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PERFORMANCE ANALYSIS OF A STEAM POWER PLANT OPERATING UNDER SUPERHEATED AND ISENTROPIC CONDITIONS

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ABSTRACT
Quality and sufficient power distribution at the present is a major challenge in many cities and industrial locations in most developing countries, like Nigeria. This is as a result of many factors which include inadequate generation and obsolete equipment. This research work entitled Performance Analysis of a Steam Power Plant Operating under Superheated and Isentropic Conditions, was undertaken to evaluate the variables that will bring about the efficient running of a typical steam power plant. With a turbine pressures of 20 bar and 2 bar, the analysis yielded a specific work output of 854.65 kJ/Kg; and plant thermal efficiency of 26.08 %. The rate of heat loss by the condenser approximates to 4114.55 J/s; and the rate of heat generation by the boiler equals 5027.74 J/s. The condition of steam at points 4 and 6_s is wet, but superheated at points 3 and 5. Optimizing the values of enthalpies at points 3 and 5, will improve the thermal efficiency of the plant. These factors, if augmented, will heighten the power output capacity of any steam thermal system.

KEYWORDS: Steam Power Plant, Feed Water Temperature, Isentropic Efficiency, Performance Analysis, Rankine Cycle with Superheat and Reheating

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INTRODUCTION

A steam turbine is a prime mover in which the potential energy of the steam is transformed into kinetic energy, and later, 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 field of industry, for power generation and for transport (Steam, 2018). Transformation of the potential energy of steam into the mechanical energy of rotation of the shaft is brought about by different means. There are several ways in which the steam turbines may be classified. The most important and common division being with respect to the action of the steam, as: impulse, reaction, combination of impulse and reaction. Other classifications are (Rajput, 2013):

(a) According to the number of pressure stages
(b) According to the direction of the steam flow
(c) According to the number of cylinders
(d) According to the method of governing
(e) According to heat drop process
(f) According to steam conditions at inlet to turbine
(g) According to their usage in industry

In reciprocating steam engine, the pressure energy of steam is used to overcome external resistance, and the dynamic action of the steam is negligibly small. Steam engine may be run by using the full pressure without any expansion or drop of pressure in the cylinder. The *steam turbine* proper could not be operated in such a manner. The turbine depends wholly upon the dynamic action of the steam. The steam is caused to fall in pressure in a passage or nozzle. Due to this fall in pressure, certain amount of heat energy is converted to kinetic energy, i.e. steam is given a high velocity. The high velocity particle of the steam impinge on the moving part of the turbine, and here suffer a change in direction of motion, and thus, give rise to change in momentum and, therefore, a force. The nozzles organize the steam so that it flows in well formed high velocity jets. Moving buckets, convert these high velocity jet to mechanical work in a rotating shaft (Ballaney, 2011). When the bucket is locked, the jet enters, and leaves with equal velocity (neglecting friction) and develops maximum force. But no mechanical work is done. As the bucket is allowed to speed up, the jet leaves more slowly and force shrinks. Steam jet does maximum work when bucket speed is just half the speed. In this condition, the moving bucket leaves behind it a trail of inert steam, since all kinetic energy is converted to work. Stating force and hence torque of this ideal turbine is double the torque at its most efficient speed. This process of expansion, and direction changing may occur once, or a number of times in succession, and may be carried out with differences of details.

An impulse turbine, as the name indicates, is a turbine which runs by the impulse of steam jet. In this turbine, the steam is first made to flow through a nozzle. Then, the steam jet impinges on a turbine blades (which are curved like buckets) and are mounted on the circumference of the wheel. The steam jet after impinging glides over the concave surface of the blades and finally leaves the turbine. The action of the jet of steam, impinging on the blade, is said to be impulse and the rotation of the rotor is due to the impulsive forces of the steam jets (Khurmi and Gupta, 2008; Stodola, 1927; Madu, 2018). The turbine is called '*simple*' impulse turbine since the expansion of the steam takes place in one set of the nozzles. In a reaction turbine, the steam enters the wheel under pressure and flows over the blades. The steam, while gliding, propels the blades and makes them to move. As a matter of fact, the turbine runner is rotated by the reactive forces of steam jets. The backward motion of the blades is similar to the recoil of a gun (Whitaker, 2006). In this type of turbine, there is a gradual pressure drop; and this takes place continuously over the fixed and moving blades. The function of the fixed blades is (the same as the nozzle) that they alter the direction of the steam, as well as allow it expand to a larger velocity. As the steam passes over the moving blades, its kinetic energy (obtained due to fall in pressure) is absorbed by them. As the volume of steam increases at lower pressure, therefore, the diameter of the turbine must increase after each group of blade rings. Since the pressure drop per stage is small, therefore, the number of stages required is much higher than an impulse turbine of the same capacity. It may be noted that an absolute reaction turbine is rarely used in actual practice. The difference between impulse and reaction turbines is summarized in Table 1.

