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Performance Enhancement of a Failed Steam Generator

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ABSTRACT

A 5 kW steam generator that has failed was refurbished by redesigning, replacing and reassembling of some critical components. The aim was to enhance the new steam generator performance by increasing the maximum steam temperature and pressure while reducing fuel consumption rate. The failed parts were identified, and standard design equations were used to redesign the critical components – including the riser, downcomer, superheater and the steam drum. Additionally, the steam gauge and pressure gauge were replaced. After the reassembled, the new steam generator was tested to determine its performance. From the experimental test, the result showed that the maximum steam temperature, maximum steam pressure dryness fraction, and fuel consumption rate were 235 ℃, 0.39 MPa, 0.95 and 2.92 kg/hr respectively, for one hour of running. These outcomes represent an improvement (%) compare to the previous studies.

Keywords: Stem generator, Palm kernel shell (PKS), Critical Components.

INTRODUCTION

For many centuries, steam generators have been designed in different forms with the sole aim of boiling water to generate steam or hot water, which is used for different functions in different homes and processing industries (Riznic, 2017). The system in which steam is generated is called a steam generator (Woodruff *et al* 2004), which encompasses the boiler drum, furnace, runners, boiler internals, mountings, and is literally is called a steam boiler. (Chattopadhyay, 2004). A steam generator is a closed vessel in which steam is produced from water by combustion of fuel. (Rajput, 2006). According to the American Society of Mechanical Engineers (ASME 2010), a steam generating unit is defined as a combination of apparatus for producing, furnishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated. While Industries like bottling companies (e.g., Nigerian bottling company), textile mills (e.g., Da viva, Lagos, Princess textile, Lagos), breweries (e.g., Nigerian breweries, Guinness Nigeria), diary and meat processing (e.g., Zartech Nigerian Limited, Ajala Farms and Food Processing company, Ibadan), food and canning (e.g., Friesland Campina Nigeria, Ekulo Group of Companies, Nigeria), beverage processing (e.g., Cadbury Nigeria Limited, Dangote sugar refinery plc), and vegetable oil processing (e.g., Nozak Oil Mill, Edo State, Adebutu Palm Oil Processing Mill, Ogun State), require wet steam for certain purposes at different stages of their processing lines; utility outfits, such as thermal power stations (e.g., Egbin Electrical Power Business Unit and AES, Lagos State), require dry steam to rotate their steam turbines for electrical power generation. Superheated steam has a desirable effect, as it decreases the moisture content of the steam at the turbine exist (Cengel, 2020). Hot water is often employed at homes for heating purpose at low pressure.

These industries need a regular supply of steam to operate their businesses. Hence, steam generators are needed to perform these functions. Steam is sometimes preferred over hot water in some applications, such as absorption cooling, sterilizers, and steam-driven equipment due to the increase in its heat content resulting from latent heat (Jekayinfa and Bamibgoye, 2008). The performance of a steam-utilizing outfit or industry solely depends upon the efficiency of its steam generator.

Steam generators may be of different shapes and sizes, depending on their applications. Steam engineers have developed, modified and derated numerous of steam generators for academic study and to meet modern world demands (Rajput, 2007). As a result of the improved technological advancement, many industries today largely

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depend on steam for equipment operation and production. Steam plays a crucial role in engineering and energy studies. In science and engineering laboratories, steam is sometimes needed to generate power, to carry out tests or for other heating applications (Mahian *et al.*, 2020; Men *et al.*, 2021)

Steam generator are made up of two major parts, namely: the furnace, where the combustion of the fuel takes place, and the boiler drum, where the separation of the steam-water mixture occurs either due to variation in their densities, assistance of boiler internals or combination of them (Loo et al, 2008; Ayodeji, 2011). Palm kernel shell (PKS) is viable fuel source for steam generators due to its high calorific value and abundance as a waste product (Nasution *et al.*, 2014; Igwebuike *et al.*, 2024). This research focuses on refurbishing a failed steam generator and enhancing its performance, which was previously developed earlier at the Mechanical Engineering Workshop of The Federal University of Technology Akure (FUTA) for generating steam for a 5.0 kW micro steam thermal power plant.

