Steam Turbine: A Review on Some Critical Parts

OMOJOGBERUN, Y. V.[1], KAREEM, B.[2], ADEYERI, M. K.[3]
[1] *Department of Mechanical Engineering, The Federal Polytechnic, Ado – Ekiti, Ekiti State. Nigeria.*
[2] *Department of Production and Industrial Engineering, Federal University of Technology, Akure, Ondo State. Nigeria.*
[3] *Department of Mechatronics Engineering, Federal University of Technology, Akure, Ondo State. Nigeria.*

Abstract- Electricity is a very important issue in the economic growth, progress and poverty eradication of any nation. The future of any country depends on the availability of electricity in that country. Steam turbine is a prime mover that is very essential in the generation of electricity. Most of the worlds' electricity is generated using steam turbine. In the operation of steam turbine, there are some critical components that are affected directly by the super heated steam. This paper presents a review on three critical components; the blade, the rotor and the sliding bearing. As a result of the effect of the direct effect of the steam on the blade, some stresses will be developed. These include the centrifugal stress due to the action of centrifugal load on the blade, thermal stress, centrifugal bending stress and dynamic stress due to changing thermal load on the blade from the steam. Thermal stress also acts on the rotor shaft since the blade is attached to it. As the rotor rotates, torque is produced which results in power generation by the alternator attached to the end of the rotor shaft. The stresses that will act on the blade must not be more than the maximum allowable stress of the blade material hence; the material will fail with time during operation. Also, the shear stress on the rotor due to effect of torque must not exceed the allowable shear stress of the rotor material. The coefficient of friction, the critical pressure and the heat generated by the bearing at both ends of the rotor must also be put into consideration and must not exceed that the bearing can withstand in the selection of appropriate materials for these critical components during design.

Indexed Terms- Blades, Rotor, Sliding Bearing, Steam Turbine and Super-heated Steam

I. INTRODUCTION

Energy plays the most vital role in the economic growth, progress, poverty eradication and security of any nation. Uninterrupted energy supply is a vital issue for all country today. Future economic growth crucially depends on the long term availability of energy from sources that are affordable, accessible and environmentally friendly (Omojogberun et al. 2022). Electrical energy has become an essential facet of life in all spheres of modern society (Stuck and Schurdak, 2012). Electricity plays an important role especially in developing economies because the efficient usage of different resources depends directly on electricity (Omar et. al., 2022).The world Electrical energy consumption in the last thirty years has doubled and keeps increasing with about 1.5% per annum (Khattak et. al., 2016). Economic and population growth are the most important drivers of growing global energy demand (Almad et. al., (2014). Electricity can be generated using a turbine as a prime mover to drive a generator. There are four basic types of turbine according to the fluid used namely; the gas turbine, steam turbine, wind turbine and water turbine. All work on the same principle but their specific design differs significantly. Steam turbine is a prime mover in steam power plant used in generating electricity. Currently, nearly 90% of the electricity produced in the United States is generated using steam turbines, while about 80% of that produced worldwide comes from steam generators. With such a substantial amount of electrical energy being produced by steam turbine generators, it is in the best interest of society to make these generators as efficient and as sustainable as possible (Stuck and Schurdak, 2012). Steam turbines are one of the most versatile and oldest prime mover technologies still in general production used to drive a generator or mechanical machinery. Steam turbine has being in use for about two hundred years for generating electricity (Khattak et al., 2016).

II. STEAM TURBINE

Any device that converts the chemical energy contained in a fuel into mechanical energy (i.e. shaft work) via combustion is called a heat engine. Heat Engines are generally classified according to the thermodynamic cycle they follow. The most common heat engine in industrial application is the steam turbine. (Kumana, 2018). The steam turbine is a mechanical device that converts thermal energy in pressurized steam into useful mechanical work (Reddy et. al., 2014).

