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Evaluating of performance of Elkhalej steam turbine power plant (KSTPP) based on energy criteria

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ABSTRACT

The performance analysis of a power plant after commissioning is essential to assess its operational behavior in comparison with the manufacturer's design specifications. Operating the power plant near its design load is crucial for achieving maximum thermal efficiency, ensuring economical operation, and reducing environmental impacts.

In this study, the performance analysis of the Elkhalej Steam Turbine Power Plant was carried out based on energy analysis criteria to evaluate the thermal efficiency and heat rate of the plant, as well as to determine the deviations between off-design conditions and actual operating loads. A thermodynamic model was developed to simulate the plant processes and evaluate the performance of its major components. The model was validated using the design specification data provided by the manufacturer.

The obtained results show that operation at lower practical loads leads to larger deviations from the design performance, while operation at higher practical loads brings the plant behavior closer to the intended design conditions and improves overall performance efficiency.

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تقييم أداء محطة الخليج للطاقة ذات التوربينات البخارية استناداً إلى معايير تحليل الطاقة

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الـمُخلص

يُعدّ تحليل أداء محطات الطاقة عقب مرحلة التشغيل الأولي أمرًا ضروريًا لتقييم سلوكها التشغيلي ومقارنته بالمواصفات التصميمية التي أعدّها المصنّع. ويُمثّل تشغيل محطة الطاقة عند مستويات حمل قريبة من نقطة التصميم ركيزةً أساسية لبلوغ أعلى كفاءة حرارية ممكنة، وتحقيق الجدوى الاقتصادية في التشغيل، والتخفيف من الآثار البيئية المترتبة عليه.

تهدف هذه الدراسة إلى تحليل أداء محطة الخليج للطاقة ذات التوربينات البخارية، وذلك بالاستناد إلى معايير التحليل الطاقة، بغية تقييم الكفاءة الحرارية ومعدل الحرارة النوعي للمحطة، وتحديد مقدار الانحرافات بين ظروف التشغيل خارج نقطة التصميم والأحمال التشغيلية الفعلية. ولتحقيق هذا الغرض، تم تطوير نموذج ثيرموديناميكي لمحاكاة العمليات الداخلية للمحطة وتقييم أداء مكوناتها الرئيسية، وقد جرى التحقق من دقة هذا النموذج بالاستناد إلى بيانات المواصفات التصميمية الصادرة عن الجهة المصنّعة.

تُظهر النتائج المتحصّل عليها أن تشغيل المحطة عند أحمال تشغيلية منخفضة يؤدي إلى انحرافات ملحوظة عن قيم الأداء التصميمي، في حين أن التشغيل عند أحمال تشغيلية مرتفعة يُقرّب السلوك التشغيلي للمحطة من الظروف التصميمية المستهدفة، مما ينعكس إيجابًا على الكفاءة الحرارية الإجمالية للمنظومة.

الكلمات المفتاحية: معدل الاستهلاك الحراري، الكفاءة الحرارية، توربينة الخليج البخارية، الحمل العملي.

1. Introduction

performance evaluation of steam turbines in practical operation focuses on measuring and analyzing their efficiency and power generation under real working conditions. In many cases, the actual operating performance deviates from the original design specifications due to factors such as mechanical wear, component degradation, and operation at loads different from the design point. Therefore, several analytical approaches are used to assess turbine performance, including thermodynamic analysis based on heat balance calculations, Computational Fluid Dynamics (CFD), and periodic operational performance testing.

One common method for evaluating steam turbine performance is the calculation of the heat rate, which helps determine the deviation between the design values and the current operating conditions. This analysis aims to identify energy losses and improve overall efficiency. Important parameters that are typically examined include the mass flow rate of steam, temperature and pressure distributions along the turbine blades, the power output of each turbine

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stage, and the isentropic efficiency of the stages. The results of one such study showed that the average overall efficiency of the turbine reached approximately 43.49%, with a minimum value of 43.13% and a maximum of 43.75%, compared with the expected design efficiency range of 44–45% (Vasa et al., 2018).