Table 1: Difference between Impulse and Reaction Turbines

Particulars	Impulse Turbine	Reaction Turbine

Pressure drop	Only in nozzles and not in moving blades	In fixed blades (nozzles) as well as in moving blades
Area of blade channels	Constant	Varying (Converging type)
Blades	Profile type	Aerofoil type
Admission of steam	Not all round or complete	All round or complete
Nozzles/fixed blades	Diaphragm contains the nozzle	Fixed blades similar to moving blades attached to the casing serve as nozzles and guide the steam
Power	Not much power can be developed	Much power can be developed
Space	Requires less space for same power	Requires more space for same power
Efficiency	Low	High
Suitability	Suitable for small power requirement	Suitable for medium and higher power requirements
Blade manufacture	Not difficult	Difficult

The following are the principal advantages of steam turbine over steam engine:

- The thermal efficiency of a steam turbine is much higher than that of a steam engine.
- The power generation in a steam turbine is at a uniform rate, therefore necessity to use a flywheel (as in the case of steam engine) is not felt.
- Much higher speed and greater range of speed is possible than in the case of steam engine.
- In large thermal stations where we need higher outputs, the steam turbine prove very suitable, as these can be made in big sizes.
- With the absence of reciprocating parts (as in steam engine) the balancing problem is minimized.
- No internal lubrication is required as there are no rubbing parts in steam turbine.
- In a steam turbine, there is no loss due to initial condensation of steam.
- It can utilize high vacuum very advantageously.
- Considerable overloads can be carried at the expense of slight reduction in overall efficiency.

A simple Rankine Cycle is the basis for steam-turbine operation. **Fig. 1** shows the flow diagram, and **Fig. 2** gives the temperature-entropy diagram of a Rankine Cycle with superheat and reheating. It has the following segments (Uppal, S. L. and Rao, 2012):

1 – 2 Feed water compressed in pump, and admitted in boiler
2 – 2' Water heated in boiler to saturated liquid state
2' – 3' Hot water converted to saturated steam
3' – 3 Steam superheated to point 3
3 Steam enters turbine
3 – 4s Steam expands in turbine
4s – 4 Steam taken out of turbine and reheated
4 – 5 Reheating of steam
5 – 6s Steam expands in turbine and gets saturated at 6s
6s – 1 Steam condenses in condenser

The cycle: 1 - 2 - 2' - 3' - 3 - 4s - 4 - 5 - 6s - 1 repeats continuously to produce superheated steam, and to drive steam turbine shaft. The average temperature at which heat is supplied to the boiler can be increased by superheating the steam. Usually, the dry saturated steam from the boiler drum is passed through a second bank of smaller bore tubes within the boiler. This bank is situated such that it is heated by the hot gases from the furnace until the steam reaches the required temperature. In modern plants, a steam receiver is used with one boiler, and is placed between the boiler and the turbine. Since the quantity of feed water varies with the different demands on the boiler, it is necessary to provide a storage of condensate between the condensate and boiler feed pump. This storage may be a surge tank or hot well.

MATERIALS AND METHOD

A closed circuit steam power plant comprises a feed-pump, a boiler, a 2-stage turbine, and a condenser. Exhaust steam from the first stage turbine is reheated before flowing to the second stage turbine, as shown in Fig. 1. The pressure entering the first stage turbine is 20 bar, while that entering the second stage turbine is 2 bar. The condenser pressure is 0.2 bar. Steam temperature at entry to each turbine is 300 ^{o}C. Isentropic efficiency of each turbine stage is 81 %. Feed water temperature is 40 ^{o}C. If the turbine output power is 1.5 MW, determine:

- Specific work output of the turbine
- Steam mass flow rate
- Plant thermal efficiency
- Rate of heat loss by the condenser
- Rate of heat generation by the boiler
- Mass flow rate of cooling water in the condenser, if the cooling water enters the condenser at 20 ^{o}C, and leaves at 35 ^{o}C