The operation of the steam turbine is based on the Rankine Cycle (Figure 1). The Rankine cycle with super heat shown in Figure 1 includes a steam receiver which receives the steam from the boiler. In modern plant, a receiver is used with one boiler and is placed between the boiler and the turbine. It is also necessary to provide a storage of condensate between the condensate and boiler feed pumps since the quantity of feed water varies with different demands on the boiler.

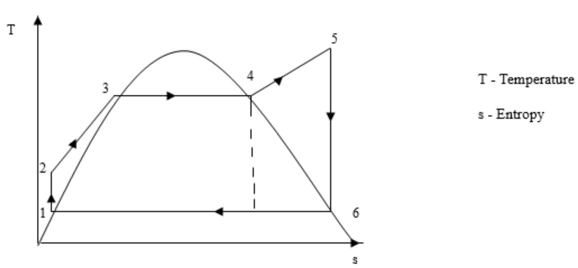

Figure 1. The Rankine Cycle for Superheated steam (Eastop and McConkey, 2003))

A schematic arrangement of a Power Station is shown in Figure 2. In this, the fuel is used to heat the water in the steam generator thereby producing the steam that leaves the boiler via a nozzle at a very high temperature and pressure. The high temperature, high pressure steam entering the turbine spins the blades that are attached to the rotor of the turbine and produces the work that turns the alternator which in turn generate electricity (electrical energy).

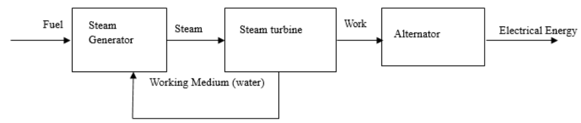

Figure 2. Schematic arrangement of a Power Station (Arunkumar *et al*, 2016).

Figure 3 shows the schematic diagram of the flow process of a steam turbine operation. The chemical energy of the fuel is converted to heat energy of the steam in the steam generator or boiler and then into kinetic energy or rotational energy of the rotating shaft (Rotor) of the turbine that turns the alternator to generate electricity.

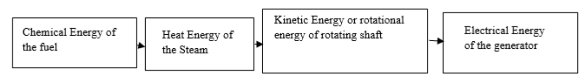

Figure 3. Schematic diagram showing the flow process of the steam turbine operation

Figure 4 shows how the fuel is used to heat the boiler that generate the high temperature, high pressure steam which enters the turbine via the nozzle at a very high speed to spin the the turbine blade and rotate the rotor or shaft which turns the alternator to generate electricity. The low temperature, low pressure steam enters the condenser where it is pumped back into the boiler for further steam generation. In the simple schematic representation shown in figure 4, a fueled boiler produces steam which is expanded in the steam turbine to produce power.

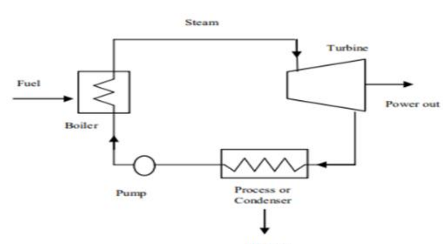

Figure 4. A schematic representation of a steam turbine power system (EPA, 2015; Darrow *et al.,* 2015)

III. STEAM TURBINE CRITICAL COMPONENTS

The steam turbine has various parts such as the blades, rotor, bearing, casing, seals valves, diaphragms, governors, labyrinth seals steam chest etc. This paper present a review on some Steam Turbine components viz the blades, rotor, and sliding bearing which were identified as critical components of steam turbine since they are directly affected by temperature, pressure and flow rate/speed of the steam.

Steam Turbine Blades

In the thermal power station, the steam turbine is the prime mover which generates enough torque to produce power from generator. Steam turbine obtains its power by the adiabatic expansion of steam flow through the blades. Turbine has several parts which participate in the conversion of kinetic energy to mechanical energy (Nurbanasari, 2014). The turbine blade in a steam turbine plays an important role in this. The failure in a steam turbine is a prevalent occurrence and has a strong correlation with the forces acting on the blade, which are centrifugal forces, centrifugal bending, steady steam bending, unsteady centrifugal forces due to lateral shaft vibration and alternating bending. Steam turbine blades are the heart of turbine which experiences the most intense static and dynamic conditions throughout their life span. Therefore, analysis of blades is compulsory to avoid any failure. Figure 5 shows the airfoil geometry of the steam turbine blade.

