72 A. Ibrahim *et al.* (2016) reported similar trend stating that as the steam pressure increases, the current output increase relatively. The results of the ANOVA in Table 4 shows that the quadratic regression modeling equation and model terms were significant at the level of $p \leq 0.05$. However, biomass utility was insignificant to the current generated, while other independent factors were significant at the level of $p \leq 0.05$. This same trend was observed for the voltage output. In Table 4, the coefficient of determination (R^2) was 0.9746, presenting a high level of correlation among the independent factors, which indicates that this model could explain 97.46% of the data. However, the coefficient of correlation (R) was evaluated to be 0.9872. This

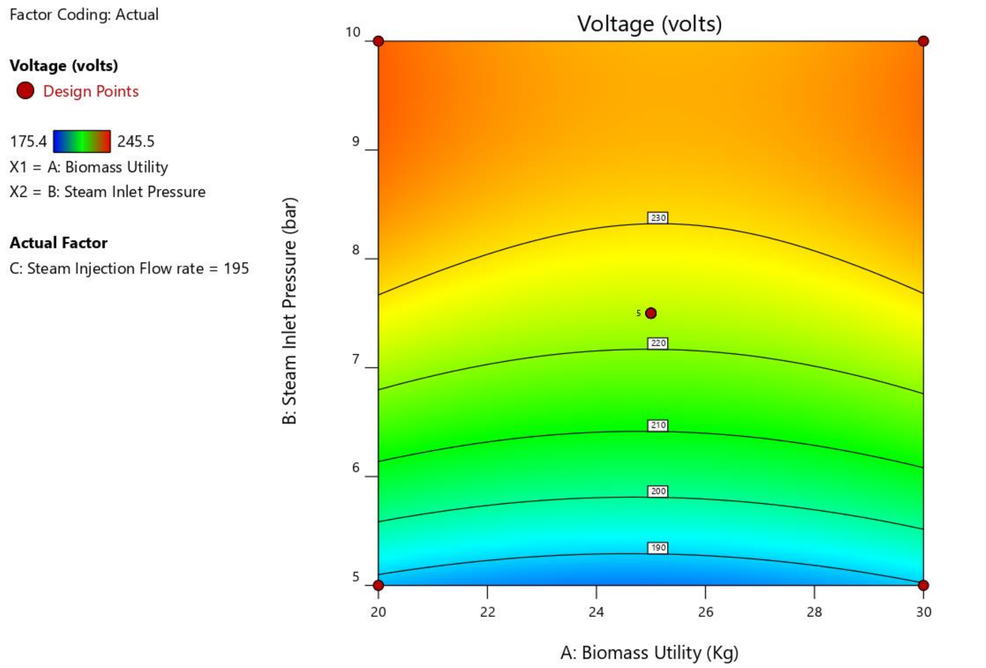

Figure 4: Surface response 2d plot showing the effect of steam inlet pressure at the optimum biomass utility of 25 kg on voltage value.

