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IMPROVING STEAM TURBINE EFFICIENCY: AN APPRAISAL

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ABSTRACT

The paper deals with an appraisal of improving steam turbine efficiency, operating at different loads. Turbine energy efficiency has a significant impact on overall steam power plant efficiency. Three new methods of increasing efficiency of turbine power plants are described: reheating of steam turbine, regenerative feed heating of steam turbine, and by binary vapour cycle of steam turbine. This is achieved by increasing average temperature of heat supply in steam turbine plant by mixing steam after superheating with products of combustion of natural gas in the oxygen. Development of this idea consists in maintaining steam temperature in the major part of expansion in the turbine at level, close to initial temperature. It also involves increasing efficiency of gas turbine plant by way of regenerative heating of the air by gas after its expansion in high pressure turbine and before expansion in the low pressure turbine. This is perfected, also, by increasing efficiency of combined cycle power plant through avoiding of heat transfer from gas to wet steam, and transferring heat from gas to water and superheated steam only.

Keywords: Steam Turbine, Energy Performance, Blade Velocity Co-Efficient, Impulse Steam Turbine, Reaction Steam Turbine.

INTRODUCTION

Steam turbine converts the thermal energy of pressurized steam into useful mechanical work, driving the electrical generator. Therefore, its efficiency has a major impact on the amount of electricity produced, also, on overall power plant efficiency. As energy demand rises constantly over the last decades, energy efficiency is an important aspect of modern economy. High efficiency power generation can reduce the primary energy consumption. The steam turbine is a prime-mover in which the potential energy of the steam is transformed into kinetic energy and latter in its turn is transformed into the mechanical energy of rotation of the turbine shaft. The turbine shaft, directly or with the help of a reduction gearing, is connected with the driven mechanism. Depending on the type of the driven mechanism, a steam turbine may be utilized in most diverse fields of industry, for power generation and for transport. Transformation of the potential energy of steam into mechanical energy of rotation of the shaft is brought about by different means. The thermodynamic performance of a steam power plant depends on many factors, including cycle arrangement and inlet and exhaust steam conditions. However, the dominant contributor to the overall power plant efficiency is the steam turbine itself. The thermodynamic and aerodynamic performance of the steam turbine is primarily determined by steam path components, including the valves, inlet nozzles, buckets, steam leakage control devices and the exhaust nozzles (Madu, Orji and Uyaelumuo, 2018).

To maximize power plant efficiency, aerodynamic and steam leakage losses in the turbine steam path must be minimized in both the rotational and stationary components. The types of efficiency losses that occur in a typical turbine stage and the approximate percentage that each type contributes to the total stage loss must be kept in perspective (Rajput, 2008). Nozzle and bucket aerodynamic profile losses, secondary flow losses, and leakage losses account for roughly 80% to 90% of the total stage losses. Nozzle and bucket profile losses can be significant if the blade shapes are not optimized for the local operating conditions. Profile losses are driven by surface finish, total blade surface area, airfoil shape and surface velocity distributions, and proper matching between nozzle and buckets to minimize incidence losses (Figure 1).

Equally, significant losses can be caused by the complex secondary flows generated as the viscous boundary layers along the inner and outer sidewalls of the steam path are turned through the blade rows. These complex, three dimension flow must be thoroughly understood before effective methods can be developed to reduce the associated losses (Vasserman and Shutenko, 2004).

