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Assembly Process and Performance of A Micro Steam Power Plant

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Abstract

Energy is an indispensable component of modern society, driving everything from industrial processes to household appliances, among the various sources of energy, steam power, a form of heat energy has played a pivotal role in the development of human civilization, paving the way for the Industrial Revolution and subsequent technological advancements. This study focused on the assembly and performance evaluation of a 5 kW steam power plant. The components of the steam power plant including steam generator, turbine and alternator which are readily available were assembled using on-site assembly: partial fabrication method of assembly. The performance evaluation of the assembled power plant was carried out measuring and recording the temperature, pressure and dryness fraction of steam from the steam generator with the maximum temperature, maximum pressure and dryness fraction being 239℃, 0.3985MPa and 0.93 respectively. The performance evaluation of the steam turbine powered alternator under changeable bed and drive mechanisms was also carried out with the turbine-alternator unit operated with axial coupling, the voltage output, rotational speed and sound level was measured and recorded to be 56V, 1152 rpm and 73dB respectively, the evaluation was also carried out with the turbine-alternator unit operated with transverse connection, the voltage output, rotational speed and sound level was measured and recorded to be 24V, 904 rpm and 71dB respectively. With the results obtained and discussed, it was noticed that the transverse connection of the turbine-alternator unit is less efficient in transferring mechanical energy to electrical output compared to the axial coupling of the unit, making the axial coupling using a flexible flange system a better and plausible power transmission method in the system. A total of Sixty-Three Thousand, Eight Hundred Naira only was spent on the successful assembly of this system.

Keywords: Steam power plant, assembly, performance evaluation, turbine-alternator unit, axial coupling.

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INTRODUCTION

Modern society is unable to operate without energy, which powers everything from home appliances to factory operations (Smil, 2017) [13].

Among the various sources of energy, steam power has played a pivotal role in the development of human civilization, paving the way for the Industrial Revolution and subsequent technological advancements (Dickinson, 2011) [2]. Despite the emergence of newer energy sources, steam power plants continue to be a reliable and efficient means of generating electricity, particularly in areas with abundant access to water resources (Woodruff et al., 2017) [14].

In an era marked by escalating concerns over energy sustainability and environmental preservation, the exploration of alternative energy sources has become paramount (Chu and Majumdar, 2012) [1]. Among these alternatives, steam power generation stands as a stalwart, offering a robust solution that amalgamates efficiency with eco-friendliness. A steam generator power plant, often referred to as a steam power plant or a thermal power plant, is a facility that converts thermal energy into electrical power through the use of steam (Sharma and Singh, 2013) [12]. It operates on the principle of thermodynamics, utilizing the heat generated from the combustion of fossil fuels or nuclear reactions to produce steam, which then drives a turbine connected to an alternator, ultimately generating electricity (Moran et al., 2018). Its major components include a boiler, turbine, alternator, condenser, and pump. The utilization of steam power has a long history dating back to the industrial revolution, and its relevance persists in modern-day energy generation (Hills, 1989) [3].

However, there is a critical need to investigate and improve the efficiency of energy producing processes in light of increasing fears about climate change and sustainability in the environment (IPCC, 2021).

Steam power plants, despite their long-standing history, are not exempt from this imperative. Palm kernel shell is a possible biomass product in the hunt for a replacement energy source.

With its higher calorific value, accessibility, and eco-friendliness, palm kernel shell offers a renewable and sustainable energy resource that can be harnessed to create efficient micro-power plants (Okoroigwe et al., 2014) [7]. The fusion of traditional steam power generation principles with innovative biomass utilization presents an exciting opportunity to enhance both efficiency and sustainability in energy generation (McKendry, 2002) [5]. Against this backdrop, the assembly and performance evaluation of a 5 kW steam power plant fueled by palm kernel shell biomass represent a convergence of classical engineering expertise with contemporary energy demands. Through hands-on experimentation and rigorous performance evaluation, this project endeavors to shed light on the feasibility and viability of biomass-fueled steam power plants (Saidur et al., 2011) [11].