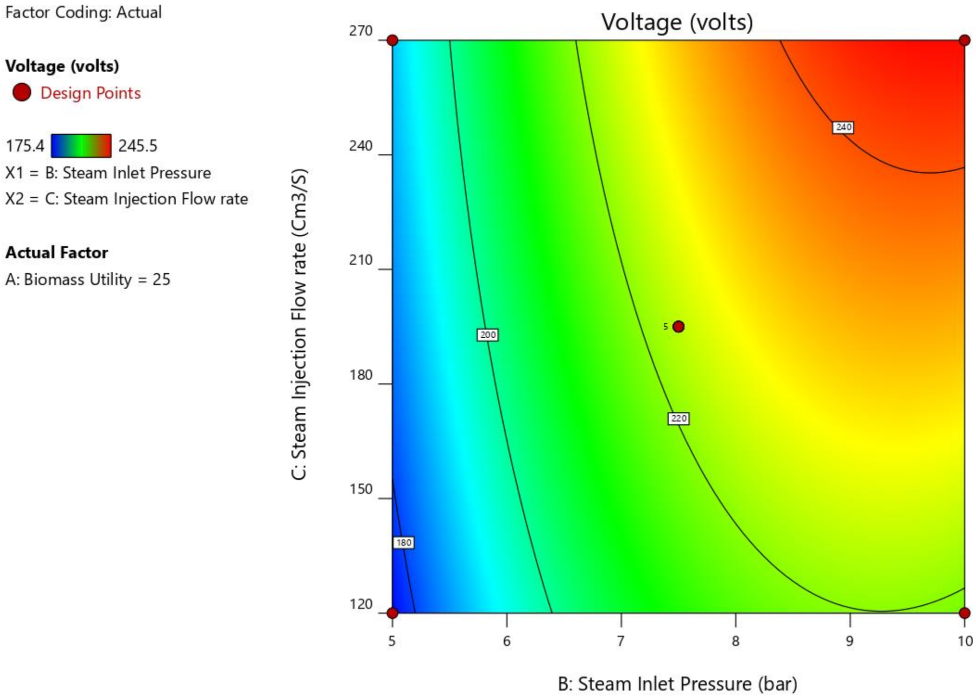

Figure 5: Response surface plots 2d showing the interaction between steam inlet flow-rate and pressure on the voltage value

showed that the actual experimental current value correlated to that of predicted values at 98.72%. Figure 7 demonstrated the level of correlation between the actual and predicted values of the current generated. An adequate precision of 19.26 was obtained, signifying a greater signal to noise ratio that was greater than 4 which showed the desirability level of the current output regression model as depicted in equation 6.

$$Y = 3.20 - 0.0062A + 0.830B + 0.524C - 0.105AB - 0.0075AC - 0.415BC + 0.1022A^2 - 0.3553B^2 - 0.0077C^2 \quad (6)$$

where, Y = Current, 3.20 = intercept coefficient (offset); A, B and C are the biomass utility, steam inlet pressure, and steam injection flow-rate respectively at linear terms (first-order), A^2, B^2, and C^2 are quadratic terms (second-order), AB, AC, and BC: interaction terms.

Figure 8 of Response Surface plots showed the predicted optimum current of 4.72 A at biomass utility of 25 kg and the steam inlet pressure tending towards 10 bar. It was displayed clearly in Figure 9, the effect of the biomass factor that remains negligible to the values of electric current output, hence biomass utility contour line remains parallel to its axis. In contrast, the steam inlet pressure increases relative to the electric current generated. The linearity of biomass coordinate shows that an increase in the biomass quantity does not affect the increase in the current values. The same trend was previously observed on the voltage values generated. The Response Surface plots of Figure 8 validated the interaction between factors A and B, on current values generated which were insignificant at a level of the p-value of 0.28930. The empirical data could be validated by considering the uniform color that exists as the biomass utility increased from