Another important method for evaluating thermal systems is exergy analysis, which investigates system performance under varying operating conditions. This method helps identify the locations and causes of energy losses within the system and determines the components that contribute most significantly to inefficiencies. The analysis indicated that the deaerator and condenser units represent the weakest parts of the system. Furthermore, the extraction unit of the first-stage high-pressure heater was identified as another area with noticeable losses. In contrast, the extraction unit of the low-pressure heater shows a high potential for energy saving. These findings provide a scientific basis for improving the operational efficiency and economic performance of steam turbine thermal systems (Khaleel et al., 2020).

The performance of thermal power stations can also be evaluated by analyzing the operational parameters of the generating units through heat balance calculations for the main plant components. In such studies, the results obtained from actual plant measurements are compared with theoretical results derived from the first law of thermodynamics. These comparisons help demonstrate the impact of operational and environmental conditions on the unit's performance. The results suggest that operating the unit at full load provides the best economic and efficiency performance, while operating at partial loads (around 40%) leads to lower thermal and overall efficiencies along with a higher net heat rate (Al-Taha & Osman, 2018).

In addition, advanced evaluation techniques combining information entropy theory and fuzzy analytical methods have been applied to assess the condition of steam turbine units. Fuzzy analysis is used to transform the original data into an evaluation matrix, while the entropy method is employed to determine the relative weight of different performance parameters. After determining these weights, a comprehensive evaluation index can be calculated for different operating conditions. When compared with results obtained using the principal component analysis method, the entropy-based method demonstrated greater objectivity and reliability. This comprehensive evaluation index can serve as an effective benchmark for fault diagnosis and performance monitoring in steam turbine systems (Lua et al., 2020).

Energy assessment studies have also focused on analyzing the role of steam turbines in electrical power production, particularly under condensing operating conditions. Since turbine efficiency directly affects the sustainability of electricity generation, maintaining proper turbine efficiency is essential. Lower efficiency levels are typically associated with turbines of smaller power capacity; however, the turbine analyzed in the study showed satisfactory performance levels under the examined conditions (Anutoiu et al., 2021).

System optimization techniques have also been proposed to enhance the thermal efficiency of power plants. One commonly used approach is the installation of outer steam coolers (OSCs) to utilize the superheated steam extracted from the turbine. A newly proposed optimization scheme suggests using the turbine extraction steam simultaneously for feedwater preheating and cold reheat steam heating. Case study results indicate that this proposed system achieves greater energy savings compared with the conventional method under similar load conditions. Additionally, the investment payback period for the new system was estimated at 3.98 years, compared with 6.93 years for the conventional system (Zhang et al., 2020).

Theoretical investigations have also been conducted to analyze the performance of power plants operating according to the reheat Rankine cycle. The cycle performance was evaluated under different operating parameters such as boiler pressure, condenser pressure, and steam temperature. The results indicated that the thermal efficiency improves significantly when the pressure ratio ranges between 0.25 and 0.35. The optimal efficiency was achieved when the pressure ratio was approximately 0.33 and

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the boiler pressure reached about 26 MPa (Sultan, 2017).

Finally, studies have also been carried out to validate the performance of Pressure Reducing Turbines (PRTs) by comparing actual operating data with predictions obtained from analytical models. The validation process involved analyzing operational data collected over several periods through an online monitoring system. The analysis focused on two key variables: generated power and effective efficiency. It was observed that the real operating conditions differed from the predicted design conditions, forcing the turbine to operate under off-design situations. Consequently, the turbine model was refined to improve its predictive capability, and the updated model demonstrated satisfactory accuracy in predicting both power output and efficiency (Vescovi et al., 2021).