By examining the efficiency, power output, and environmental impact of the assembled power plant, valuable insights will be gained into the practical application of biomass-based energy generation. In essence, this project embodies a multifaceted endeavour: a quest for sustainable energy solutions, an exploration of innovative biomass utilization, and a pursuit of engineering excellence. Through the assembly and evaluation of a 5 kW steam power plant fueled by palm kernel shell biomass, which was aimed to contribute to the advancement of sustainable energy technologies and pave the way towards a greener, more resilient energy future (Panwar et al., 2011) [10].

The research was aimed to address the urgent need for sustainable and efficient energy sources that leverage local resources. Reliable and ecologically sound renewable energy solutions are becoming more and more in demand as global frets about climate change and the depletion of fossil fuels expand.

This project specifically explores the viability of small-scale biomass power generation, using palm kernel shells as a fuel source due to their high calorific value and availability. The research team chose an on-site, partial fabrication assembly method to make the process flexible and cost-effective, especially in resource-limited environments, this approach ensured efficient component integration and adaptability, facilitating the assembly of the plant without compromising on quality. Additionally, the use of palm kernel shells as fuel reflects a commitment to renewable and accessible energy sources, aligning the project with sustainability goals.

In evaluating the performance of the power plant, the maximum temperature, pressure and dryness fraction readings were taken, the research also compares two configurations, axial coupling and transverse connection to determine the most effective setup for converting mechanical energy into electrical output. This comparison is crucial, as it identifies the configuration that best maximizes energy efficiency and minimizes vibrations, both of which are essential for consistent and reliable power generation. By focusing on these design considerations, the study aims to advance sustainable energy technologies, enhancing the practicality and performance of small-scale steam power plants in real-world applications.

A steam power plant is a structure that changes thermal energy into mechanical and then electrical energy, usually from the burning of fuels or other heat sources. This is carried out by using steam to power a turbine that is connected to an electric generator.

MATERIALS AND METHODS

The materials needed for the assembly and performance evaluation of the steam power plant includes the components of the steam power plant, fasteners, test and calibration devices. The steam power plant components; boiler, turbine and alternator are readily available, awaiting assembly.

1. *Boiler (Steam Generator):* The boiler is one f the major components of the steam power plant. It turns water into steam by scorching it to a high temperature and pressure. The fuel is made by using the shells of palm kernels. The turbine receives the high-pressure steam made in the boiler.
2. *Steam Turbine:* The part that transforms the steam's thermal energy into mechanical energy is the turbine. The rotor rotates as the high-pressure steam flows over the turbine blades. A source of electricity is powered by this rotating conduct.
3. *Alternator (Generator):* The alternator, which is included to the turbine, transforms the spinning turbine's mechanical energy into electrical current. An electric current is created when the turbine rotates, turning the generator's rotor inside a magnetic field.
4. *Condenser:* The turbine's exhaust steam gets chilled and condensed back into water in the condenser.

This condensed water, or condensate, is collected and to be reused in the boiler, which improves overall efficiency and conserves water [6].

The components used for the assembly process and performance evaluation are presented in Table 1.

Table 1. Components used and their sources.

S/N	Components/materials	Quantity	Capacity	Source
1.	Steam generator	1	5 kw	Readily available
2.	Steam turbine	1	5kw	Readily available
3.	Alternator	1	5kw	Readily available
4.	Steam pipe	1	$\frac{1}{2}$inch	Local market
5.	Union connector	2	$\frac{1}{2}$inch	Local market
6.	Elbow connector	2	$\frac{1}{2}$inch	Local market
7.	Thread seal tape	1	_	Local market
8.	Fibre packing	2kg	_	Local market
9.	Glue	2	_	Local market
10.	Leather	2	_	Local market
11.	Instrumentation	2	_	Local market

