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Efficiency Analysis of the Third Unit in Al-Khoums Steam Power Plant, Libya

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تحليل كفاءة الوحدة الثالثة بمحطة الخمس البخارية، ليبيا

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Abstract

The thermal and overall efficiency of the third unit in the Al-Khoums steam power plant were investigated in this paper. Two samples of data have been used: the first was collected from the start-up data sheet of the power plant with a load of 120 MWH, and the second was collected in June 2023 with a load of 96 MWH. This study reveals that the thermal efficiency of the unit decreased by 9.4% (from 40.4% to 36.6%) due to the life of the plant and the stoppage of extraction lines, and the overall efficiency decreased by 8.7% (from 36.7% to 33.5%). Moreover, heat rejected by the condenser increased in the second sample by 44 kJ/kg. Steam cycles for both study samples were presented by T-S diagrams using Engineering Equation Solver software (EES), and it was clear from those diagrams that the efficiency of the high-pressure turbine in the first sample is higher than the second one.

Keywords: *Al-Khoms steam power plant, Overall efficiency, Steam power plant, Steam turbine, Thermal efficiency.*

الملخص

تم دراسة الكفاءة الحرارية والكفاءة الكلية للوحدة الثالثة بالمحطة البخارية الخمس، حيث تم استخدام عينتين من البيانات في هذا البحث، العينة الأولى تم جمعها من سجلات التشغيل الاختباري للمحطة بحمل 120 ميغاواط ساعة والثانية تم جمعها في يونيو 2023 بحمل 96 ميغاواط ساعة. تبين من خلال هذه الدراسة أن الكفاءة الحرارية للوحدة قيد الدراسة انخفضت بنحو 9.4 ٪ (من 40.4٪ إلى 36.6٪) بسبب عمر المحطة وإيقاف خطوط الاستنزاف، وانخفضت الكفاءة الكلية أيضًا بنحو 8.7٪ (من 36.7٪ إلى 33.5٪). إضافة إلى ذلك، ازدادت الحرارة المطروحة بواسطة المكثف في العينة الثانية بمقدار 44 kJ/kg. تم عرض الدورات الحرارية لعينتي الدراسة بواسطة مخطط T-S باستخدام برنامج حل المعادلات الهندسية (EES)، وكان واضحًا من تلك المخططات أن كفاءة التوربين عالي الضغط للعينة الأولى أعلى من الثانية.

الكلمات الدالة: محطة الخمس البخارية، الكفاءة الكلية، محطة القدرة البخارية، التوربين البخاري، الكفاءة الحرارية.

1. Introduction

In thermal power plants, fuel is ignited in boilers to heat water in order to generate steam, which expands in turbines driving them to work, to rotate electrical generator and then generate electricity (Anjali & Kalivarathan, 2015). These energy transformations result in energy losses. currently, 38% efficiency can be reached in critical power plants, while it is 41% in supercritical plants. The most important components that affect the efficiency of thermal power plants are boilers, turbines, and generators. The main energy losses in power plants are thermal losses in boilers and pipes, energy losses in the generator, and mechanical losses (Zhang, 2020).

2. Problem Statement and Methodology

All power plants lose their efficiency due to their continuous operation and other reasons. After years of operation, a plant will no longer be operating at its best levels (Anjali & Kalivarathan, 2015). Not all thermal energy can be transformed into mechanical power, according to the second law of thermodynamics. There is always heat lost to the environment (Ibrahim *et al.*, 2010). The aim of this study is to investigate the thermal efficiency of the third unit of the Al-Khoms steam power plant using start-up data as study sample one and June 2023 data as study sample two to obtain the effect of the operation period on its efficiency. In this work, start-up data of the power plant with a load of 120 MWH and June 2023 data with a load of 96 MWH of the Al-Khoms steam power plant were used to investigate the efficiency of the power plant. Engineering Equation Solver (EES) software and AutoCAD software have been used to analyze and draw both samples of the data using efficiency equations, and then the results have been compared with each other to obtain the effect of the plant life on its efficiency.