Motivation

The research was aimed to address the unreliable energy supply in Nigeria, which has left the society socially and economically backward. Developing a micro power plant steam generator will be a very good alternative for generating electricity, especially in areas that are off grid. To enhance the efficiency of the failed steam generator, the boiler drum, was relocated from outside to inside the furnace, reducing thermal losses and retaining heat within the system. Additional, the riser was positioned under the boiler drum to enhance natural circulation, as the density difference between steam and water creates a natural flow pattern, increasing the overall efficiency of the system (Gupta, 2018; Fedorov 2024).

Furthermore, an automated draught fan (air circulating system) was integrated into the system to optimize fuel burning rate, improving the steam quality (dryness fraction) and increasing the air supply for the combustion of the palm kernel shell and the removal of flue gases. This balances air-fuel mixture, minimizes excess air and reduces heat losses, significantly enhancing the efficiency of the steam generator (Pachaiyappan *et al* 2015, Amitkumar *et al* 2017). The needed instrumentation such as the temperature measuring instrument and pressure gauge were procured and replaced to ensure accurate monitoring and control of steam.

(i) Boiler Drum Unit:

The boiler drum comprises of two sections: a cylindrical topmost part and a conical base section, which collectively form the steam and water space. It occupies the topmost section of the steam generator. It is made from stainless steel of 3 mm thickness for corrosion resistance and to withstand high pressure and temperature.

(ii) Downcomer Tube:

The is a tube that conveys water from the water tank to the furnace in the boiler. The downcomer allows the water to fall by gravity from the water drum.

(iii) Riser tube:

It conveys wet steam from the furnace to the boiler drum. Its discharge is located by the side of the boiler drum to facilitate easy discharge of the mixture.

(iv) Superheater:

It is located above the steam space of the steam generator. It enables the wet steam from steam space gain additional heat due to convection and radiation as the steam flows through the coil turns before discharging it to where it is needed.

Design Procedure

The machine was visually inspected to identify of the faulty parts/components. The inspection revealed that the

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superheater exit port needed to be remolding, the temperature gauge has dial is melted and pressure gauge requires a new dial. A diagnosing of the steam generator was conducted to define the problem in steam drum, riser, downcomer and superheater. Pressure and leakage test were performed, indicating that riser and superheater were leaking while the boil drum and downcomer had rusted were leaking.

The faulty parts of were redesign for as detailed in equation 2-5, and the fabrication procedure and reassemble of the failed parts are presented Table 1. The design analysis results are shown in Table 2. An automated draught fan was incorporated to enhance air supply to the system. The fabricated parts were then assembled and the newly developed machine was evaluated. The results were documented and compared to the test results before failure.

MATERIALS AND METHODS

The method of used in the fabrication of the identified parts is welding, a popular techniques used in boiler fabrication (Raji *et al.*, 2012). The critical components to be redesigned in the steam generator include the boiler drum, downcomer, riser and superheater. The fabrication process, design and material selection for each component are presented in Table 1. The materials used in this study can be classified as fabrication material, evaluation materials, and the instrumentation. The fabricated components were primarily made from stainless steel, selected based on appropriate equations (formulae) and engineering standards, considering the various properties: corrosion resistance, high tensile strength, durability, temperature resistance, easy formability.

The palm kernel shell used for the evaluation was sourced within Akure Metropolis. The instrumentation used, the temperature gauge (Model: WIKAI, 500 ^oC/950 ^oF) and pressure gauge (Model: WIKAI, 40 bar/600psi) to determine the maximum steam temperature and maximum steam pressure. These instruments were procured for the study.

Design Consideration

In the redesign, fabrication and evaluation of the steam generator, the following factors were taken into consideration:

1. Production of a maximum quality of steam with minimal fuel consumption
2. Pressure and temperature of steam: The system must be designed to withstand the high temperature and pressure when working under serve condition.
3. Velocity of fluid at difference stages: The velocity of water and steam must be considered to prevent vibration in the boiler drum and connected pipes.
4. Material selection: The material selection for fabrication of each component must be able to withstand high temperature, corrosion and must be durable.
5. Availability of the material: The selected material for part redesign are standard and easily accessible at any period of time when it is needed.
6. Cost of material (economic consideration)
7. Mechanical constraints: The system must be design to withstand mechanical stresses and ensure safe and efficient operation of the steam drum.