The method employed for the assembly and performance evaluation of the 5 kW steam power plant followed these steps: moving the components to be assembled to the assembly site, improving the already designed and fabricated components i.e. boiler and turbine, lagging the steam pipe from the boiler to the turbine and reducing the diameter of the steam turbine's nozzle to get a uniform diameter of pipe from the boiler to the turbine, incorporation of a D.C draught fan to enhance the air supply system, re-assembly of the components, Additionally, effectiveness evaluation tests were conducted to compare the performance of the steam-powered turbine and alternator alongside or without the vibrator isolator when they are connected transversely with sets of belts and pulleys or axially with a flexible flange interaction.

Performance data with the results from previous performance evaluation. Figure 1 shows the assembly flow diagram of the plant.

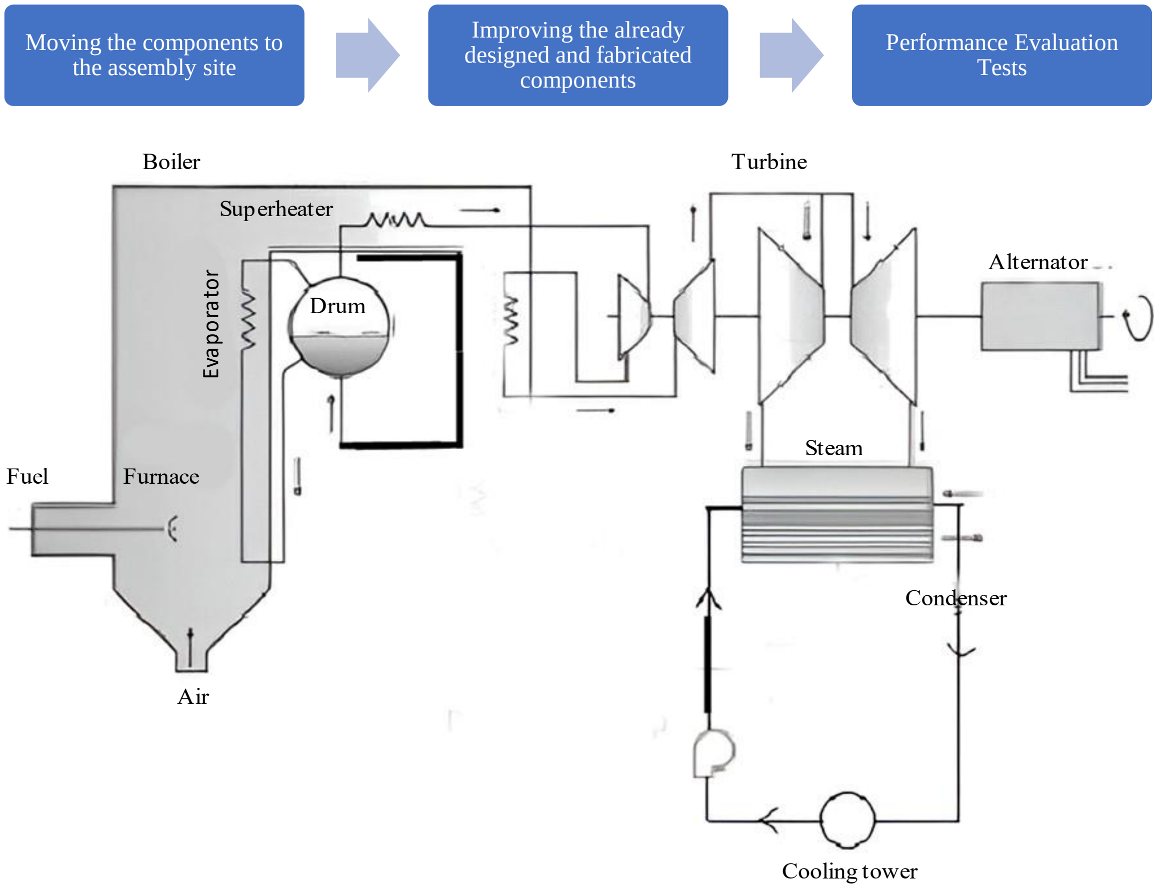

Figure 1. Steam power plant assembly flow diagram.