Nomenclature

$Q_{in-steam}$	amount of heat adding to steam (kw)	h_{si}	Isentropic enthalpy at state i (Kj/kg)
m_s	mass flow rate of steam (Kg/s)	m_{ECP}	mass flow rate of extracting condenser pump (kg/s)
m_{bsi}	mass flow rate of bleeding steam at hater i (Kg/s)	W_{ECP-ac}	Acual absorbing power of ECP (kw)
W_{T-ac}	Actual output power of turbine (KW)	W_{ECP-S}	Isentropic absorbing power of ECP(Kw)
W_{T-S}	Isentropic output power of turbine (KW)	m_{FWP}	mass flow rate of feed water pump (kg/s)
h_i	enthalpy at state i (Kj/kg)		

2. Description of the processes of Elkhalej steam turbine power plant:

The working fluid in the power plant is first heated in the boiler until it reaches a superheated steam state. This steam then expands in the High-Pressure Turbine (HPT). Before entering the reheating process, the steam is extracted at the first bleeding point (state 5) within the HPT. After reheating, the steam enters the Intermediate-Pressure Turbine (IPT), where expansion continues. During this stage, two additional steam extraction points occur at states 7 and 8. The steam subsequently flows into the Low-Pressure Turbine (LPT), where expansion proceeds further, accompanied by four extraction points at states 10, 11, 12, and 13. The resulting vapor–liquid mixture exits the turbine system at state 14 and is fully condensed in the condenser to reach state 15. The condensate is then pressurized by a pump to state 16 and directed through the first preheating system, which consists of Heater 1 through Heater 4, raising its condition to state 27. Afterward, the feedwater is preheating in dearator (28,1), and then pumped again to state 2 and passes through the second preheating system (Heaters 6 and 7), reaching state 30. At this point, the water is adequately preheated and ready to re-enter the boiler, completing the cycle.

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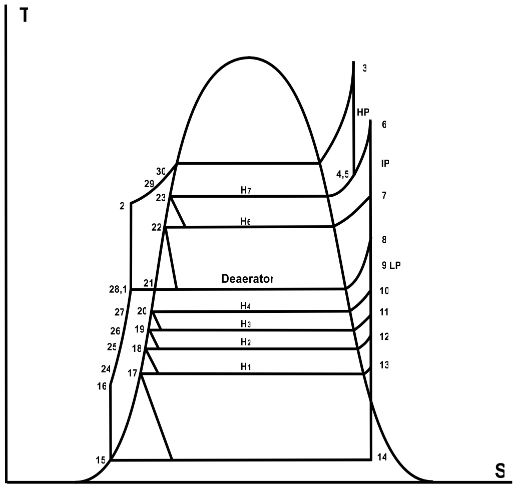

Fig.1: T-S diagram of processes of Elkhalej steam turbine power plant

Elements of cycle:

1. Boiler
2. Steam turbine
3. Dearator
4. Six heaters

3. Governing equation of the thermodynamic processes of KSTPP

Adding heat in boiler:

$$Q_{in-boiler} = LHV_{diesel} * mf_{diesel} \tag{3.1}$$

5. Condenser
6. Extracting condenser pump
7. Feed water pump

$Process\ 1 \rightarrow 2\ (Isentropic\ process)$

$Process\ 2 \rightarrow 3\ (Isobaric\ process)$

$Process\ 3 \rightarrow 4\ (Isentropic\ process)$

$Process\ 4 \rightarrow 6\ (Isobaric\ process)$

$Process\ 6 \rightarrow 9\ (Isentropic\ process)$

$Process\ 9 \rightarrow 14\ (Isentropic\ process)$

$Process\ 14 \rightarrow 15\ (Isobaric\ process)$

$Process\ 15 \rightarrow 16\ (Isentropic\ process)$

$$\begin{aligned} Q_{in-steam} = m_s\,(h_3 - h_{30}) \\ + \ (m_s - m_{bs7}) \\ * \ (\ h_6 - h_4\ ) \end{aligned} \tag{3.2}$$

Efficiency of boiler**:**

$$\eta = \frac{Q_{in-steam}}{Q_{in-boiler}} \tag{3.3}$$

Producing power by turbine in three stages HPT, IPT and LPT:

$$\begin{aligned} W_{T-ac} = m_S(h_3 - h_4) \\ + (m_s - m_{bs7})(h_6 - h_7) \\ +\left(m_s - m_{bs6,7}\right)(h_7 - h_8) \\ + \left(m_s - m_{bs,5,6,7}\right) * \\ (h_9 - h_{10}) + \left(m_s - m_{bs4,5,6,7}\right)(h_{10} \\ - h_{11}) \\ +\left(m_s - m_{bs3,4,5,6,7}\right)(h_{11} - h_{12}) \\ +\left(m_s - m_{bs2,3,4,5,6,7}\right) \\ * (h_{12} - h_{13}) + \left(m_s \right. \\ \left. - m_{bs1,2,3,4,5,6,7}\right)(h_{13} \\ - h_{14}) \end{aligned} \tag{3.4}$$