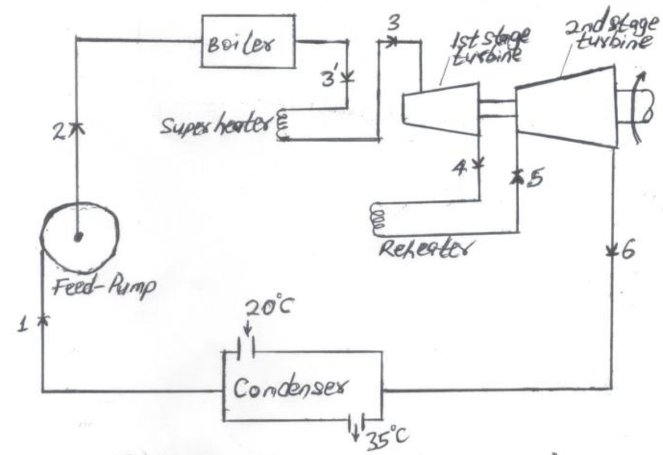

Fig 1: Flow Diagram of Rankine Cycle with Superheat and Reheat

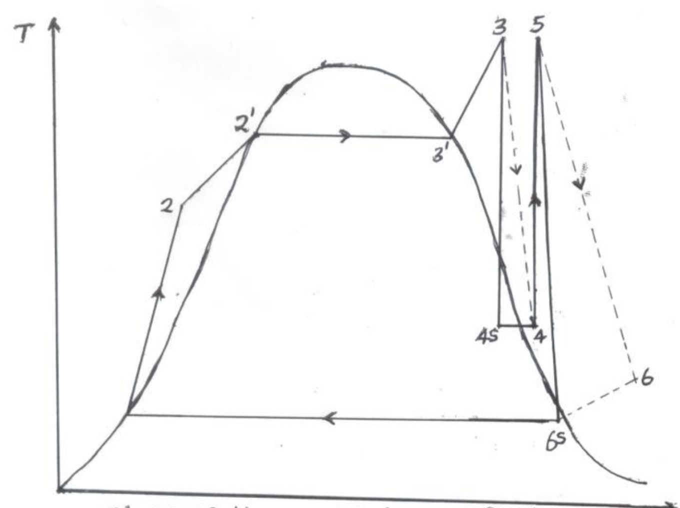

Fig. 2: T-S Diagram of Rankine Cycle with Superheat and Reheat

RESULTS AND DISCUSSION

Note: The saturated water – pressure table, and the superheated water table were used throughout the analysis.

At Point 1

P_1 = 0.2 bar = 20 kPa
T_1 = 60.06 ^oC
V = 0.001017 m^3/Kg
S_1 = 0.8320 KJ/KgK
h_1 = 251.42 KJ/Kg

At Point 2

T_2 = 40 ^oC
h_2 = 167.53 KJ/Kg

At Point 3

P_3 = 20 bar = 2 MPa
T_3 = 300 ^oC
S_3 = 6.7684 KJ/KgK
h_3 = 3024.2 KJ/Kg

At Point 4

$S_4 = S_3$ = 6.784 KJ/KgK
P_4 = 2 bar = 200 kPa = 0.2 MPa

At 2 bar, S_g = 7.1270 kJ/KgK > S_4; therefore, condition at Point 4 is wet steam

$S_4 = S_{f_4} + X_4(S_{fg_4})$
$6.7684 = 1.5302 + X_4(5.5968)$
$X_4 = 0.9359$
Thus, $h_{4_S} = h_{f_4} + X_4(h_{fg_4})$
$= 504.71 + 0.9359(2201.6)$
$= 2565.19$ kJ/Kg

In order to get h_4, we apply thermal efficiency relation, thus;

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4_s}}$$

$$0.81 = \frac{3024.2 - h_4}{3024.2 - 2565.19}$$

Therefore, h_4 = 2652.42 kJ/Kg

At Point 5

P_5 = 200 kPa
T_5 = 300 ^oC
S_5 = 7.5081 kJ/KgK
h_5 = 3072.1 kJ/Kg

At Point 6_s

$S_{6_s} = S_5$ = 7.5081 kJ/KgK < S_g at 200 kPa. Therefore, the condition as 6_s is wet.
It follows that; $S_{6_s} = S_{f_6} + X_6(S_{fg_6})$
$7.5081 = 0.8320 + X_6(7.0752)$
$\therefore X_6 = 0.9436$
We proceed to evaluate h_{6_s} thus;
$h_{6_s} = h_{f_6} + X_6(h_{fg_6})$
$= 251.42 + 0.9436(2357.5)$
$= 2475.96$ kJ/Kg
To get h_6, we use the formula;
$h_6 = h_5 - (h_5 - h_{6_s})\eta_T$; where η_T = Isentropic efficiency of each turbine
$= 3072.1 - (3072.1 - 2475.96)\ 0.81$
$= 2589.23$ kJ/Kg

Note: Now that we are done determining the parameters, we proceed with the analysis.