Performance Evaluation Procedure

The steam generator performed preliminary testing, specifically the leakage test and the functioning test, following the assembly and improvement of the found components.

The leakage test was conducted on the welded joints and pipe connector joints, after the joints have been confirmed to be leakage free, the performance evaluation tests were performed.

The steam power plant was then subjected to experimental tests on 2nd of October, 2024. A known volume of water had to pay into the system, whose thermodynamic property was already established at around 1:27 pm, when the experiment began at a room temperatures of 34°C.

During the operational process, 10 litres of clean water of temperature of 24°C was used for the performance evaluation [7]. This was charged through the feed water inlet of the steam generator, and the system was fired. In an hour, 2.92 kg PKS were used, with losses accounted for. Starting with the initial values prior to performing the test, the temperature and pressure values of the developed superheated steam were recorded at 10-minute intervals during one hour of operation of the steam power plant. The test was taken four times, and the average results were displayed.

However, not all the water supplied is converted completely to steam; a certain fraction of this working fluid always exists to occupy the water space. According to Nag (2008) and Osafehinti (2011), equivalent evaporation is the amount of water that escapes from and at 100 °C to produce saturated steam at this temperature by taking the same amount of heat as used in the steam generator under real circumstances of operation.

The following parameter were used for the evaluation of the steam generator: the quantity of feedwater, the temperature of the feed water, quantity of feed fuel, mass of fuel used, temperature of the surrounding, maximum pressure of the steam produced, maximum temperature of the steam produced, time required for the steam production and the steam quality (dryness). During operational process, 10 litres of clean water of temperature of 24 ℃ was charged through the feed water inlet of the steam generator. In an hour, 2.92 kg PKS were used, accounting for losses. For one hour of operation, the temperature and pressure observations of the produced super heated steam were recorded at 10-minute intervals, beginning with the first observations before to the test [8,9].

The maximum steam temperature, maximum steam pressure and dryness fraction obtained were 239°C, 0.3985 MPa and 0.93 respectively and this was attained in 1 hour of the PKS combustion.

Tests were conducted to gauge the performance of the steam-powered turbine and alternator, both with and without the vibrator isolator, when along transversely with sets of belts and pulleys or axially with a flexible flange connector.

The steam turbine and alternator were mounted on the adjustable steel-framed bed, for the axial coupling, the turbine was connected to the alternator using a flexible flange coupling and for the transverse connection, the components were linked using a belt and pulley system.

For each setup (axial and transverse), the experiment was repeated twice; once with the vibration isolator inserted between the steam turbine base and the steel-framed bed, and once without the isolator with the following experimental measurements recorded;

a. Voltage output (in volt)
b. Rotational speed of the alternator (in rpm)
c. Sound level (in decibels, dB)

RESULTS AND DISCUSSION

After the assembly and improvement of the identified components, preliminary tests namely the leakage test and operating test were carried out on the steam generator. The results from the leakage test performed on the assembled system is presented in the Tables 2-6;

Table 2. leakage test results.

Components	Performance
Boiler Drum	Satisfactory
Steam Pipe	Satisfactory
Steam Turbine	Satisfactory
Temperature Gauge	Satisfactory
Pressure Gauge	Satisfactory
Downcomer	Satisfactory

Table 3. Temperature at Time intervals.

Time (minutes)	Temperature (℃)
0	34
10	65
20	109
30	133
40	155

50	198
60	239

Temperature and Time trends during PKS combustion process

These outcomes indicate that the temperature values were increasing steadily with time.

In other to establish the relationship between temperature and time, the graph of temperature against time was plotted in Figure 2.