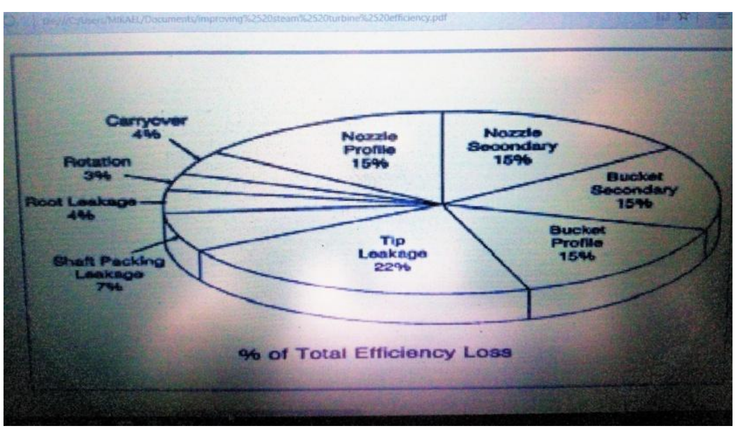

Figure1: Typical HP Turbine Stage Efficiency

Losses Modes

HP turbine stage efficiency losses steam leakage through the seals between stationary and rotating components of the turbine constitutes an efficiency loss because the leakage flow does not contribute to the work output of the stage. This loss can be quite significant, particularly at bucket tips. In short high pressure (HP) stages, the tip leakage loss are driven by the high-stage pressure levels and the relatively larger amount of radial clearance area compared to the nozzle flow area. In taller intermediate pressure (IP) and low pressure (LP) stages, the tip leakage loss is driven by the higher reaction levels at the bucket tips, which increases the pressure drop across the bucket tip. Steam leakage through the diaphragm shaft packing and shaft end packing also causes losses, but these are generally of lesser magnitude than tip leakage losses. Equal attention must be paid to the losses in stationary flow path components, such as inlets, valves, and exhausts. Any pressure drop occurring in these components constitutes a loss, unavailable energy and a reduction in work output (Vasserman and Shutenko, 2004). Key Elements of Aerodynamic Development Programs Development efforts had been underway at GE for many years to better understand and reduce the various losses listed above. The objective of this long term program was to develop specific design features, for both new turbine sand retrofits of existing units that maximize overall turbine efficiency while maintaining a high degree of reliability and cost effectiveness. Most aspects of this multifaceted development program were being conducted in cooperation with other company components, such as Aircraft Engines, Gas Turbine and Corporate Research and Development (CRD). The four key elements of GE's overall aerodynamic development program were: development of better computational fluid dynamics (CFD) computer programs, which allow more accurate predictions of the complex behavior of the steam flow in the turbine; development of new design concepts to improve both baseline and sustained efficiency, making full use of the new CFD codes; an extensive laboratory test program to validate the CFD codes and verify the predicted efficiency gains; development of a suite of powerful automation and optimization tools to allow design implementation of advanced aerodynamic design features on a custom basis to maximize efficiency for each specific application in short design cycle times. This paper reviews recent advances in GE steam path technology resulting from these development initiatives and the impact of these advances on current GE steam turbine designs.

Steam, and combined cycle turbine power plants are generating major part of the energy used by humanity. Hence, increase of their efficiency is important. Steam turbine plants are characterized by high thermodynamically efficiency for achievable maximum temperature of steam but relatively low values of this maximum temperature. Combined cycle power plants are incorporating positive features of steam and gas turbine power plants; however transfer of substantial part of the heat from gas to steam causes substantial losses of efficiency due to irreversibility of heat transfer processes.

Steam Turbine Power Plant:

We have proposed to increase average temperature of heat supply in the steam turbine power plant which would in turn increase its efficiency. In the first case, it is achieved by way of mixing superheated steam with the products of combustion of natural gas in oxygen on the high temperature parts of isobaric processes of initial and intermediate superheating of the steam (Vasserman and Shutenko, 2006). In second case, average temperature of heat supply is further increased on account of maintaining of steam's temperature during major part of its expansion in the turbine close to initial temperature at the turbine's inlet. To achieve this, additional heat is supplied to the steam during its expansion in the turbine (Figure 2).