3. Plant Description

Al-Khoms steam power plant is one of Libya's power stations. It has four units with a capacity of 120 MW per unit, working on HFO, LFO and NG. The plant was started in 1982, and it is still operating and feeding the public network to date (Ibrahim *et al.*, 2010). During that period, the station was subjected to several emergencies and periodic maintenance, but the operating time and life span of the station play a major role in reducing its efficiency and thus changing the standard data recorded at the start-up. The general layout of the components of the third unit of the studied plant is presented in Figure (1) using AutoCAD software. The variables used in this study have been illustrated in Tables (1-3).

Table 1. Data of the plant recorded at the initial start-up in 1982 (120 MW)

Point	**P [bar]**	**S [kJ/kg.K]**	**T [°C]**	**h [kJ/kg]**	**v [m³/kg]**	**x**
1	0.054	0.4914	34	142.4	0.001006	
2	15.5	0.4908	34	143.8	0.001005	
3	4.3	1.801	146	615.1	0.001086	
4	155	1.816	149	637.5	0.00108	
5	152	2.586	230	992.9	0.001192	
6	128	6.567	535	3433	0.0266	
7	30	6.66	329	3065	0.08667	
8	27	7.385	535	3538	0.1357	
9	4.8	7.464	296	3056	0.5406	
10	0.054	7.464	34.25	2286	23.22	0.8854

Table 2. Data of the plant recorded in June 2023 (96 MW)

Point	**P [bar]**	**S [kJ/kg.K]**	**T [°C]**	**h [kJ/kg]**	**v [m³/kg]**	**x**
1	0.15	0.6516	46	192.6	0.00101	
2	12	0.6511	46	193.6	0.00101	
3	4	1.739	140	589.3	0.00108	
4	130	1.726	140	597.5	0.001072	
5	130	1.726	140	597.5	0.001072	
6	125	6.548	525	3410	0.02683	
7	26	6.978	395	3226	0.1143	
8	26	7.403	535	3539	0.141	
9	4.6	7.484	296	3057	0.5644	
10	0.15	7.484	46	2373	13.26	0.9119