$$\begin{aligned} W_{T-S} = m_S(h_3 - h_{4s}) \\ + (m_s - m_{bs7})(h_{6s} - h_{7s}) \\ +\left(m_s - m_{bs6,7}\right)(h_{7s} - h_8) \\ + \left(m_s - m_{bs,5,6,7}\right) \\ (h_{9s} - h_{10s}) + \left(m_s - m_{bs4,5,6,7}\right)(h_{10s} \\ - h_{11s}) \\ +\left(m_s - m_{bs3,45,6,7}\right)(h_{11s} - h_{12s}) + \\ \left(m_s - m_{bs2,3,4,5,6,7}\right)(h_{12s} - h_{13s}) \end{aligned} \tag{3.5}$$

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$$+\left(m_s - m_{bs1,2,3,4,5,6,7}\right)(h_{13s} - h_{14s})$$

Efficiency of turbine:

$$\eta = \frac{W_{T-ac}}{W_{T-S}} \tag{3.6}$$

Removing heat by sea water in condenser:

$$Q_{out} = \left(m_s - m_{bs1,2,3,4,5,6,7}\right)(h_{14} - h_{15}) \tag{3.7}$$

Absorbing power by ECP:

$$W_{ECP-ac} = m_{ECP}(h_{16} - h_{15}) \tag{3.8}$$

$$m_{ECP} = m_s - m_{bs5,6,7} \tag{3.9}$$

$$W_{ECP-S} = m_{ECP}(h_{16S} - h_{15}) \tag{3.10}$$

Efficiency of pump:

$$\eta = \frac{W_{ECP-S}}{W_{ECP-ac}} \tag{3.11}$$

Absorbing power by FWP:

$$W_{FWP-ac} = m_{FWP}(h_2 - h_1) \tag{3.12}$$

$$W_{FWP-S} = m_{FWP}(h_{2S} - h_1) \tag{3.13}$$

$$m_{FWP} = m_{ECP} + m_{w5,6,7} \tag{3.14}$$

Energy balance in heaters:

$$\sum_{i=1}^{n} Ei_{in} = \sum_{i=1}^{n} Ei_{out} \tag{3.15}$$

$$E_i = h_i m_{bsi} \tag{3.16}$$

Energy balance in heater 7:

$$\begin{aligned} &h_5(m_{bs7}) + \left(m_{FWP} - m_{spray}\right)h_{29} \\ &= h_{23}m_{w7} + \left(m_{FWP} - m_{spray}\right)h_{30} \end{aligned} \tag{3.17}$$

$$m_{wi} = m_{bsi} \tag{3.18}$$

$$m_{bs7} = \frac{\left(m_{FWP} - m_{spray}\right)(h_{30} - h_{29})}{(h_5 - h_{23})} \tag{3.19}$$

$$m_{spray} = 7.6\%\, m_{FWP} \tag{3.20}$$

Energy balance in heater 6:

$$\begin{aligned} &h_7(m_{bs6}) + h_{23}m_{w7} \\ &\qquad + \left(m_{FWP} - m_{spray}\right)h_2 \\ &= h_{22}\left(m_{w6,7}\right) + \left(m_{FWP} - m_{spray}\right)h_{29} \end{aligned} \tag{3.21}$$

$$\begin{aligned} &m_{bs6} \\ &= \frac{(h_{22} - h_{23})m_{w7} + \left(m_{FWP} - m_{spray}\right)(h}{(h_7 - h_{22})} \end{aligned} \tag{3.22}$$