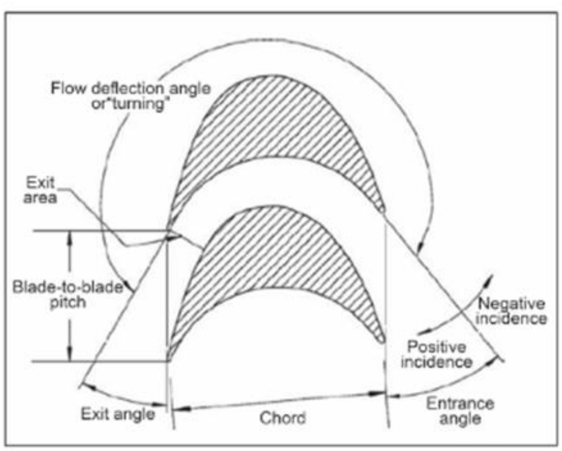

Figure 5. Airfoil Geometry (Kareem *et al*., 2018)

- Possible Loads on the Steam turbine Blade

The Centrifugal force on the blade

Steam turbine is a fundamental component in most electrical power generation systems around the world. Their efficiency and capital cost are dependent on the quality of the blade root which secures the thermodynamic aerofoil sections to the high speed rotor. Steam turbine converts the heat energy of the steam into useful work. The nozzles or fixed blades in the turbine are designed to direct the steam flow into well-formed, high-speed jets as steam expands from inlet to exhaust pressure (Ganesh *et al.,* 2016). The blade and the blade attachment belong to the most highly stressed components in a steam turbine generator. The high turbine speed and the dead weight of the blade makes the steam turbine to be subjected to enormous centrifugal forces during plant operation (Maha, 2018). Figure 6 shows the Load and Stress Distribution due to Centrifugal Stress. Figure 7 is the schematic representation of centrifugal force acting on a rotating shaft.

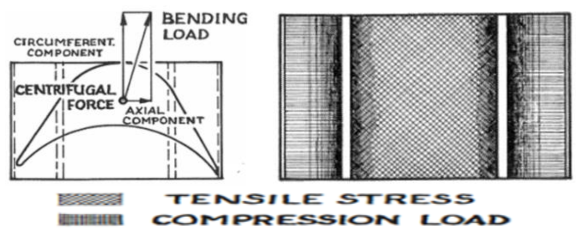

Figure 6. Load and Stress Distribution due to Centrifugal Stress (Naumann, 2007)

Evaluation of the Centrifugal force

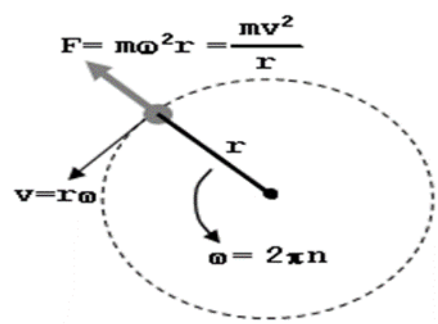

Figure 7. Schematic representation of centrifugal force (Vegi, 2013)

The centrifugal force on an element dr at a radius r is given by

$dF = (\gamma a dr)\omega^2$ (Vegi, 2013) (1)

where, γ = specific weight of blade material, kg/m^3

a is blade cross-sectional area, m^2; and

ω is angular velocity = $\frac{2\pi N}{60}$ (rad/sec)

Total centrifugal force exerted at the blade root is

$$F_c = \int_{r_r}^{r_t} \gamma a d r \omega^2 = \frac{\gamma a \omega^2}{2}(r_t^2 - r_r^2) \quad (2)$$

where, r_t is tip radius, and r_r is root radius

the relationship becomes; $F_c = \frac{\gamma a}{2\pi} A (\frac{2\pi N}{60})^2$ (3)

where:

A is annular area = $A = \pi(r_t^2 - r_r^2)$

(Vegi, 2013)

- Centrifugal Stress on the blade

The centrifugal loads caused by rotation are the primary source of stress on the blade (Ganesh *et. al.*, 2016). Blades are important components of steam turbine which can failed due to the stress arising from centrifugal and bending forces (Heidari and Amini, 2017). The blade in the steam turbine is exposed not only to stress due to centrifugal force but also to stress due to the pressure of steam on the blade. Equation 4 is used to determine the centrifugal or tensile stress which occurs basically at the root of the blade.

$s_c = \frac{F_c}{a_{root}} \pi r^2$ (Vegi, 2013) (4)

where; S_c, F_c and a_{root} are centrifugal or tensile stress, centrifugal force on the blade and root area of the blade respectively.

- Thermal load on the blade

The thermal effect on the blade results in thermal stress and thermal strain and as the temperature approaches high extremes, the blade material expands by a significant amount. The Strain related to this change in temperature is given by the Equation 5.

$$\varepsilon_T = \alpha(\Delta T) \quad (5)$$

where ε_T is the strain in the blade material in a specific direction and α represents the linear thermal coefficient of the same material after a change in temperature (ΔT) have been determined. Since the material properties are known, basic Hooke's law will be used to determine the magnitude of the expansion by using the Equation 6.

$$\delta_T = \varepsilon_T x L \quad (6)$$

The thermal stress on the blade can also be determined using Equation 7

$$\sigma_{thermal} = E^* \alpha^* \Delta t \quad (7)$$

where;

E is Young Modulus of the material, α is Coefficient of thermal expansion and,

- Centrifugal Bending Stress

If the gravity center of the blade section and the gravity center of the blade root are not in a straight line at different heights, centrifugal bending stress is generated and because centrifugal force acts on the center of mass and periphery of this area, which causes the tensile stress to concentrate on one side of the blade's center of gravity line and the other is compressive stress. The blade is designed to compensate for the airflow load at the center of the tip of the blade. Blade designers use the effect of centrifugal bending to counter the effects of airflow bending (Zhu, 2019).

$$\sigma_b = {My}/{I} \quad (8a)$$

When the strain is known, the bending stress can also be calculated using the equation

$$\sigma_b = \varepsilon \times E \quad (8b)$$

where; ε, E are Strain on the blade and Young Modulus of the blade material respectively.

- Dynamic Stress

Dynamic stress is as a result of the vibration generated in the turbine blades due to non-uniform flow of the steam. For example, nozzle-wake interactions and structural features interfere with airflow. The vibration of the blade leads to the fluctuation of the stress in the blades. If the amplitude of the stress fluctuation is very small, the stress induced does not exceed the stress the material can bear, but sometimes it is more than the blade material can bear. At given amplitude, the blades undergo high cycle fatigue, causing them to suddenly fail after many cycles, and greater stress fluctuations will lead to greater stress in the blades. The low fatigue cycles which lead to blade failure are relatively few. The dynamic pressure can be considered only in a situation where there is a greater stress fluctuation than blade material cannot bear.

- The Steam Turbine Rotor

The steam turbine rotor is the spinning component that has wheels and blades attached to it. The blade is the component that extracts energy from the steam. The rotor carries the blades which converts the thermal energy of the steam into the rotary motion of the shaft and as the shaft rotate, torque is transmitted that leads to the generation of power. Figure 7 shows a typical steam turbine rotor to which the blades are attached.

Figure 7. Steam Turbine Rotor

- The Torque Transmitted by the Rotor Shaft

Since the rotor is a rotating element during operation, torque will be transmitted during operation. The torque transmitted can be calculated using Equation 9 and the power can be calculated using Equation 10

Torque transmitted by rotor shaft = $\frac{\pi \times \tau \times D^3}{16}$ (9)

where; D and τ are the rotor shaft diameter and the shear stress respectively

Shear stress of the material is given by

$Shear\ stress = 0.75\ \times (ultimate\ tensile\ strength)$ (Roymech.org, 2023) (10)

$$Power = \frac{2\pi NT}{60} \quad (11)$$

where; N and T are the rotor speed in revolution per minute (rpm) and torque respectively.