Design Criteria

The following assumptions were considered in the course of redesigning and fabricating these identified parts/components of the steam generator and evaluating it, according to Oladosu, (2017), Chattopadhyay, (2014), Nag, (2004)

1. The maximum steam temperature of the steam generator is 250 ℃
2. Inlet pressure of steam generator is 50 kPa

3. Exist pressure of the steam generator is 350 kPa
4. Efficiency of the steam generator is 90 %
5. Power output is 5.0 kW
6. Isentropic efficiency is 86 – 88 %
7. Calorific value of palm kernel shell is 22.51370×10^3 kJ/Kg
8. Downcomer diameter ranges from 150 mm to 200 mm
9. Circulation velocity ranges from 0.4 m/s to 1.4 m/s
10. The circulation ratio of steam is within the range from 6 to 25
11. The velocity at superheater falls between the range 10 to 12 m/s.
12. Initial temperature of water is 24℃.

A. Determination of the Expected Steam and Fuel Consumption Rate

The expected steam and fuel consumption of a steam generator are the amounts of steam and fuel that the steam generator is designed to produce and supply for use. These are critical parameters that need to be determine. The steam and fuel consumption per hour can be determine using equation (1) as describe by Nag (2004)

$$\frac{m_s}{m_f} = \frac{h_1 - h_{f3}}{\eta \times cv} \qquad (1)$$

where: m_s is mass of the steam generated per hour Kg/h, h_1 is enthalpy of the steam in kJ/Kg

h_{f3} is enthalpy of the feed water in kJ/Kg, c_v is caloric value of the palm kernel shell in kJ/Kg

m_f is mass of fuel in kg/h.

B. Determination of the Size of the Boiler Drum

The total volume of the boiler drum is determined boiler using equation (2)

Volume of boiler drum, $V = \pi {r_1}^2 h_1 + \frac{1}{3} \pi {r_2}^2 h_2 \qquad (2)$

Where: r_1 is the radius of the cylindrical section in m, h_1 is the height of the cylindrical section in m, r_2 is the radius of the conical section in m, h_2 is the height of the conical section in m

C. Determination of the number Riser tube

According to Nag (2011), the number of riser tubes is determined using equation (3)

$$n = \frac{w_s}{w} \qquad (3)$$

where: w_s is the mass flow rate of saturated water entering the riser kg/s, w is the rate of steam in the riser tuber in kg/s

D. Determination of the number tubes of the Downcomer

The number of tube of the downcomer was determined using the equation recommended by Nag (2007)

$$m_f = \left(\frac{n \pi D^2}{4}\right) \rho_f V \qquad (4)$$

where: m_f is mass flow rate of saturated water in the downcomer in kg/s, n is number of tubes, D is diameter of

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downcomer in mm, ρ_f is density of saturated water at the boiler drum pressure in kg/m^3, V is average velocity of water in the downcomers in m/s

E. Determination of the number of coils of the Superheater

The number of coils of the superheater was determined using the equation described by Nag, (2004)

$$m_s = n\frac{\pi}{4}d^2\frac{V_s}{V_g} \quad (5)$$

where; d is the inner diameter of the super heater tube (in mm); V_s is the average velocity of the steam in the superheater (m/s), n is the number of coils superheater, V_g is specific volume of the superheated steam in m^3/kg, m_s is mass of the steam generated in kg per hour.