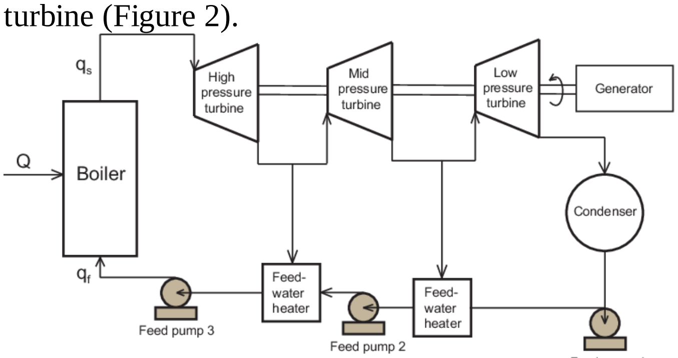

Figure 2: Typical Steam Turbine Power Plant

MATERIALS AND METHOD

In order to fully utilize the available energy of the steam for maximum efficiency, the complex three dimensional flow fields throughout the turbine must be accurately predicted. In particular, a better understanding is needed of the effects of wet steam, viscosity, and unsteady rotor stator interactions if the remaining losses are to be reduced. Recent advances in the development of CFD computer programs have provided GE with the tools needed to achieve better designs with reduced cost and shorter design cycle time (Madu and Nwankwo, 2018).

Viscous Euler CFD Code: In the early 1980s, the GE steam turbine, gas turbine and aircraft engine businesses began a long term joint research program with CRD to study secondary flow phenomena using a combined analytical and experimental approach. Analytical investigations included the development of complex computational fluid dynamics computer codes based on three dimensional formulations of the inviscid Euler equations and the viscous Navies-Stokes equations. The initial inviscid code was developed by CRD and called the EULER3D program. A viscous code that included turbulence models was later developed by GE Aircraft Engines and called the Viscous Euler program. Comprehensive experimental investigations were conducted to test the validity of the predictions made by the EULER3D code. These tests utilized CRD's large-scale wind tunnel test facility, and the results are described in detail. In this study, EULER3D predictions of the flow in a subsonic turbine nozzle cascade were compared to cascade test data, including lampblack and oil flow visualization studies. Comparisons were made for nozzles with both parallel and diverging sidewalls, and the code was able to predict inviscid flows in turbine blade passages quite well. A unique flow visualization method was developed for the wind tunnel facility to aid in understanding the physics of secondary flows. The flow particle trajectories were obtained by shining a strobe light on helium filled zero-buoyancy soap bubbles injected into the flow. Figure 3 clearly shows one leg of the "horseshoe" vortex spiraling around the nose of a nozzle cascade with parallel sidewalls. In the last few years, the Viscous Euler code has replaced EULER3D as the analysis code of choice for a wide variety of turbo-machinery design problems. Improvements in computer technology have made it practical to run viscous codes such as Viscous Euler on a network of high-powered workstations, without the need for supercomputers. The Viscous Euler calculation grid on a blade-to-blade plane for a high pressure bucket vane is a priority. A similar calculation grid is generated for the nozzle passage, and a complete stage solution is obtained by automatically iterating between the nozzle and bucket solutions as they run in parallel on separate workstations. For a complete 3D solution, up to 250,000 grid points might be needed in each blade passage to accurately resolve secondary flow details (Yadav, 2011). Mach number contours for this same vane in subsonic flow, and the trailing.

RESULTS AND DISCUSSION

Efficiency of steam turbine is mainly three types. As per blades movement and steam supply, steam turbine efficiency is different types. Diagram efficiency of steam turbine or blading efficiency of steam turbine is the ratio of work done on the blades to the energy supplied to the blades. The quantities used in diagram efficiency are directly related to the velocity diagram of steam turbine.