Energy balance in heater 5:

$$\begin{aligned} &h_8 m_{bs5} + h_{22}m_{w7,6} + m_{ECP}h_{27} \\ &\qquad = m_{FWP}h_{28} \end{aligned} \tag{3.23}$$

$$\begin{aligned} &m_{bs5} \\ &= \frac{(m_{FWP}h_{28} - m_{ECP}h_{27} - h_{22}m_{w,6,7})}{h_8} \end{aligned} \tag{3.24}$$

$$\begin{aligned} &m_{bs5} \\ &= \frac{(m_{FWP}(h_{28} - h_{27}) + (h_{27} - h_{22})m_{w,6,}}{(h_8 - h_{27})} \end{aligned} \tag{3.25}$$

Energy balance in heater 4:

$$\begin{aligned} &h_{10}m_{bs4} + m_{CEP}h_{26} \\ &\qquad = h_{20}m_{w4} + m_{CEP}h_{27} \end{aligned} \tag{3.26}$$

$$m_{bs4} = \frac{(m_{CEP}(h_{27} - h_{26}))}{(h_{10} - h_{20})} \tag{3.27}$$

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Energy balance in heater 3:

$$h_{11}(m_{bs3}) + (m_{CEP})h_{25} + h_{20}(m_{w4}) = h_{19}(m_{w3,4}) + (m_{CEP})h_{26} \quad (3.28)$$

$$m_{bs3} = \frac{((h_{19} - h_{20})m_{w4} + m_{CEP}(h_{26} - h_{25}))}{h_{11} - h_{19}} \quad (3.29)$$

Energy balance in heater 2:

$$h_{12}(m_{bs2}) + (m_{CEP})h_{24} + h_{19}(m_{w3,4}) = h_{18}(m_{w2,3,4}) + (m_{CEP})h_{25} \quad (3.30)$$

$$m_{bs2} = \frac{((h_{18} - h_{19})m_{w,3,4} + m_{CEP}(h_{25} - h_{24})}{(h_{12} - h_{18})} \quad (3.31)$$

Energy balance in heater 1:

$$h_{13}(m_{bs1}) + (m_{CEP})h_{16} + h_{18}\,(m_{w2,3,4}) = h_{17}(m_{w1,2,3,4}) + (m_{CEP})h_{24} \quad (3.32)$$

$$m_{bs1} = \frac{(h_{17} - h_{18})m_{w,2,3,4} + (m_{CEP})(h_{24} - h_{1}}{h_{13} - h_{17}} \quad (3.33)$$

Overall efficiency of power plant:

$$\eta = \frac{W_{T-ac} - (W_{ECP-ac} + W_{FWP-ac})}{Q_{in-S}} \quad (3.34)$$

Heat rate of power plant:

$$Heat\ rate = \frac{LHV_{diesel} * mf_{diesel}}{(W_{T-ac} - (W_{ECP-ac} + W_{FWP-ac}))} \quad (3.35)$$

4. Validation:

To verify the accuracy of the thermodynamic model of the Alkhaleej steam turbine power plant, the model was executed using the design input parameters provided by the manufacturer. The obtained results were then compared with the design specification output data, including efficiency, output power, and the mass flow rate of the bleeding steam This should explore the significance of the results of the work, not repeat them.

Table.1: Validation of thermodynamic model with design specification

	η	W_{net} (Mw)	m_{bs1} (kg/s)	m_{bs2} (kg/s)	m_{bs3} (kg/s)	m_{bs4} (kg/s)	m_{bs5} (kg/s)	m_{bs6} (kg/s)	m_{bs7} (kg/s)
Design data	**0.455**	**354.14**	**23.3**	**9.1**	**7.78**	**9.0**	**10.5**	**12.09**	**23.6**
model	**0.459**	**353.87**	**23.95**	**8.88**	**7.8**	**8.89**	**10.497**	**12.08**	**23.7**

5. Results and discussion

Table. 2 presents a comparative analysis of the quantities of bleeding steam extracted from feedwater heaters 1 through 7 at two operating loads, 170 MW and 250 MW, for the Alkhalej Steam Power Plant. These values were determined based on energy balance calculations applied to the feedwater heating system. The bleeding steam system plays a crucial role in improving the thermal efficiency of the plant by preheating the feedwater prior to entering the boiler.