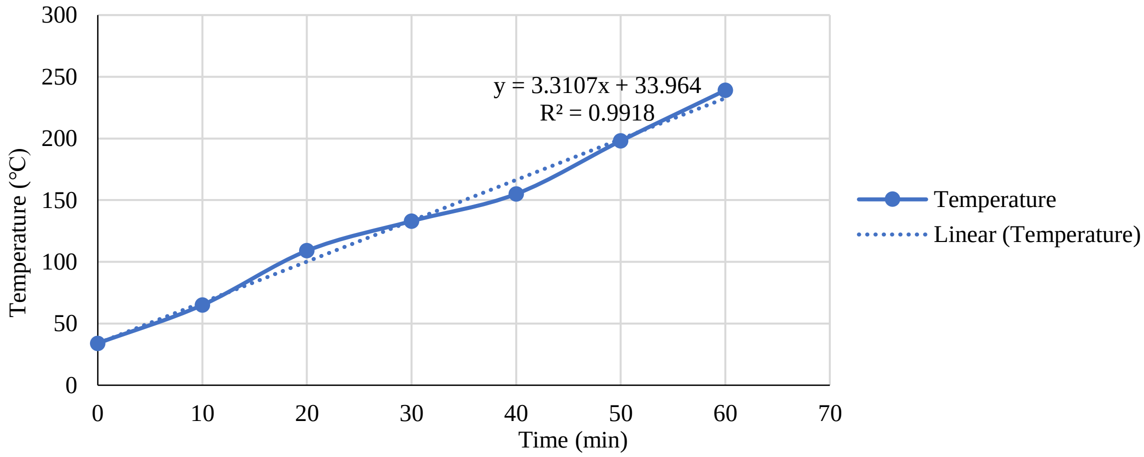

Figure 2. Plot of temperature against time.

Table 4. Pressure at Time Intervals.

Time (minutes)	Pressure (MPa)
0	0
10	0.0108
20	0.0445
30	0.1910
40	0.3004
50	0.3068
60	0.3985

Pressure and Time Trends During PKS Combustion Process

These outcomes also indicate that the pressure values were increasing steadily with time.

In other to establish the relationship between pressure and time, the graph of pressure against time was plotted in Figure 3.

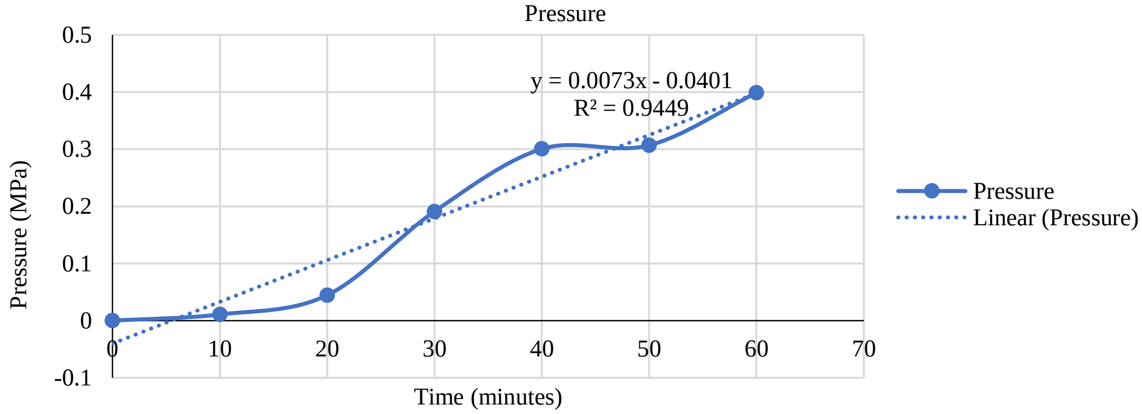

Figure 3. Plot of pressure against time.

Table 5. Temperature and Pressure at time interval.