Table 1: Fabrication procedure and reassemble of identified failed parts

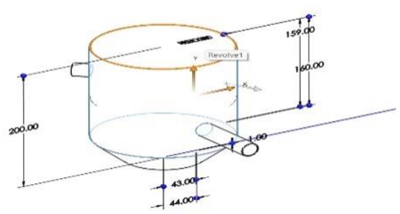
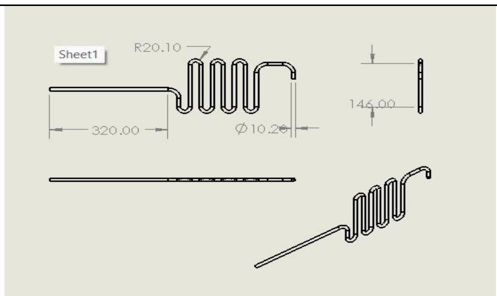
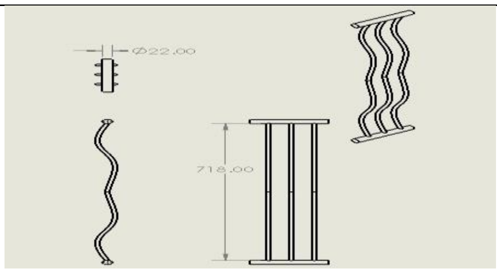
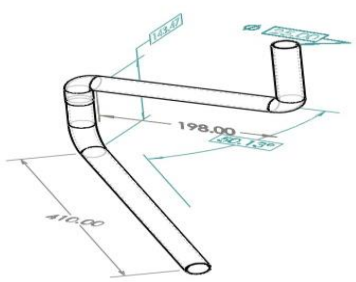
Component	Fabrication process	Component design and measurement	Material used and reason
Steam drum	Cutting of material and welding of plate		Stainless steel: affordable, weldable, malleable, high conductivity.
Superheater	Cutting of material, welding and bending of tube		Stainless steel: Corrosion resistance, temperature resistance, high tensile strength
Riser	Cutting of material, welding and bending of tube		Stainless steel: Corrosion resistance, temperature resistance, high tensile strength
Downcomer	Cutting of material, welding and bending of tube		Stainless steel: Corrosion resistance, temperature resistance, high tensile strength

Table 2: Summary of the design analysis

Summary of the Design Analysis				
Component of Machine	Equation Number	Parameter	Calculated Results	Adopted Results
Boiler drum volume (m^3)	2	π, r, h	0.042	0.04
Number of Riser tubes	3	w_s, w	3.33	4.00
Number of downcome tube	4	m_f, π, D, ρ_f,V	0.55	1.00
Number of superheater coils	5	m_s, π, d, V_s,V_g	2.5	3.00

Evaluation Procedure

After the redesign and reassembling of the identified components, preliminary tests namely the leakage test and operating test were carried out on the steam generator. The leakage test was conducted on the welded joints by pressurizing the system with a pressure of 1.5 bar base on the size of the steam generator for 24 hours to observe if there will be drop in the pressure. After 24 hours, it was observed that there is no drop in pressure in the system, thus the system is free leakages. The system was then subjected to experimental test on 15th of February 2024. The experimentation started around 3: 14 pm at a room temperature of 34 ℃ by charging a known volume of water into the system whose thermodynamic property has already been determined.

During the operational process, 10 liters of clean water of temperature of 24 ℃ was used for the performance evaluation. 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. Temperature and pressure values of the generated superheated steam were recorded at 10 minutes intervals for 1 hour of running starting from the initial values before the test was carried out. The test was conducted three times, and the results obtained were presented on average basis. 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. The quantity of water evaporated from and at 100 ℃ to produce saturated steam at this temperature by absorbing same amount of heat as used in the steam generator under actual operating conditions is known as equivalent evaporation (Nag 2008; Osafehinti S. I 2011)

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 liters of clean water of temperature of 24 ℃ were used for the performance evaluation. This was charged through the feed water inlet of the steam generator. In an hour, 2.92 kg PKS were used, accounting for losses. Temperature and pressure values of the generated superheated steam were recorded at 10-minutes intervals for 1 hour of running, starting from the initial values before the test was carried out. The test was conducted three times and the results obtained were presented on average basis.

The maximum steam temperature, maximum steam pressure and dryness fraction obtained were 234 ^{0}C, 0.3985 Mpa and 0.93 respectively and this was attained in 1 hour of the PKS combustion.