Let

V_1 = Absolute velocity of inlet steam in m/s, m = Mass of steam supplied in kg/s, V_{r1} = Velocity of steam relative to moving blades at entrance,(see velocity diagram of steam turbine) V_{r2} = Velocity of steam relative to moving blades at exit, So, energy supplied to the blade/sec,

$$= \frac{m\,v_1^2}{2} \quad J/S$$

As we all know that the work done on the blades per second,

$$= m\,(V_{r1} + V_{r2})\,V \quad J/s$$

So, Diagram or blading efficiency equation of steam turbine is,

$$\eta_b = \frac{m\,(V_{r1} + V_{r2})\,V}{m\,V^2/2} = \frac{2\,(V_{r1} + V_{r2})\,V_b}{V^2} \quad J/s$$

1. *Nozzle Efficiency of Steam Turbine:* Nozzle efficiency of steam turbine is the ratio of energy supplied to the blades per kg of steam to the total energy supplied per stage per kg of steam.

The energy supplied to the blades per kg of steam

$$= \frac{V_1^2}{2} \ (injoules)$$

So, Nozzle Efficiency equation of steam turbine is,

$$\eta_n = \frac{V_1^2\,/\,2}{1000\,h_d} = \frac{V_1^2}{2000\,h_d}$$

2. *Gross or Stage Efficiency of Steam Turbine:* Gross efficiency of steam turbine or stage efficiency of steam turbine is the ratio of the work done on the blades per kg of steam to the total energy supplied per stage per kg of steam. Calculation of gross or stage efficiency of steam turbine is:
3.

Let, h_1 = Enthalpy or total heat of steam before expansion through the nozzle in kJ/kg of steam, h_2 = Enthalpy or total heat of steam after expansion through the nozzle in kJ/kg of steam, Enthalpy or heat drop in the nozzle ring of an impulse wheel,

$$h_d = h_1 - h_2 \ (in\ kJ\,/\,kg)$$

Total energy supplied per stage = 1000 h_d J/kg of steam. Work done on the blade per kg of steam,

$$= 1\,(V_{r1} + V_{r2})\,V \quad J/kg \ of \ steam$$

Gross or stage efficiency

,

$$\eta_s = \frac{(V_{r1} + V_{r2})\,V}{1000\,h_d} = \frac{(V_{r1} + V_{r2})\,V}{1000\,(h_1 - h_2)}$$

We know that the Gross efficiency is the multiplication of blading efficiency and stage efficiency

Stage Efficiency = Blading Efficiency x Nozzle Efficiency.

All the above, steam turbine efficiency formula are important for both impulse and reaction turbine.

How to Improve Steam Turbine Efficiency: The performance of *steam turbine efficiency* can be discussed with the help of its internal efficiency characteristics. Some modern methods are used to improve the turbine efficiency. These methods are very easy and interesting too. Now we will discuss how to improve steam turbine efficiency as well as the power developed by the turbines. Though there are so many methods to improve the steam turbine efficiency but we only discuss the popular three methods. These three methods are used in modern steam turbines to improve their efficiency (Naradasu, Konijeti and Alluru, 2007). The methods are:

1. Reheating of steam turbine
2. Regenerative feed heating of steam turbine
3. Binary vapour cycle of steam turbine

Reheating Cycle of Steam Turbine: In this system, the steam's ability to work may be slightly increased by reheating the steam during its passing through the turbine. Steam first enters into the turbine at superheated state. Now steam's pressure and temperature is improved by efficiency of Rankine cycle. This will increase its expansion ratio and steam has become wet condition at the end of expansion. Now wet steam is exhausted from that the turbine and it is not good for turbine. It reduces erosion and internal loss of the turbine. This problem may be solved by reheating the steam at a constant pressure by the flue gases until it is again in the superheated state and use for turbine. The superheated steam is now taken back into the turbine to complete its expansion through the turbine. At a certain limit, steam's performance will be slightly increased with the help of this process. The block diagram of reheating of steam is shown Figure 3.