- Thermal Stress in Rotor

Thermal stress plays important role during turbine cold start up. When power plant starts up and down or changes load, the internal of rotor metal will produce the temperature gradient, due to the presence of the temperature gradient, rotor will produce thermal stress in the unstable conditions. When steam turbine starts up, the temperature of rotor surface gradually rise with steam temperature rising, temperature of the central part change lag behind the rotor surface, the rotor of steam turbine is subjected to variations in short period of time due to this start and stop cycle of the turbine. This causes sudden changes in the temperature with transient thermal stress in the rotor. The surface of the rotor may produce crack and the stress field of the rotor is influenced by the temperature field, when temperature is biggest between rotor center and surface, the thermal stress is maximum (Bian and Li, 2013).

The Equation for thermal strain comes from the linear coefficient of thermal expansion multiplied by the change in length of the element

$$\alpha = \frac{l - l_o}{l_o t} \quad (12)$$

where α is the temperature coefficient of thermal expansion

l = final length of the rotor shaft

l_o = initial length of the rotor shaft

$\delta l,\ is$ due to temperature increase and is given by

$$\delta l = \alpha l dt \quad (13)$$

- The Steam Turbine Bearing

Bearing is a mechanical element that allows relative motion between two parts such as shaft and housing thereby reducing friction between the moving part (Bhandari, 2014). Bearing aids in the rotation of objects (BYUU's, 2022). The bearing is used at the end of rotor to support the weight of the rotor. Sliding bearing is typically provided to the entire steam turbine to maintain axial position of the rotor. The major type of bearing used in the steam turbine is the Babbitt bearing. This is because Babbitt alloys offers corrosion resistance, excellent wetting, low wear and friction resistance and are known for their hard/soft composition.

The major parameter considered in the design of the sliding Babbitt bearing are the coefficient of friction, the critical pressure and the heat generated during the operation of the steam turbine.

- The Coefficient of Friction in the Design of Sliding Bearings

The coefficient of friction in the design of bearings is of great importance, because it affords a bearing the means for determining the loss of power due to bearing friction. The coefficient of friction of a full lubricated Journal bearing is a function of three variables which are;

$\frac{ZN}{P_b}, \frac{d}{c}, \frac{l}{d}$

Coefficient of friction may be expressed as

$$\mu = \varphi(\frac{ZN}{P_b}, \frac{d}{c}, \frac{l}{d}) \quad (14)$$

μ, φ, Z, N, P_b, d, l and c are coefficient of friction, a frictional relationship, absolute viscosity of the lubricant (kg/m-s), Speed of the Journal bearing in rpm, bearing pressure on the projected bearing area in (N/mm^2) (bearing pressure can be calculated using; load on journal/$l \times d$), diameter of the journal, length of the bearing and diametral clearance respectively.

The coefficient of friction for journal bearings

$\mu = \frac{33}{10^8}\left(\frac{ZN}{P_b}\right)\left(\frac{d}{c}\right) + k$ (Khurmi and Gupta, 2019) (15)

k = factor to correct for end leakage and it depends upon the ratio of length to the diameter of the bearing (i.e. l/d) for instance, k = 0.002 for l/d ratio of 0.75 to 2.8 (Khurmi and Gupta, 2019).