RESULTS AND DISCUSSION

The list of components identified that require redesign comprises basically of a conical shape boiler drum, runners (downcomer and riser,) superheater while temperature gauge and pressure guage were procured from the market. The design and procurement of parts of the machine were done in line with some design criteria and standard engineering equations.

After the reassembling, leakage and operational tests showed that refurbished boiler is free from leakages.

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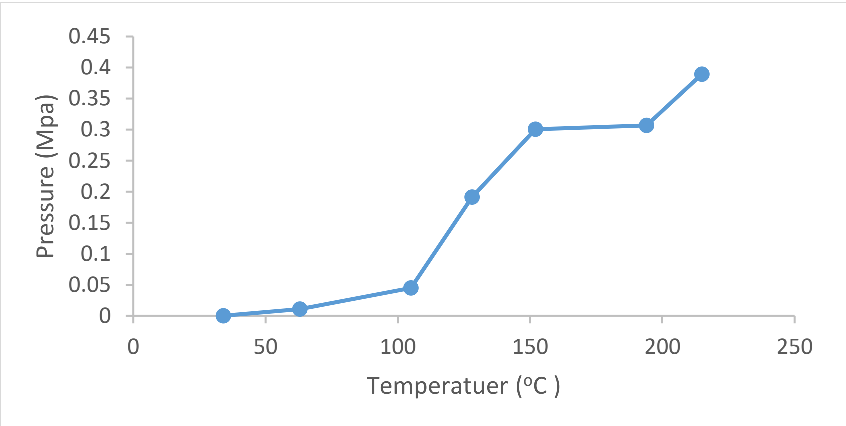
Table 3: Summary of the average values of temperature and pressure recorded at 10 minutes interval.

Time (minutes)	Pressure (Mpa)	Temperature (°C)
0	0	34
10	0.0108	63
20	0.0445	105
30	0.1910	128
40	0.3004	152
50	0.3068	194
60	0.3985	234

These outcomes indicate that temperature and pressure were increasing steadily with time.

In other to establish the relationship between pressure and temperature, the graph of pressure against temperature was plotted in Figure 1

Figure 1: Pressure and Temperature Trends during PKS combustion process



The curve on Figure 1 shows that the pressure is increasing as temperature increases. Figure 2 and Figure 3 illustrates the graphs of pressure against time and temperature against time. Both graphs show that as pressure increases as the time increases and also the temperature increases with time.