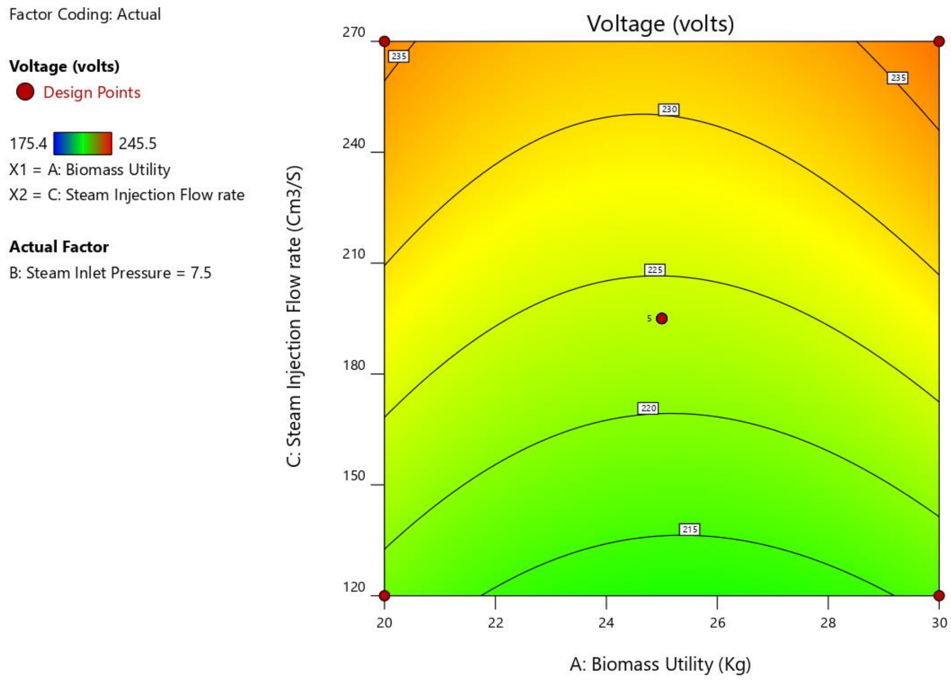

Figure 6: Surface response 2d plot showing the effect of steam injection flow rate at maximum biomass utility of 25 kg

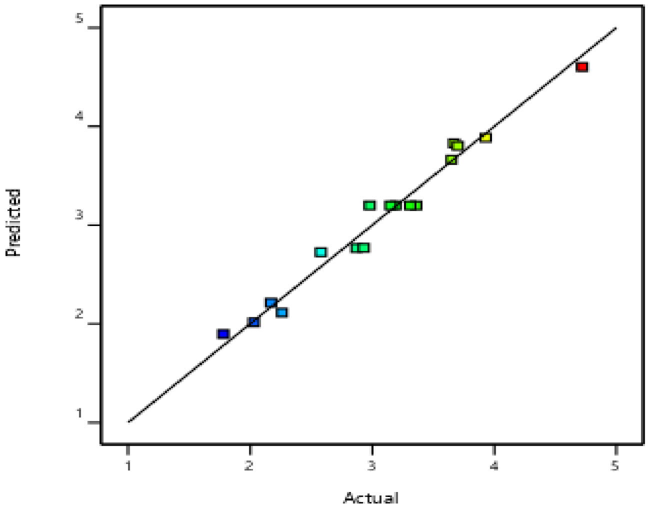

Figure 7: Predicted current against the actual current

20-30 kg for respective levels of the steam inlet pressure generated until the peak current output of about 4.72 A was attained. Likewise, in Figure 9 of Response Surface plots, the optimum predicted current value was 4.72 A at the interaction of biomass utility and steam inlet flow-rate. The interaction of factors AC was likewise insignificant as shown in Table 4, having a P-value of 0.9370. The Response Surface contour for the interaction of factors A and C (Figure 10) showed that biomass utilities from 20 to 30 kg had a negligible effect on the current generated when compared with the linear increase of the current output as the steam injection flow-rate increased from 120 to 270 cm^3/sec. However, contrary to the interaction between AB and AC independent factors, the interaction of BC was highly significant to the current values generated; with P-value of 0.0027 and F-value of 29.81. In Figure 10, the optimum predicted current value was 4.72 A was clearly shown at maximum steam inlet pressure and flow-rate of 10 bar and 270 cm^3s^{-1}, respectively.