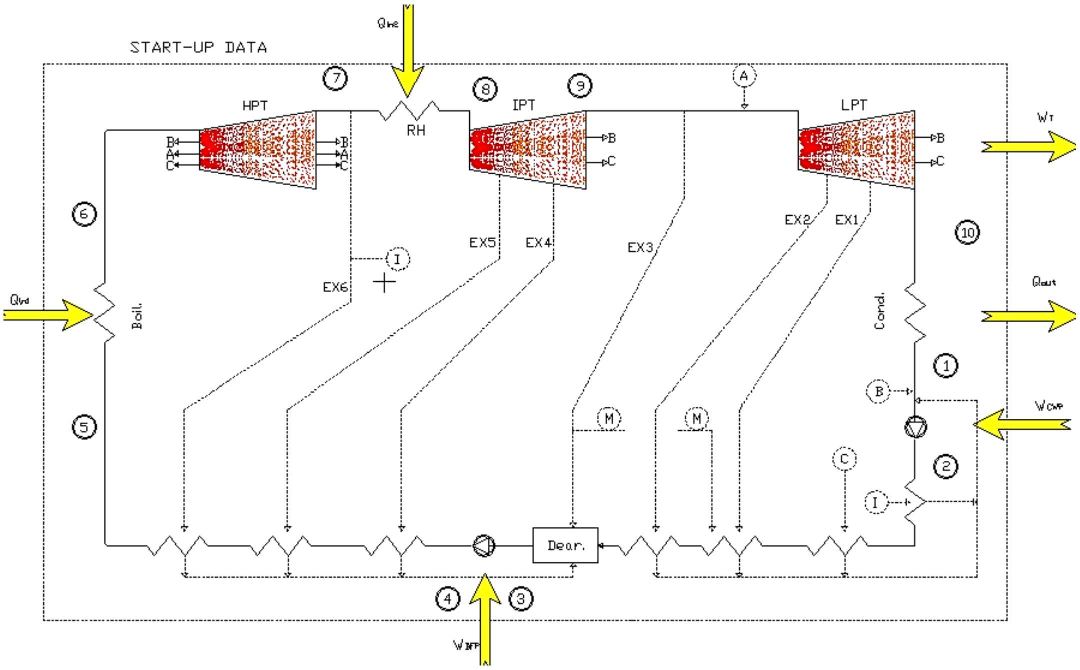


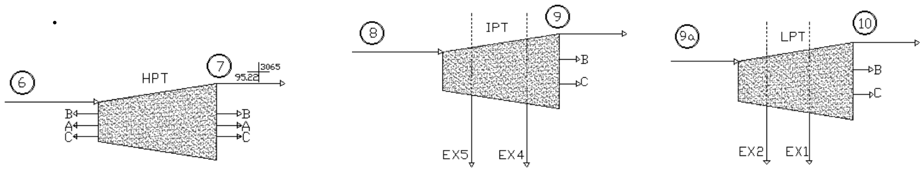
Figure 1. System Schematic Diagram of Al- Khoms Power Station

Table 3. Data collected from the third unit of the plant

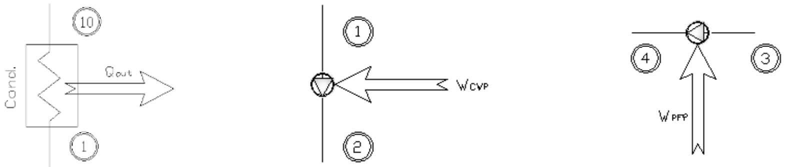
Data	**Start-up Data**	**Jun-2023 Data**
h_{ex1}[kj/kg]	2697	2697
h_{ex2}[kj/kg]	2892	2892
h_{ex4}[kj/kg]	3327	0
h_{ex5}[kj/kg]	3395	0
m_{ex1}[kg/s]	5.5	5.5
m_{ex2}[kg/s]	4.6	4.6
m_{ex4}[kg/s]	3.32	0
m_{ex5}[kg/s]	3.85	0
m_8 [kg/s]	88.72	92.95
m_9[kg/s]	76.59	87.94

4. Thermal Efficiency Calculation

To obtain the efficiency of a complex steam cycle such as the one in which the Al-Khoms steam power plant operates, the calculations must be divided according to the parts of the steam cycle, and then calculation formulas are used for each part individually. Figure (2) shows brief drawings of the steam cycle components drawn using AutoCAD software. The values that are used in the following calculations have been taken from Tables (1-3).



HPT IPT LPT



condenser Circulation pump Boiler feeding pump

Boiler Re-heater

Extraction lines Extraction lines

Figure 2. Sketches of plant parts drawn by AutoCAD

Efficiency calculations can be done using the following equations with the help of Figure (2). The work produced by HPT, IPT and LPT can be calculated using the direct method as following (Mrzljak *et al.*, 2019; Zhang, 2015; and Kapooria *et al.*, 2008):

$$\mathrm{W_{hpt}} = \mathrm{h_6} - \mathrm{h_7} \tag{1}$$

$$\mathrm{W_{Ipt}} = (\mathrm{h_8} - \mathrm{h_{ex5}}) + (1 - Y_1) * (\mathrm{h_{ex5}} - \mathrm{h_{ex4}}) + (1 - (Y_1 + Y_2)) * (\mathrm{h_{ex4}} - \mathrm{h_9}) \tag{2}$$

where the extraction lines ex4, ex5 and ex6 are neglected for June 2023 data because they are out of service, and terms Y_1, Y_2 are calculated as following:

$$Y_1 = \frac{\mathrm{m_{ex5}}}{\mathrm{m_8}} \tag{3}$$

$$Y_2 = \frac{\mathrm{m_{ex4}}}{\mathrm{m_8}} \tag{4}$$

$$\mathrm{W_{lpt}} = (\mathrm{h_9} - \mathrm{h_{ex2}}) + (1 - \mathrm{X_1}) * (\mathrm{h_{ex2}} - \mathrm{h_{ex1}}) + (1 - (\mathrm{X_1} + \mathrm{X_2})) * (\mathrm{h_{ex1}} - \mathrm{h_{10}}) \tag{5}$$

$$X_1 = \frac{\mathrm{m_{ex2}}}{\mathrm{m_9}} \tag{6}$$

$$X_2 = \frac{\mathrm{m_{ex1}}}{\mathrm{m_9}} \tag{7}$$

$$\mathrm{Q_c} = \mathrm{h_{10}} - \mathrm{h_1} \tag{8}$$

$$\mathrm{W_{Cwp}} = \mathrm{v_1} * (\mathrm{p_2} - \mathrm{p_1}) \tag{9}$$

$$\mathrm{W_{BFP}} = \mathrm{v_3} * (\mathrm{p_4} - \mathrm{p_3}) \tag{10}$$

$$\mathrm{Q_B} = \mathrm{h_6} - \mathrm{h_5} \tag{11}$$

$$\mathrm{Q_{RH}} = \mathrm{h_8} - \mathrm{h_7} \tag{12}$$

The heat added by extraction lines to the system;

$$\mathrm{Q}_{ex4,5,6} = \mathrm{h_5} - \mathrm{h_4} \tag{13}$$

$$\mathrm{Q}_{ex1,2,3} = \mathrm{h_3} - \mathrm{h_2} \tag{14}$$

where $\mathrm{Q_{ex}}$4, 5, and 6 are equal to zero for Jun 2023 data because these extraction lines are out of service. Finally, there is an amount of energy that will go out of the system as wasted heat, as shown in Figure (3) that can be calculated as following:

$$Q_{waste} = \left(Q_B + Q_{RH} + Q_{ex4,5,6} + Q_{ex1,2,3} + W_{Cwp} + W_{BFP}\right) - \left(W_{HPT} + W_{IPT} + W_{LPT} + Q_c\right) \quad (15)$$

Using calculated data above, the thermal efficiency can be calculated as following (Onwuamaeze, 2018; Karakurt, 2015; Ibrahim *et al.*, 2010; and Kapooria *et al.*, 2008):

$$\mathrm{Q}_{in} = \mathrm{Q}_{\mathrm{B}} + \mathrm{Q}_{\mathrm{RH}} + \mathrm{Q}_{ex4,5,6} + \mathrm{Q}_{ex1,2,3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

$$\mathrm{Q}_{out} = \mathrm{Q}_{\mathrm{c}} + \mathrm{Q}_{\mathrm{waste}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

$$\eta_{\mathrm{th}} = \left[\frac{(\mathrm{W}_{\mathrm{HPT}} + \mathrm{W}_{\mathrm{IPT}} + \mathrm{W}_{\mathrm{LPT}}) - (\mathrm{W}_{\mathrm{CWP}} + \mathrm{W}_{\mathbf{BHF}})}{\mathrm{Q}_{in}}\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (18)$$

Or:

$$\eta_{\mathrm{th}} = \left[\frac{\mathrm{Q}_{in} - \mathrm{Q}_{out}}{\mathrm{Q}_{in}}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

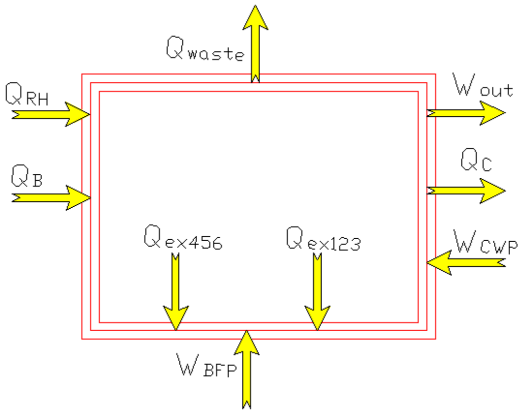


Figure 3. Energy flow schematic diagram of the thermal cycle drawn by AutoCAD software