- The Critical Pressure of the Journal Bearing

This is the pressure at which the cut film breaks down so that metal to metal contact begins. It is called critical pressure or the minimum operating pressure. It is obtained as

$P_c = \frac{ZN}{4.75 \times 10^6}\left(\frac{d}{c}\right)^2\left(\frac{l}{d+l}\right)$ N/mm^2 (Khurmi and Gupta, 2019) (16)

For steam turbine (Main)

Bearing pressure (P_b) = 0.7 MPa to 2 MPa, Z = 0.002 to 0.016 kg/m-s, $\frac{ZN}{P_b} = 14$, $\frac{c}{d}$ = 0.001 and $\frac{l}{d} = 1 \ to\ 2$

For safety reason the highest values are taken from the table in machine Design by Khurmi and Gupta, 2019

If $\frac{l}{d}$ = 2 , therefore, l = 2d

Substituting into the equation

$$P_c = \frac{ZN}{4.75 \times 10^6}\left(\frac{d}{c}\right)^2\left(\frac{2d}{d+2d}\right) \quad (17)$$

- Heat Generated in a Journal Bearing

The heat generated in sliding journal bearing is given by the Equation 19

$Q_g = \mu WV$ (Nm/s or J/s or watts) (Khurmi and Gupta, 2019) (18)

where;

μ is Coefficient of friction, W is load on the bearing in Newton

Load on bearing = Pressure on the bearing in N/mm^2 ✕ projected area of the bearing in mm^2

= P (l ✕ d) (19)

V is Rubbing Velocity (m/s) = $\frac{\pi dN}{60}$ (20)

N is speed of Journal in rpm = shaft speed

Therefore,

$$Q_g = \mu P(lxd)\left(\pi dN/60\right) \quad (21)$$

CONCLUSION

In the steam turbine operations, the various stresses on the blades (centrifugal stress, centrifugal bending stress and the dynamic stress) must be put into consideration during design, the torque and power transmitted by the rotor as well as the coefficient of friction, the critical pressure and the heat generated by the steam turbine bearing are very vital on these critical steam turbine components. These critical components determine the efficiency of the steam turbine and inappropriate attention on these parts can affect the efficiency of the steam turbine and indirectly on the whole steam power plant. In order to ensure the efficiency of these critical turbine components (blade, rotor and bearing), it is necessary to ensure that;

i. the combine stresses (centrifugal stress, centrifugal bending stress and the dynamic stress) must not be higher than the ultimate (maximum allowable) stress of the blade material.
ii. the allowable shear stress at the design stage must not exceed that of the possible rotor material to be chosen.
iii. the critical bearing pressure as well as the heat generated by the bearing should not exceed that which the bearing can withstand.

In order to ensure this, it is necessary to find out at the design stage that the stresses on the blades, rotor and coefficient of friction as well as maximum pressure and heat generated on the bearing does not exceed that the material can withstand by developing a system models (either mathematical or computer model) for estimating these parameters to accommodate for temperature changes as well as vibration for optimum power delivery.

ACKNOWLEDGMENT

I want to acknowledge Mr. Yele Ewuola Omojogberun for his immense support in my academics, Prof. B. Kareem for his encouragement and guidance as well as Prof. M. K. Adeyeri for his advice.

REFERENCES

[1] M. S. Ahmad, M. E. Mohamed and S. S. Ibrahim - Overview of Alternative Fuels with Emphasis on the Potential of

[2] LNG as Future Marine Fuel. Proceedings of the institution of Mechanical Engieers. Part M. Journal of Engineering for Marine Enviroment, 2014.

[3] S. Arunkumar, V. Tamilvanan, K.R. Sathishkumar, S. Suresh and K. Tamilselvan, - Optimizing the Parameters of 210 MW Steam Turbine Operation and Maintenance. South Asian Journal of Engineering and Technology Vol. 2, No.23, 2016, pp. 1 – 5.

[4] S. Bian, and W. Li Calculation of Thermal Stress and Fatigue Life of 1000MW Steam Turbine Rotor. Energy and Power Engineering. Vol. 5, 2013, pp. 1484 – 1489.

[5] K. Darrow, A. Tidball, J. Wang and A. Hampson - Technology Characterization – Steam Turbine. Catalogue of Combine Heat and Power Technologies, 2015, pp 4-3 – 4-10

[6] Ganesh, D. Jagan, and D. Padma The Design and Analysis of Steam Turbine blades Effect with HP and IP. International Journal of Scientific Progress and Research. Vol. 26, No. 3, 2016, pp 16 – 122.