Figure 2: Pressure and Time Trends during PKS combustion process

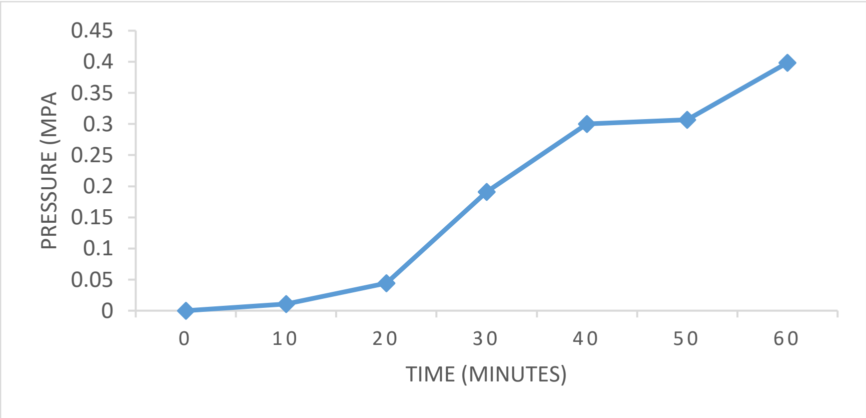


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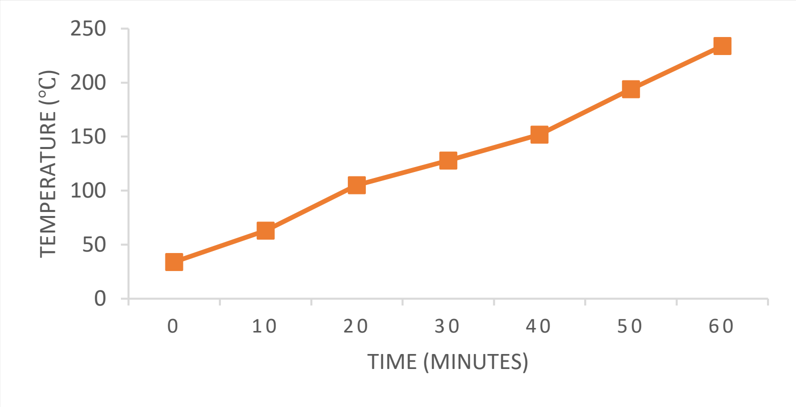
Fig. 3: Temperature and Time trends during PKS combustion process



Performance Improvement Test

It is important to carry out the performance improvement test on the refurbished steam generator so as to determine the actual performance and efficiency of the steam generator and how much it has improved when compared with the failed one produced by Oladosu *et al* (2007).

Performance improvement test was carried out using equation (6).

$$\% \text{ improvement} = \frac{outcome\ from\ this\ result\ - oladosu\ et\ al\ 2017}{oladosu\ et\ al\ 2017} \times 100\% \qquad (6)$$

Table 4: Result comparison

Parameters	Outcome from this research	Oladosu *el al*., 2017	Performance improvement (%)
Exit temperature (^{0}C)	234	220	4.55
Pressure (Mpa)	0.39	0.38	2.63
Fuel feed rate (kg/h)	2.92	3.00	5.00
Dryness fraction	0.93	0.98	5.10

CONCLUSION

A failed 5.0 kW steam generator powered by palm kernel shell has been successfully redesign, reassembled and evaluated. The parts/components that needed to be refurbished were identified and redesigned/replaced. The design, fabrication and procurement of parts of the machine were done in line with some design criteria and standard engineering equations. The most important feature of this machine is the insertion of the steam drum into the furnace and the incorporation of an automated blowing unit (Model: AFL) which was powered by a 12 V D.C source.

The redesigned parts are the steam drum, riser, downcomer and the superheater. Why the component to be replaced, the temperature, pressure gauges and the tap where sort for and replaced. After the refurbished components/parts were assembled, various tests were carried out. The test includes the leakage test and operating test. Every welded joint was tested for leakages by passing water through the water tank, tubes and steam drum. This is necessary in other to ensure a free leakage system when the system is functioning under severe condition of high temperature and pressure. The redesign steam generator successfully passed the test. Operating test was conducted after the leakage test. In operating test, a fuel feed rate of 2.92 kg/hr produced maximum steam temperature, pressure of 234℃ and 0.39 MPa respectively in 1 running hour.

The refurbished steam generator was evaluated using the following parameter: maximum steam temperature, maximum steam pressure, quantity fuel supplied, quantity of feedwater, feedwater temperature and temperature of the surrounding. Full experimental test was carried out on steam generator and the results were compared with the failed one produced by Oladosu *et al* (2017). These results show an improvement on the past research result because of the insertion the boiler drum into furnace, the use of an automated blowing unit and the replacement of the failed components/parts.

From the foregoing, it could be concluded that the usage of this machine would reduce the problem of unreliable energy supply in Nigeria especially for the rural dwellers by increasing the quantity of steam required by a 5.0 kW micro steam thermal power plant.

RECOMMENDATION

Base on the results obtained from the study the following recommendation were made: That an automated feeding system should be developed to reduce fuel wastage and ensure a steady discharge of the fuel into the combustion chamber promoting a stable combustion process which will invariably increase the maximum steam temperature and maximum steam pressure thus enhancing the overall performance of the steam generator.