First Analysis: Determination of the Specific Work Output of the Turbine, w

$W = (h_3 - h_4) + (h_5 - h_6)$
$W = (3024.2 - 2652.42) + (3072.1 - 2589.23)$
W = 854.65 kJ/Kg

Second Analysis: Determination of the Steam Mass Flow Rate

$$\dot{m}_S = \frac{Turbine\ \ Output\ \ Power}{\text{Specific Work Output of the Turbine}}$$
$$= \frac{1500000}{854.65}$$
= 1.76 Kg/s

Third Analysis: Determination of the Plant Thermal Efficiency, η_{th}

$$\eta_{th} = \frac{Specific\ Work\ Output}{Gross\ Heat\ Input}$$
$$= \frac{W}{(h_3 - h_2) + (h_5 - h_4)}$$
$$= \frac{854.65}{(3024.2 - 167.53) + (3072.1 - 2652.42)}$$
$$= 26.08\ \%$$

Fourth Analysis: Determination of the Rate of Heat Loss by the Condenser

$Q_c = \dot{m}_S(h_6 - h_1)$
$= 1.76\ (2589.23 - 251.42)$
$= 4114.55$ J/s

Fifth Analysis: Determination of the Rate of Heat Generation by the Boiler

$Q_b = \dot{m}_S(h_3 - h_2)$
$= 1.76\ (3024.2 - 167.53)$
$= 5027.74$ J/s

Sixth Analysis: Determination of the Mass Flow Rate of Cooling Water in the Condenser, if the Cooling Water enters the Condenser at 20 ^oC, and leaves at 35 ^oC

$\dot{m}_S(h_6 - h_1) = \dot{m}_w\, c_{p_w} (\Delta T)$

Where c_{p_w} = Specific heat capacity of water; ΔT = Temperature differential, $\dot{m}_w$ = Mass Flow Rate of Cooling Water in the Condenser

$1.76(2589.23 - 251.42) = \dot{m}_w\ (4.186 \times 15)$

$\dot{m}_w = 65.53$ Kg/s

The specific work output of this contrivance, depends largely on the values of enthalpies at point 3 and point 5 in the T – S diagram. An increase in these parameters implies a corresponding increase in the value of the specific work output, and vice versa. Similarly, the mass flow rate of the steam varies linearly with the isentropic efficiency of each turbine in the system. On the other hand, an increase in the specific work output of the plant brings about an unavoidable decrease in the steam mass flow rate. Moreover, it can be deduced from analysis three that the thermal efficiency of the plant is a function of the specific work output of the plant, and enthalpies at points 3, 2, 5 and 4. Unlike the specific work output of the plant, these enthalpies have inverse relations with the plant thermal efficiency. The rate of heat loss in the condenser and heat generation in the boiler, are governed by the steam mass flow rate. They are equally contingent on enthalpy values at points 6, 1 and 3, 2 respectively.

CONCLUSION

A steam turbine is a device that extracts thermal energy from pressurized steam and uses it to do mechanical work on a rotating output shaft. Because the turbine generates rotary motion, it is particularly suited to be used to drive an electrical generator. It is a modified heat engine that derives much of its improvement in thermodynamic efficiency from the use of multiple stages in the expansion of steam, which results in a closer approach to the ideal reversible expansion process. An ideal steam turbine is considered to be an isentropic process, or constant entropy process, in which the entropy of the steam entering the turbine is equal to the entropy of the steam leaving the turbine. No steam turbine is truly isentropic, however, with typical isentropic efficiencies ranging from 0.2 - - 0.9, based on the application of the turbine. To maximize turbine efficiency, the steam is expanded, doing work, in a number of stages. These stages are characterized by how the energy is extracted from them and are known as either *impulse* or *reaction* turbines. Most steam turbines use a mixture of the reaction and impulse designs; each stage behaves as either one or the other, but the overall turbine uses both. Typically, lower pressure sections are reaction type and higher pressure stages are impulse type. In the above analysis, a closed circuit steam power plant was the focus. Different assumptions made on different stages of the analysis were based on the individual judgment of the researcher, and could assume other values for different designers.

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