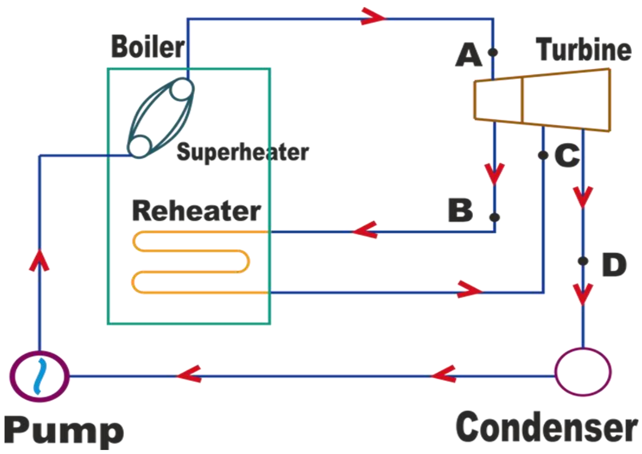

Figure 3: Block Diagram of Reheat Cycle

Advantages of the Reheat Cycle

The rating of steam in a turbine has the following advantages:

1. It increases the efficiency of the turbine.
2. It increases the work done through the turbine.
3. It reduces erosion and Internal loss of the turbine as because of increase in dryness fraction of steam at exhaust.

In reheat cycle, superheated steam enters into the turbine at a point A, shown in the picture. After that it expands is entropically as shown in the vertical line AB. Now steam becomes wet condition and again it is heated by constant pressure and temperature. Again the steam expands is entropically indicating the next stage of the turbine, by vertical line CD. Here is the h-s diagram of reheat cycle.

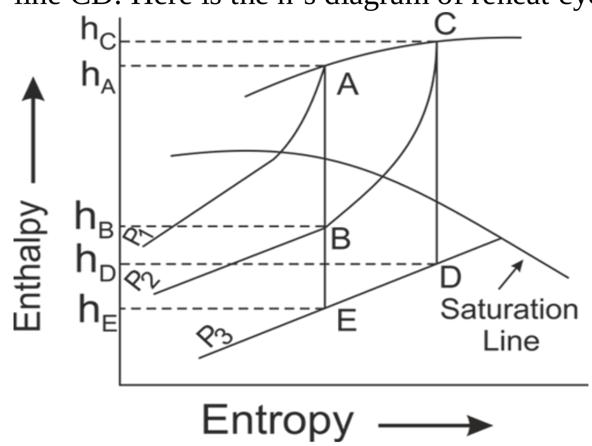

Figure 4: h-s Diagram of a Reheat Cycle

Let,

h_A = Enthalpy or total heat of steam at a point A.
h_B, h_C, h_D = Corresponding values at B, C and D.
h_{fd} = Enthalpy or sensible heat of water at D.

We know that the total heat supplied to the steam is the summation of total heat at a point A and the heat supplied during the reheating between B and C.

So, total het supplied =Total heat at A + Heat supplied between B and C

$$= h_A + [(h_C - h_B) - h_{fD}]$$

We also know that the work done,

$$= Total\ heat\ drop = (h_A - h_B) + (h_C - h_D)$$

And efficiency,

$$\eta = \frac{Work\ Done}{Total\ heat\ Supplied} = \frac{(h_A - h_B) + (h_C - h_D)}{h_A + [(h_C - h_B) - h_{fD}]}$$

Regenerative Feed Heating Cycle of Steam Turbine: The dry saturated steam is coming from the boiler and enters into the turbine at higher temperature. In the turbine it expands is entropically to a lower temperature as the same as Rankine and Carnot cycle. Worthy of note is that the heat is not added at higher temperature in the Rankine cycle, and Rankine cycle is less efficient than the Carnot cycle. Now the steam is coming from the turbine and condensed in the condenser. So a large amount of heat is rejected from the condenser as shown in the area DEFG. This heat is now pumped back and circulated around the turbine casing in the opposite direction to the steam flow in the turbine. The hot steam re-enters into the boiler. This type of steam heating is called Regenerative Heating (Figure 5). But due to heat loss, steam turbines expansions are no more isentropic and it flows through the path BC, which is exactly parallel to EA.