Time (minutes)	Pressure (MPa)	Temperature (℃)
0	0	34
10	0.0108	65
20	0.0445	109
30	0.1910	133
40	0.3004	155
50	0.3068	198
60	0.3985	239

Pressure and Temperature trends during PKS Combustion Process

These outcomes also indicate that the pressure values were increasing steadily with the temperature values.

In other to establish the relationship between temperature and pressure, the graph of pressure against time was plotted in Figure 4.

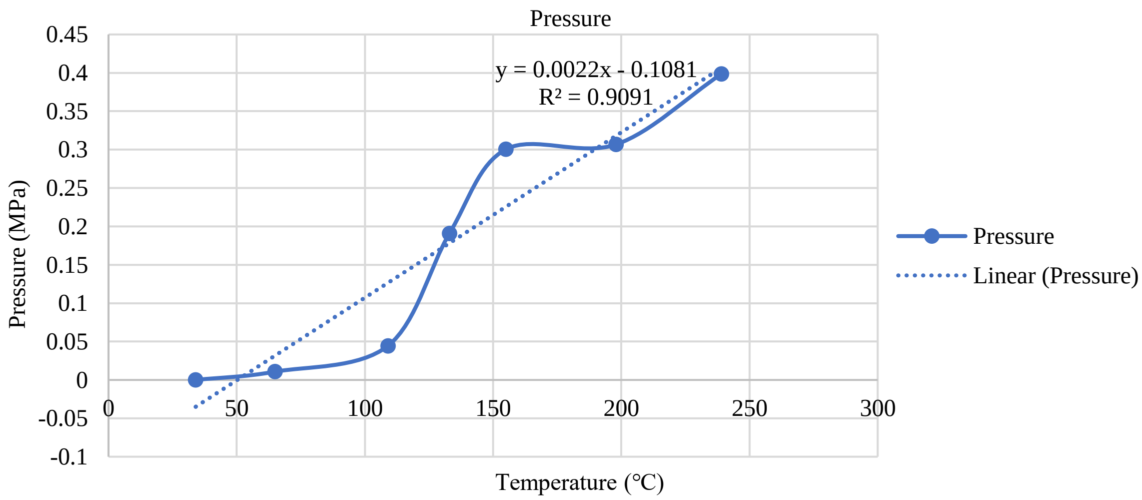

Figure 4. Plot of pressure against temperature.

Performance Characteristics

After reassembling of the steam generator, the steam generator was tested and the performance improvement (%) was compared with Oladosu *et al* 2007 using the equation below:

$$\% \text{ improvement} = \frac{\beta - \lambda}{\lambda} \times 100 \% \quad (1)$$

where:

β is the outcome of this study

λ is the outcome from Oladosu *et al* 2017

Table 6. Result of the Performance Characteristics on comparison with the Past Research.

Performance parameters	Rated design capacity	Outcome from this research	Oladosu *el al.*, 2017	Performance difference (%)
Steam temperature (°C)	250	239	220	8.64
Steam pressure (MPa)	0.35	0.39	0.38	2.63
Fuel consumption rate (kg/h)	25	2.92	3.0	2.67
Dryness fraction	0.78	0.93	0.95	0.03

Experimental Data obtained with the Steam Turbine and Alternator Connected Together Using Belt and Pulley System

With the Components Mounted on a Vibration Isolator

Table 7 presents the performance data of the system with the components mounted on a vibration isolator.

Table 7. With the components mounted on a vibration isolator.

S/N	Displacement, S(mm)	Velocity, v(mm/s)	Acceleration, a(mm/s^2)	Voltage, V(v)	Rotational Speed, N(rpm)
1	2.9	65.0	1.6	24.0	904
2	1.9	49.0	1.3	9.0	701

With the Components Mounted Without a Vibration Isolator

Table 8 presents the performance data of the system with the components mounted without a vibration isolator.

Table 8. With the components mounted without a vibration isolator.