[7] T. D. Eastop, and A. McConkey - Applied Thermodynamics For Engineering Technologists. Pearson Educational (Singapore) Pte. Limited Indian Branch, Patparganj, 5th Edition, 2003, pp 332 -335.

[8] M. Heidari, and K. Amini - Structural Modification of Steam Turbine Blade. Mechanical Engineering, Science and Technology international Conference, 2017, pp. 1 - 7

[9] B. Kareem, T. Ewetumo , M. S. Adeyeri, A. Oyetunji and O. E. Olatunji - Design of Steam Turbine for Electric Power Production Using Heat Energy From Palm Kernel Shell. Journal of Power and Energy Engineering, 2018, pp. 111-125.

[10] M. A. Khattah, M. A. Ashraff, M. Ikmal and A. Syafiq -- Common Types of Fuels in Steam Power Plant. A review. Journal of Advanced Rsearch in Fluid Mechanics and Thermal Sciences. Vol. 23, No. 1, 2016, pp. 1- 24.

[11] R. S. Khurmi, and J. K. Gupta - A Textbook on Machine Design. 14th Edition Eurasia Publishing House (PVT), Ram Nagia. New –Delhi, 2019, pp. 962 -1020.

[12] J. D. Kumana - Essentials of Steam Turbine Design and Analysis. The Global Home of Chemical Engineers, 2018. https://www.aiche.org/resources/pub

[13] K. Maha and E. I. Nwankwo - Evaluation of the Impact of High Exhaust Temperature in Steam Turbine Operation. Research Journal of Mechanical Operation..Vol. 1, No.1, 2018, pp. 1 - 9.

[14] H. G. Naumann - Steam Turbine Blade Design Options: How to specify or Upgrade. Proceedings of the 11th Turbo machinery Symposium, 2007, pp. 29 – 50.

[15] M. Nurbanasari and H. Abdurrachim - Investigation of Leakage on Water Wall Tube in a 660 MW Supercritical Boiler. Journal of Failure Analysis and Prevention Vol. 14, 2014, pp. 657 – 661.

[16] J. K. Omar, F. A. Ismail, T. K. Ibrahim and S. H. B. Abu Hassan - Energy and Exergy Analysis of steam Power Plants A Comprehensive Review on Classification, Development, improvement and Configurations. Ain Shams Engineering Journal. Vol. 13, Issue 3, 2022.

[17] Y. V. Omojogberun, D. Oigbochie and G. L. Onibon - Harnessing Geothermal Energy As Alternative Source of Energy. International Advanced Research Journal in Science, Engineering and Technology. Vol. 9, Issue 6, 2022, pp. 218 – 223.

A. S. Reddy, M. D. I. Ahmed, T. S. Kumar, A. V. K. Reddy and V. v. P. Bharathi Analysis of Steam Turbines. International Journal of Engineering and Science. Vol. 3, Issue 2, 2014.

[18] M. C. S. Reddy - Design and Analysis of Steam Turbine Rotor. International Journal of Mechanical Engineering and Technology.Vol 6, Issue 11, 2015, pp. 195 – 201.

[19] M. D. Robertson and D. Waton - A design Analysis of Steam Turbine Blade Roots Under Centrifugal Load. The Journal of Strain Analysis for Engineering Design 1st Publication, 1990.

[20] RoyMech - Shear Strength of Metals, 2020. https://roymech.org>shear_tensile

[21] Z. Stuck and S. Schurdak - Steam Turbine Blade Design. 12th Annual Freshman Conference. Conference Session B6, 2012.

[22] L. K. Vegi - High Pressure Impulse Steam Turbine Blade. International Journal of Scientific and Engineering Research. Vol. 4, Issue 6, 2013, pp. 562 -571.

[23] M. Zhu - Design and Analysis of Steam Turbine Blades. 3rd International Conference on Fluid Mechanic and Application. Journal of Physics: Conference Series 1300, 2019, pp. 1-7.