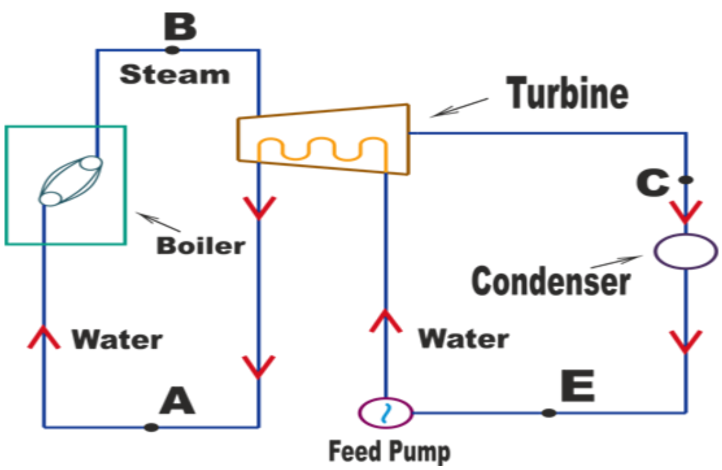

Figure 5: The Regenerative Cycle

Heat transferred to the liquid EAGF is equal to the heat transferred from the steam represents BPQC. At a constant temperature, heat is supplied to the working fluid and heat is rejected from the working fluid shown by the curve AB and CE. This, also, is represented by the area ABPG and CQFE.CQFE is equal to RPGD and it is equal to the presence of the heat rejected in the Carnot cycle. That's why the efficiency of ideal regenerative cycle is equal to the efficiency of Carnot cycle. But practically ideal regenerative cycle of steam turbine is not possible (Figure 6) because, liquid feed water can't supply the necessary heat to the steam turbine and moisture content is increased for the heat transfer. Since ideal regenerative cycle of steam turbine is not possible, so some sort of advantages that could be got, is the bleeding of the steam.

Bleeding: In regenerative heating, some steam is carried out from the turbine at certain points during its expansion. This steam is fed into the feed water heater increasing its temperature and then supplied to the boiler, and is known as bleeding. Using this process, there is a slight increase in efficiency but there is also a decrease in the horsepower developed.

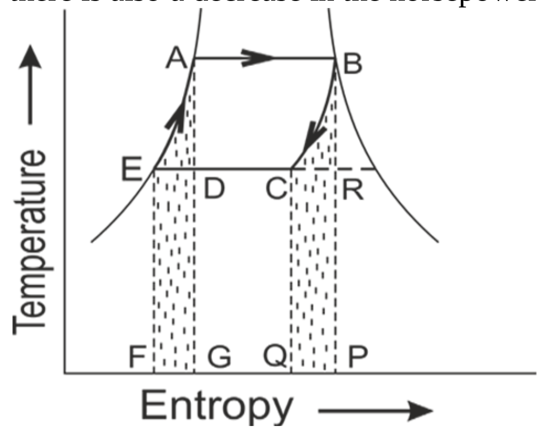

Figure 6: T-S Diagram of a Regenerative Cycle

Binary Vapour Cycle: Binary paper plans, Mercury is used to increasing the temperature of the plant without increasing its pressure. Actually, maximum possible efficiency of any steam Engine is given by the equation:

$$\eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

In the above equation T_1 is the higher temperature at which heat is absorbed and T_2 is the lower temperature at which heat is rejected. So if we increase the plant efficiency then we must increase the T_1 temperature because T_2 is fixed by the atmospheric condition. In a steam plant if T_1 is increased correspondingly some pressure is also increased. That's why Mercury vapour is used because it has the temperature range at low pressure. The critical temperature of mercury vapour is 588.4 c at a critical pressure of 21 bars.