REFERENCES

1. Amitkurmar, M, Tiwari G., Katoke P., Talmale K, (2017). “Case Study on Efficiency of Efficiency of Boiler and Factors Affecting it”. International Journal for Science Research and Development (IJSRD). ISSN (online): 2321-0613, pp 1790-1793.
2. American Society of Mechanical Engineers (ASME) 2010 Boiler and Pressure Vessel Code (BPVCK http://go.asmc.org /bpvc10).
3. Ayodeji O.Z., (2011) “Effects and controls of Boiler Rupture in Lagos State Steam Thermal Power Station” M. Eng. Thesis
4. Cengel, Y. A. and Boles, M. A., (2020) "Thermodynamics: An Engineering" Approach, 9th Edition, McGraw Hill, Companies Inc.
5. Chattopanadhyay, P. (2004): “Boiler Operation Engineering Questions and Answers” Second Edition, India, Tata McGraw-Hill Ltd
6. Fedorov, A.I. (2024). Optimization of Drum Internals of CCPP Heat Recovery Steam Generator with Multiple Forced Circulation. Power Technol Eng 57, 746-749. https://doi.org/10.1007/s.10749-024-01729-7
7. Igwebuike, C.M, Oyegoke, T. “Decarbonizing Our Environment via the Production of Biomass Methanation in Developing Nations: A Waste Management Tool. Pure Appl. Chem., 1-20
8. Jekayinfa S. O and A. I “Bamgboye, Energy use analysis of selected palm-kernel oil mill in south western Nigeria”. Energy, 33, 2008, 81 – 90
9. Loo. S. V. and Koppejan, J. “Handbook of biomass combustion and co-firing Earthscan”. International Conference on Energy and Environment. 67(6), 2008, 70-75.
10. Mahian, O., Mirzaie, M. R., Kasaeian, A., & Mousavi, S. H. (2020). Energy analysis in combined heat and power systems: A review. Energy Conversion and Management, 226, 113467. https://doi.org/10.1016/j.enconman. 2020.113467
11. Men, Y., Liu, X., & Zhang, T. (2021). A review of boiler waste heat recovery technologies in the medium-low temperature range. Energy, 237, 121560. https://doi.org/10.1016/j.energy.2021.121560 5
12. Nag P.K (2004) “Power Plant Engineering”. 3rd Edition. The McGraw-Hill Companies
13. Nag P.K (2007) “Heat and Mass Transfer” Second Edition, Tata McGraw Hill Publishing New Delhi.
14. Nag, P.K. (2008): “Power Plant Engineering”. Second Edition, Tata-McGraw-Hill Publishing Company Ltd New Dehil.
15. Nag P. K. (2011): Power Plant Engineering Third Edition: Tata McGraw-Hill New Delhi.
16. Nasution, M. A., Herawan, T. and Rivani, M., (2014) “Analysis of Palm Biomass as Electricity from Palm Oil Mills in North Sumatera”. Energy Procedia. 34(5), 2014, 166 –172.
17. Osafehinti S. I., Ayodeji, O. Z (2011) “Modeling of 1.0 MW-h Combustible Waste Fuel Steam Thermal Station: A Panacea for Rural/Off-Grid Areas’ Electrification” Journal of Energy Technologies and Policy

www.iiste.org ISSN 2224-3232 (Paper) ISSN 2225-0573 (Online) Vol.8, No.3, 2018

18. Pachaiyappan R., Prakash J, Dasa. (2015). 'Improving the boiler efficiency by optimizing the combustion air', Applied Mechanics and Materials. Pp 238-242
19. Raji T. O., Oyewole, O. M and Salau, T. A (2012). "New features for performance enhancement of experimental model bubbling fluidized bed combustor". International Journal of Scientific and Engineering Research. 3(1): 217 – 226.
20. Rajput R. K (2006). "Fluid Mechanics and Hydraulic Machines in SI Units", Third Edition, New Delhi: S. Chand & Company Ltd. Ram Nagar.
21. Rajput R. K (2007). "Thermal Engineering", Laxmi Publications Ltd., New Delhi
22. Riznic, J. (2017). Introduction to steam generators—from Heron of Alexandria to nuclear power plants: Brief history and literature survey. Steam Generators for Nuclear Power Plants, 3-33.
23. Woodruff E.B., Lammers H.B. and Lammers T.F., "Steam Plant Operation", 8th Edition. The McGraw-Hill Companies, Available: www.digitalengineeringlibrary.com, Accessed: September 7, 2010, 200