4.3. Validation of Response Surface Methodology using Desirability model

The results of the response surface plot were validated using the desirability model. Constrains for the factors iterations were selected according to Table 5, by considering both independent and dependent factors at a range between minimum and maximum levels. The desirability model generated ninety solutions of iterative steps as indicated in Table 6, which showed that iterative step number 63 has the optimum iterative variables and responses at the desirability of 1. The desirability solution of Table 6, predicted optimum independent variables and responses to be 25.036 kg, 10 bar, and 270 cm^3s^{-1}, 244.901 V and 4.603 A for biomass utility, steam inlet pressure, and flow rate; voltage and current generated, respectively. In Figure 11 of desirability plots, the corresponding optimum voltage and current were found to be 249.592 V and 4.786 A, respectively. The empirical values of both desirable responses were almost the same values as that of desirability solution values and nearer to the actual variables deduced from the experimental values on Table 3 at 9th run with corresponding values of 245.5 V and 4.72 A for voltage and current output, respectively. Hence, RSM plots predicted values and desirability solution values validated experimental run 9 to be the optimum run for the optimum output power for the newly developed indigenous thermal power plant.

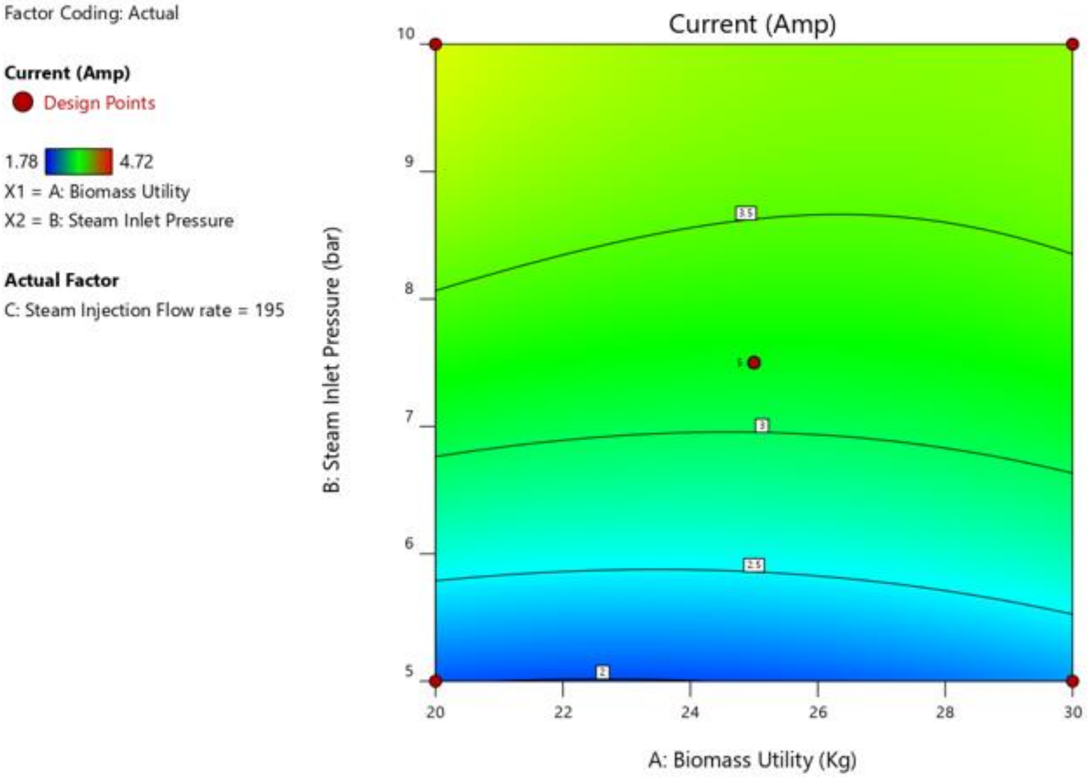

Figure. 8: Surface response 2d plot showing the effect of steam inlet pressure at biomass utility of 25 kg on electric current values