5. Overall Efficiency

Overall efficiency is the ratio between the net energy produced in the electric generator and the thermal energy entering the boiler by the fuel, and it can be calculated as following (Al-Taha, & Osman, 2018; and Adegboyega & Odeyemi, 2011);

$$\eta_{\mathrm{o}} = \frac{\text{heat equivelant of electric output}}{\text{input energy from fuel combustion}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

$$\eta_{\mathrm{o}} = \frac{\text{energy generated (MWH/day) x 860000 (Kcal/MWH)}}{\dot{\mathrm{m}}_{\mathrm{fuel}}(\mathrm{m}^3/\mathrm{day})\text{ x dinsity (Kg/m}^3\text{) x heat value (Kcal/kg)}} \quad \ldots\ldots\ldots\ldots \quad (21)$$

Parameters of Eqn. (21) can be substituted by variables that have been obtained from the third unit of the Al-Khoms steam power plant data sheet, as illustrated in Table (4).

Table 4. Input Data for Eqn. (21) power plant data sheet

	Sample one (Start-up Data)	Sample two (Jun-2023 Data)
Energy generated (MWH)	120	96
Energy generated (MWH/day)	2880	2319
m_{fuel} (m^3/day)	776.1	663.5
Heat value (KCal/kg)	9601.6	9843.1
HFO density (kg/m^3)	905	905

6. Results and Discussion

The results of the calculation for start-up data and June 2023 data are shown in Table (5). Data in tables 1 and 2 have been plotted on the T-S diagram as illustrated in Figures (4 and 5), respectively, using the Engineering Equation Solver program (EES). Figures (4 and 5) clearly represent the differences in efficiency between the two study samples. It is clear from those figures that the efficiency of HPT in the first study sample (start-up data) is higher than the second one (June 2023 data), as indicated by the slope of the HPT line (points 6 and 7). In addition, the exit temperature of HPT is much lower in the first study sample than the second sample, and the pressure of the condenser in the first sample is lower than the second one, which influence on the efficiency of the cycle. Figure (6) shows a sample of the calculations done by the EES program.

Table 5. Results of the Calculation for both Study Samples

Data	**Start-up Data**	**Jun-2023 Data**
W_{hpt} [kJ/kg]	368	184
W_{Ipt} [kJ/kg]	457	482
W_{lpt} [kJ/kg]	704	636
Q_c [kJ/kg]	2144	2180
W_{CWP} [kJ/kg]	1.554	1.197
W_{BFP} [kJ/kg]	16.37	13.61
Q_B [kJ/kg]	2440	2813
Q_{RH} [kJ/kg]	473	313
$Q_{ex1, 2, 3}$ [kJ/kg]	471	396
$Q_{ex4, 5, 6}$ [kJ/kg]	355	0
Q_{wast} [kJ/kg]	85	53
Q_{in} [kJ/kg]	3740	3521
Q_{out} [kJ/kg]	2229	2233
η_{th} [%]	40.4	36.6
η_o [%]	36.7	33.5