The results indicate a clear increase in the quantity of extracted steam with rising plant load. At the operating load of 170 MW, the bleeding steam accounted for approximately 25.5% of the total steam flow (compared to 26.3% at the off-design specification load of 175 MW). At 250 MW, this proportion increased to about 29.5% (compared to 28.9% at the off-design specification load of 245

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MW. This trend reflects enhanced regenerative heating performance, which contributes directly to improved overall thermal efficiency at higher loads.

Table.2: Faction bleeding steam

	m_{bs1}/m_s	m_{bs2}/m_s	m_{bs3}/m_s	m_{bs4}/m_s	m_{bs5}/m_s	m_{bs6}/m_s	m_{bs7}/m_s	m_{bsT}/m_s
170 (Mw)	**0.062833**	**0.036932**	**0.026713**	**0.030257**	**0.020835**	**0.012758**	**0.064977**	**0.255304**
250 (Mw)	**0.066661**	**0.03573**	**0.025837**	**0.028821**	**0.037855**	**0.029865**	**0.070621**	**0.295389**

The overall efficiency of a steam power plant is largely governed by the performance of its main components, including the boiler, steam turbine, condenser, and feedwater pumps. Typically, boiler efficiency ranges from 80% to 95%, while the isentropic efficiency of steam turbines lies between 80% and 90%. Losses within the system are mainly due to heat transfer to the surroundings, irreversibility processes and mechanical friction. Figure 2 illustrates the efficiencies of the main components of the Alkhalej steam power plant under practical operating loads (170 MW and 250 MW). The results show that all components exhibit higher efficiencies at 250 MW, which explains the improved overall plant performance at this load compared to 170 MW.

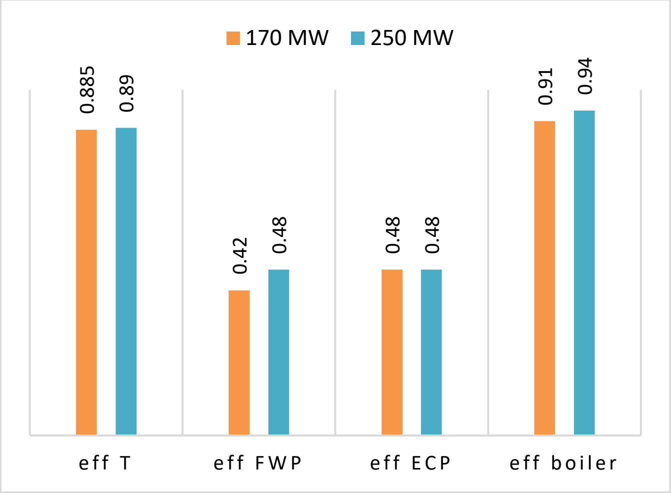

Fig.2: Efficiency of components of Elkhalej steam turbine power plant

Efficiency is a key engineering, economic, and environmental parameter in thermal power plants, defined as the ratio of useful electrical output to total energy input. Modern steam power plants typically achieve thermal efficiencies ranging from 33% to 48%, while advanced reheat cycle plants can reach up to 50%. Enhancing thermal efficiency leads to reduced fuel consumption, lower operational costs, and decreased environmental impact. Figure 3 illustrates the thermal efficiency of the Alkhalej power plant under both practical loading conditions (170 MW and 250 MW) and off-design conditions (175 MW and 245 MW). The results show that increasing the practical load by approximately 22% improves efficiency by about 2.54%, whereas a 20% increase under off-design conditions results in a smaller improvement of about 0.78%. This difference can be attributed to deviations from optimal design conditions. Specifically, the thermal efficiency at 175 MW (design specification) is about 43.32%, compared to 41.8% at the practical load of 170 MW.