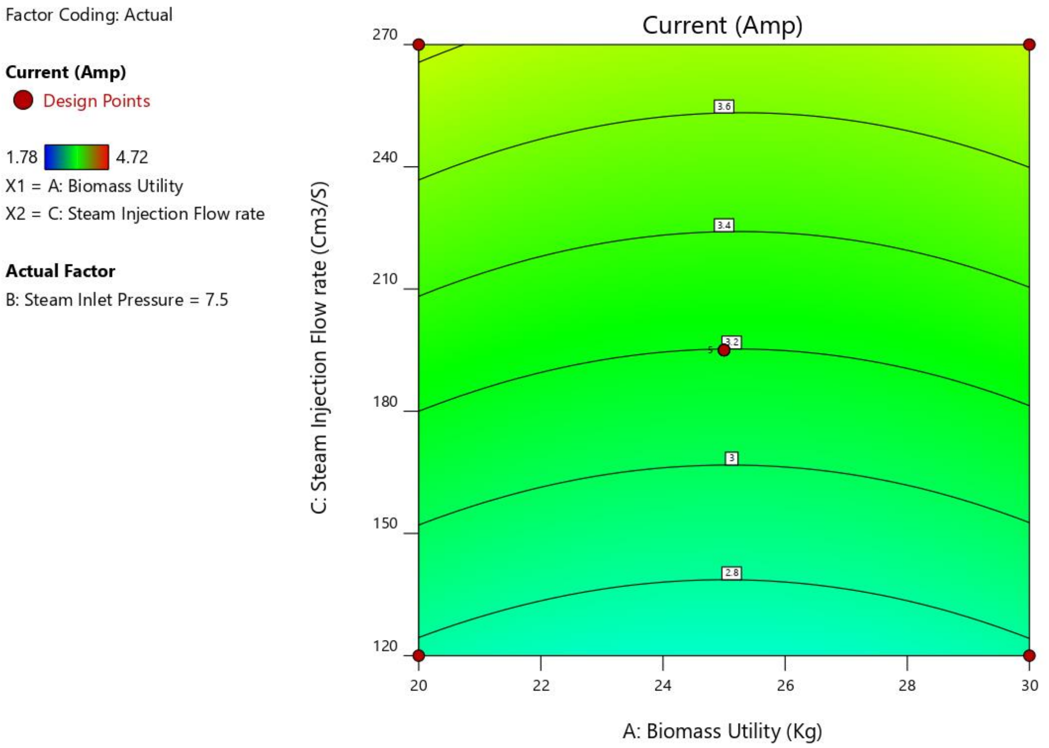

Figure. 10: Surface response 2d plot showing the effect of steam inlet flow-rate at biomass utility of 25 kg on electric current values

Table 5: Constraints selected for optimizing experimental data using desirability plots

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Biomass Utility	is in range	20	30	1	1	3
B: Steam Inlet Pressure	is in range	5	10	1	1	3
C: Steam Injection Flow rate	is in range	120	270	1	1	3
Voltage	Maximize	175.4	245.5	1	1	3
Current	Maximize	1.78	4.72	1	1	3