S/N	Displacement, S(mm)	Velocity, v(mm/s)	Acceleration, a(mm/s^2)	Voltage, V(v)	Rotational Speed, N(rpm)
1	1.4	77	1.1	12.0	808
2	1.2	57	0.8	10.0	751

Experimental Data obtained with the Steam Turbine and Alternator connected together using Flange Coupling System

With the Components Mounted on a Vibration Isolator

Table 9 presents the performance data of the system with the components mounted on a vibration isolator

Table 9. With the components mounted on a vibration isolator.

S/N	Displacement, S(mm)	Velocity, v(mm/s)	Acceleration, a(mm/s^2)	Voltage, V(v)	Rotational Speed, N(rpm)
1	1.53	45.1	14.2	56	1152
2	1.392	45.3	19.7	56	1152

With the Components Mounted Without a Vibration Isolator

Table 10 presents the performance data of the system with the components mounted without a vibration isolator

Table 10. With the components mounted without a vibration isolator.

S/N	Displacement, S(mm)	Velocity, v(mm/s)	Acceleration, a(mm/s^2)	Voltage, V(v)	Rotational Speed, N(rpm)
1	1.375	45.4	14.37	56	1152
2	1.322	46.1	20.2	56	1152

Table 11. Summary of the performance evaluation of the steam powered alternator and turbine.

Parameters Measured	With Axial Coupling	With Transverse Connection
Maximum Voltage	56v	24v
Maximum Speed	1152rpm	904rpm
Maximum Sound Level	73dB	71dB

Table 7 and Table 8 presents the experimental data of when the steam turbine and alternator are connected using a belt and pulley system, both with and without a vibrator isolator. The primary parameters include displacement (S), velocity (v), acceleration (a), voltage (V) and speed (N).

The displacement values ranges with the vibrator isolator ranges between 1.9 mm and 2.9 mm, while without the isolator, the displacement is 1.2 mm to 1.4 mm. With the use of isolator, the displacement is slightly higher, this is a result of the system's ability to absorb and cushion vibrations rather than transmitting them to the supporting bed.

The velocity with the isolator ranges from 49 mm/s to 69 mm/s and without the isolator, it is 57 mm/s to 77 mm/s. Without the isolator, higher velocities were recorded, this indicates that the vibrational energy is not absorbed effectively and it is transferred through the machine and foundation.

The acceleration values are higher with the vibration isolator (1.3 mm/s^2 to 1.6 mm/s^2) than without vibration isolator (0.8 mm/s^2 to 1.1 mm/s^2). Higher acceleration when using the vibration isolator shows that while the isolator allows some freedom of movement, it prevents harmful forces from being transmitted to the bed.

The voltage output generated with the vibration isolator ranges from 9V to 24V, while without the isolator, it ranges between 10V to 12V. The voltage output is higher with the use of vibration isolator, this suggests that the system experiences less mechanical loss from vibrations transmitted to the adjustable bed. Therefore, more mechanical energy is available for conversion into electrical energy leading to a higher voltage output.

The speed values with the vibration isolator ranges from 701 rpm to 904 rpm while without the isolator, it is 751 rpm to 808 rpm. The vibration isolator minimizes the amount of vibrational energy that affects the system's rotational components, allowing more mechanical energy to be converted into rotational motion, hence reaching higher speeds.

Table 9 and Table 10 presents experimental data when the steam turbine and alternator are connected using a flexible flange coupling system again with and without a vibration isolator.

The displacement values with the use of vibration isolator ranges between 1.392 mm and 1.53 mm while without the use of isolator, they are between 1.322 mm and 1.375 mm. The displacement is relatively small in both cases, but slightly higher with the isolator, indicating that the system is absorbing more vibration energy with the isolator in place.

The velocity values with the vibration isolator ranges between 45.1 mm/s and 45.3 mm/s, while without the isolator, they range between 45.1 mm/s and 46.1 mm/s. The velocity values are close in both cases, but the slightly higher values without the vibration isolator suggests more direct transmission of vibrational forces to the adjustable bed.