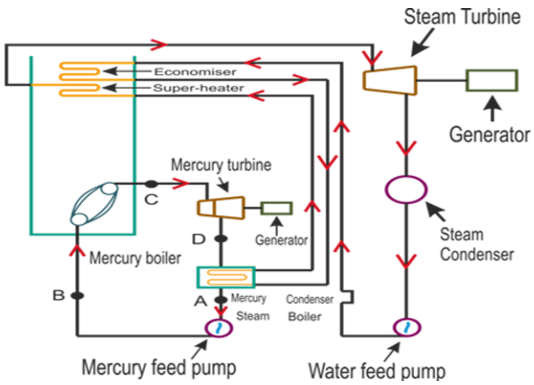

Figure 7: The Binary Vapour Cycle

In Figure 7 above, liquid mercury is coming from a heater to boiler, where it is evaporated. After that, it flows and expands in the mercury turbine at low pressure limit. Now Mercury exhausts to the Mercury condenser steam boiler where its latent heat is given out to the hot feed water. The Mercury is then returned to the mercury liquid heater and completes the cycle.

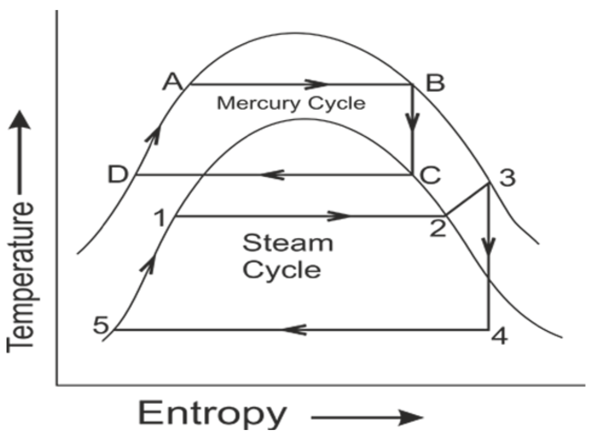

Figure 8: T-S Diagram of Binary Vapour Cycle

In the above T-S diagram of binary vapour cycle, ABCD represents the Mercury cycle and 1-2-3-4-5 line shows the steam cycle.

CONCLUSION

Steam Turbines are one of the main energy consuming equipment's, even though not much attention is paid to them. Trimming of operating parameters are essential for efficient operation of these turbines. The illustrations given in this paper reveal the impacts of the operating conditions on steam turbines. Huge benefits can be reaped by optimizing operating parameters, by minor modifications and even by replacing old inefficient turbines. New methods of increasing efficiency of steam, gas and combined cycle power plants are being proposed.

REFERENCES

Madu, K. E., Orji, M. U. and Uyaelumuo, A. E. (2018). Fluid Structure Interaction Analysis of a Micro-Hydrokinetic Turbine Rotor Blade. *Research Journal of Mechanical Operations*, 1 (1): 10-23.

Madu, K. E. and Nwankwo, E. I. (2018). Evaluation of the Impact of High Exhaust Temperature in Steam Turbine Operation. *Research Journal of Mechanical Operations*, 1 (1): 1-9.

Naradasu, R. K., Konijeti, R. K. and Alluru, V. R. (2007). Thermodynamic analysis of heat recovery steam generator in combined cycle power plant. *Thermal Science*, 11 (4): 143-156.

Rajput, R. K. (2008). *A Textbook of Power Plant Engineering*. Laxmi Publications Ltd. Pp. 4-9.

Vasserman, A. A. and Shutenko, M. A. (2004). Using oxygen and natural gas for increasing efficiency of steam turbine power plants. *Technical gases*, 2:39 - 42.

Vasserman, A. A. and Shutenko, M. A. (2006). Increasing efficiency of steam turbine power plants by means of isothermal expansion of working substance. *Industrial heat and power engineering*, 28:47-52.

Yadav, R. (2011). *Fundamentals of Power Plant Engineering: Conventional and Non-Conventional.* Central Publishing House publication. P. 23. *Fundamentals of Power Plant Engineering: Conventional and Non-Conventional.* Central Publishing House publication. P. 29.