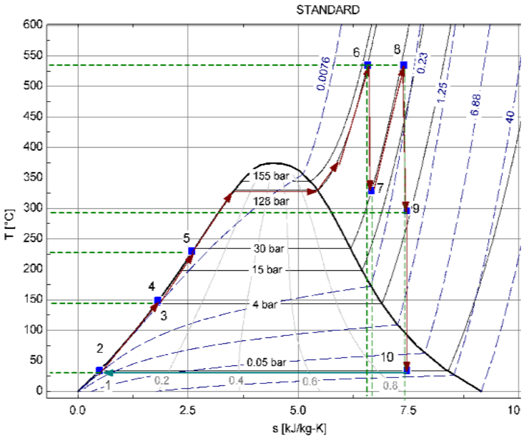


Figure 4. T_S diagram of start-up data

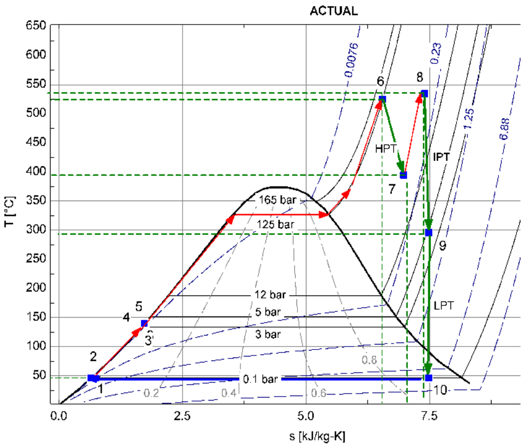
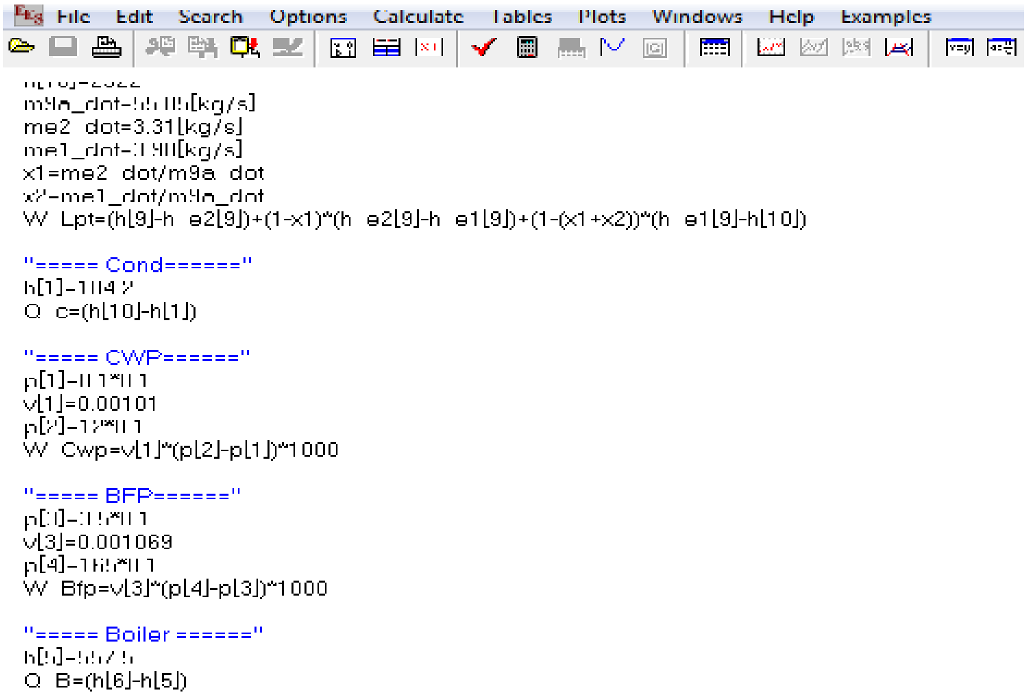


Figure 5. T_S diagram of Jun-2023 data



```
m9a_dot=[illegible][kg/s]
me2 dot=3.31[kg/s]
me1_dot=[illegible][kg/s]
x1=me2 dot/m9a dot
x2=me1_dot/m9a_dot
W Lpt=(h[9]-h e2[9])+(1-x1)*(h e2[9]-h e1[9])+(1-(x1+x2))*(h e1[9]-h[10])

"===== Cond======"
h[1]=[illegible]
Q c=(h[10]-h[1])

"===== CWP======"
p[1]=[illegible]
v[1]=0.00101
p[2]=[illegible]
W Cwp=v[1]*(p[2]-p[1])*1000

"===== BFP======"
p[3]=[illegible]
v[3]=0.001069
p[4]=[illegible]
W Bfp=v[3]*(p[4]-p[3])*1000

"===== Boiler ======"
h[5]=[illegible]
Q B=(h[6]-h[5])
```