The acceleration values range from 14.2 mm/s^2 to 19.7 mm/s^2 with the vibration isolator and from 14.37 mm/s^2 to 20.2 mm/s^2 without the isolator. These values are marginally higher without the isolator, showing that the presence of the isolator slightly dampens vibrational forces transmitted through the system.

The voltage output remains constant at 56V both with and without the vibration isolator, indicating that the coupling system is more efficient at transferring mechanical energy to electrical output regardless of the isolation setup.

The speed is also constant at 1152 rpm in both cases. The speed stability indicates that the coupling system provides a more uniform and direct power transfer between the turbine and alternator compared to the belt and pulley system.

Comparative Discussion of the Power Transmission Cases (Flexible Flange Coupling and Belt and Pulley Connection)

1. *Efficiency:* The flange coupling system is clearly more efficient than the belt and pulley system. It maintains consistent voltage output (56V) and speed (1152 rpm) in both isolated and non-isolated conditions, whereas the belt and pulley system shows lower voltage output and inconsistent speed.
2. *Effect of the Vibration Isolator:* The vibration isolator has a more pronounced effect on the belt and pulley system, reducing the velocity and acceleration but also impacting voltage output negatively. For the flange coupling system, the isolator's effect is minimal, showing only slight changes in mechanical parameters while maintaining consistent electrical output.
3. *Vibrational Damping:* The use of the vibration isolator is more beneficial in the belt and pulley system, where it helps to reduce the transmission of vibrations to the adjustable bed. Nevertheless, this ultimately results in a decrease in energy utilization.
4. The belt and pulley system is less efficient in transferring mechanical energy to electrical output compared to the flange coupling system.

CONCLUSION

This research focuses on the assembly and performance evaluation of a steam generator fired with palm kernel shell as fuel utilized in a 5 kW micro steam power plant (steam turbine and alternator) earlier developed at Mechanical Engineering workshop at the Federal University of Technology Akure. Each component to be assembled were inspected and checked for damages and modifications to ease the chosen method of assembly. The system was put jointly in its entirety, and its performance was determined.

An important feature of this system is the incorporation of an automated draught fan (Model: AFL) which was powered by a 12 V D.C source and the lagging of the steam pipes.

The performance parameters were taken with different instrumentations to evaluate the performance characteristics of the system and from the experimentation, the results obtained for the maximum steam temperature, maximum steam pressure and dryness fraction were 239℃, 0.39 MPa and 0.93 respectively, which can be used for household purposes, industrial applications and generation of electricity when connected with necessary gadgets.

The flange coupling system is more efficient than the belt and pulley system. It records consistent voltage output (56V) and speed (1152 rpm) in both isolated and non-isolated conditions, also the vibration isolator has a more pronounced effect on the belt and pulley system, reducing the velocity and acceleration but also impacting voltage output negatively. For the flange coupling system, the isolator's effect is minimal, showing only slight changes in mechanical parameters while maintaining consistent electrical output.

The use of the vibration isolator is more beneficial in the belt and pulley system, where it helps to reduce the transmission of vibrations to the adjustable bed. However, this comes at the cost of reduced energy efficiency.

Due to the challenges encountered during evaluation phase of the project, the following recommendations are hereby made; the performance evaluation result shows that axial coupling using a flexible flange coupling performs better than transverse connection with belt and pulleys. For future implementations or improvements, it is recommended to use axial coupling configuration. Further research should focus on the unaccountable heat losses within the components and find a way of reducing them to continuously enhance the system.

Also, further research should perform long-term durability tests on both axial coupling and transverse connection to assess wear and tear, maintenance requirements and long-term performance stability.

To help provide a stable fire process, which will inevitably raise the maximum temperature and maximum pressure of the steam produced, an automated feeding system should be devised to minimize fuel waste and maintain a constant fuel discharge into the combustion chamber.

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