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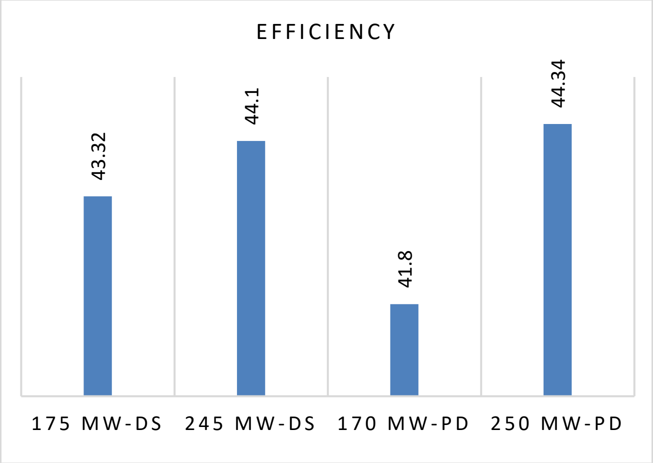

Fig.3: Efficiency of Elkhalej steam turbine power plant of practical load and design specification

The heat rate is another important parameter used to evaluate plant performance, representing the amount of heat input required to generate one kilowatt-hour of electricity. A lower heat rate indicates higher efficiency. Figure 4 compares the heat rate values at practical loads (170 MW and 250 MW) with their corresponding design loads (175 MW and 245 MW). The results demonstrate that increasing the load leads to a reduction in heat rate. However, the heat rate under practical operating conditions remains higher than that of the design specifications, indicating relatively lower efficiency during real operation.

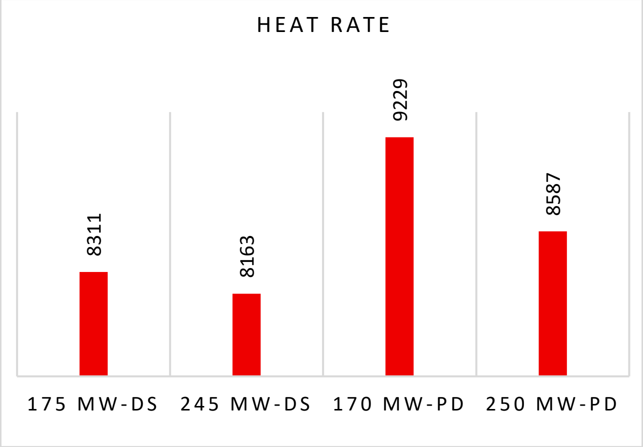

Fig.4: Heat rate of Elkhalej steam turbine power plant of practical data and design specification

6. Conclusion:

Based on the results and discussion presented above, the performance evaluation of the Alkhalej Steam Turbine Power Plant was carried out by comparing the design operating conditions (175 MW and 245 MW) with the actual operating loads (170 MW and 250 MW). The thermal efficiency at the design loads of 175 MW and 245 MW was found to be approximately 43.32% and 44.1%, respectively, while the corresponding efficiencies under practical operating conditions at 170 MW and 250 MW were 41.8% and 44.43%. The results indicate that increasing the operating load leads to a reduction in the heat rate, which reflects an improvement in plant efficiency. Nevertheless, the heat rate under actual operating conditions remains higher than the design values, indicating relatively lower efficiency during real plant operation.

In general, it can be concluded that the performance analysis of the Alkhalej Steam Power Plant demonstrates that increasing the operating load significantly improves the thermal efficiency and overall performance of the system. The increase in bleeding steam at higher loads enhances feed-water heating, which reduces fuel consumption and improves cycle efficiency. In addition, the main components of the plant operate more effectively at higher loads, resulting in better energy conversion performance. However, a noticeable deviation still exists between the practical and design performances, as evidenced by the higher heat rate and lower efficiency values under actual operating conditions. This deviation highlights the importance of optimizing operating parameters, improving maintenance practices, and minimizing system losses to achieve performance closer to the design specification

In conclusion, the performance analysis of the Alkhalej steam power plant demonstrates that increasing the operating load significantly enhances both thermal efficiency and overall system performance. The increase in bleeding steam with higher loads improves feedwater heating, which reduces fuel consumption and boosts efficiency. Additionally, the main components of the plant operate more effectively at higher loads, contributing

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to improved energy conversion. However, a noticeable gap remains between practical and design performance, as indicated by higher heat rate values and lower efficiencies under real operating conditions. This highlights the importance of optimizing operational parameters and maintaining equipment performance to minimize losses.

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