Figure 6. Sample of Engineering Equation Solver program calculation

The thermal efficiency of sample one was 40.4%, and that of sample two was 36.6%. This result shows that the thermal efficiency has dropped by 9.4% due to the life of the plant and the stoppage of extraction lines. The overall efficiency of sample one was 36.7%, and that of sample two was 33.5%, with a decrease of 8.7%. As it can be seen, the overall efficiency is less than thermal efficiency due to the effect of alternator efficiency.

The moisture fraction at the end of a low-pressure turbine, as presented by point 10 in the T-S diagram and Tables (1 and 2), is 0.88 and 0.91 for samples one and two, respectively, which is within the permissible limit for the moisture at the end of the low-pressure turbine, as indicated by previous studies (Kapooria *et al.*, 2008). This will prevent the vapor from condensing during its expansion, which can seriously damage the turbine blades.

4. Conclusion

From this study, some points can be concluded, as listed below:

- The thermal efficiency of the third unit of the plant is decreased by about 9.4% (from 40.4% to 36.6%) due to the life of the plant and the stoppage of the extraction lines (extraction line 4, extraction line 5 and extraction line 6), which leads to an increase in the heat rejected by the condenser in the amount of 44 kJ/kg.
- The overall efficiency is reduced by an amount of 8.7% (from 36.7% to 33.5%).
- The T-S diagram has been drawn using the Engineering Equation Solver program (EES), which clearly represents the difference in HPT efficiency between the two study samples.
- By observation of the line slope of HPT (point 6 to point 7) on T-S diagrams, it can be found that the efficiency of HPT in the first study sample (start-up data) is higher than the second one (June 2023 data), which means higher efficiency.
- The exit temperature of HPT is much lower in the first study than the second sample, and the pressure of the condenser in the first sample is lower than the second one, which reduces the efficiency of the cycle as a whole. Many other reasons affected the efficiency, like the isentropic efficiency of turbines and wasted heat in the environment.

Symbols Description

Symbol	**Meaning**
HFO	Heavy fuel oil
LFO	Light fuel oil
NG	Natural gas
HPT	High pressure turbine
IPT	Intermediate pressure turbine
LPT	Low pressure turbine
W_{hpt}	Work of high pressure turbine
W_{Ipt}	Work of Intermediate pressure turbine
W_{Lpt}	Work of Low pressure turbine
h	Specific enthalpy
Q_c	Specific heat removed by condenser
Q_B	Specific heat added by boiler
Q_{RH}	Specific heat added by re-heater
Q_{wast}	Specific heat lost to the ambient
Q_{in}	Total specific heat added to the system
Q_{out}	Total specific heat extracted from the system
W_{Cwp}	Work of circulation pump
W_{BFP}	Work of boiler feed water pump
$\mathbf{m_{fuel}}$	Flow of the fuel to the boiler
m	mass flow
m_{ex}	steam mass flow in extraction lines
η_{th}	Thermal efficiency
η_o	Overall efficiency
x	Moisture Fraction
h_{ex1}	Specific enthalpy of extraction line 1
h_{ex2}	Specific enthalpy of extraction line 2
h_{ex3}	Specific enthalpy of extraction line 3
h_{ex4}	Specific enthalpy of extraction line 4

h_{ex5}	Specific enthalpy of extraction line 5
h_{ex6}	Specific enthalpy of extraction line 6
$Q_{ex1,2,3}$	Specific heat added by extraction lines 1, 2 and 3
$Q_{ex4,5,6}$	Specific heat added by extraction lines 4, 5 and 6
v	Specific volume
P	pressure
T	Temperature
S	Entropy
Y	Specific enthalpy fraction for IPT
X	Specific enthalpy fraction for LPT

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