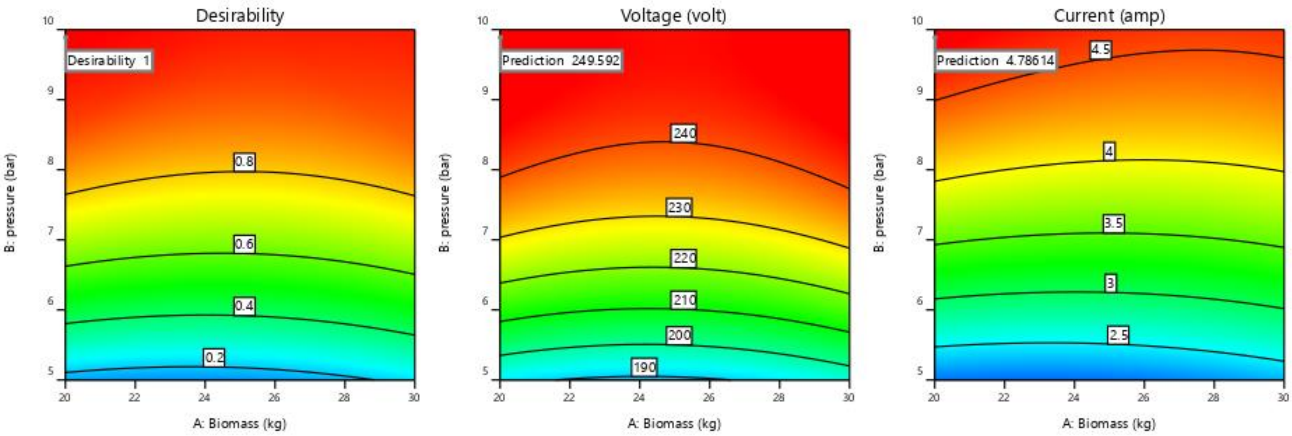

Figure 11: Desirability overlay plot showing optimum responses value.

Table 6: Ninety iterative Solutions of Desirability Analysis

Number	Biomass Utility	Steam Inlet Pressure	Steam Injection Flow rate	Voltage	Current	Desirability	
1	20.000	9.833	265.000	249.069	4.720	1.000	
2	20.707	9.933	267.659	248.142	4.735	1.000	
3	20.010	9.890	269.253	249.592	4.786	1.000	
4	20.579	9.819	269.650	248.607	4.737	1.000	
5	20.330	9.877	269.865	249.077	4.770	1.000	
6	20.298	9.973	269.766	249.105	4.796	1.000	
7	20.167	9.874	269.610	249.341	4.776	1.000	
8	20.201	9.798	267.664	249.016	4.730	1.000	
9	20.277	9.798	268.170	248.941	4.732	1.000	
10	20.933	9.976	269.847	248.046	4.760	1.000	
-	-	-	-	-	-	-	
-	-	-	-	-	-	-	
15	21.391	9.965	269.152	247.287	4.724	1.000	
-	-	-	-	-	-	-	
-	-	-	-	-	-	-	
33	21.561	9.956	269.963	247.167	4.723	1.000	
30	20.683	9.976	269.515	248.406	4.771	1.000	
-	-	-	-	-	-	-	
-	-	-	-	-	-	-	
61	29.601	10.000	270.000	249.034	4.581	0.976	
62	29.468	10.000	269.999	248.799	4.579	0.976	
63	25.036	10.000	270.000	244.901	4.603	0.976	SELECTED
-	-	-	-	-	-	-	
-	-	-	-	-	-	-	
89	30.000	8.992	270.000	248.534	4.356	0.936	
90	30.000	8.008	211.779	235.044	3.561	0.718	

5. CONCLUSION

In this research work, an indigenous thermal power plant was developed and evaluated. The performance evaluation of the plant in terms of electrical current and voltage output was measured and statistically analyzed. A peak power output of 1.2 kW was generated, measured and visually indicated. The measured voltage and current values were 245.5 V and 4.74 respectively. The thermal efficiency was 46.49%, while the optimum independent variables were 25 kg, 10 bar, and 270 cm^3s^{-1} for the biomass utility, steam inlet pressure, and steam injection flow rate, respectively. Summarily, electrical power generation depends greatly on the capacity of the boiler, boiler steam pressure and the steam injection flow rate values. The efficiency can also be improved by insulating the boiler, fully, the discharge pipe, the turbine and recycling the exhaust steam from the turbine back to the boiler to eliminate wastage and enhance thermal efficiency and power output. Conclusively, there are possibilities of mass-production and upgrading this indigenous off-grid biomass powered thermal plants in Nigeria and sub-Sahara Africa in different capacities instead of depending on fossil fuel which characterized with global warming effect. More importantly, adopting this work will eventually empower small and medium scales entrepreneurs to generate electricity on their own without depending on the national grid and fossil fuel consumption.

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