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Thermal Performance of Coal-Fired Power Plant based on Number of Feedwater Heaters

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ABSTRACT

This study aims to investigate the feasibility of using a feedwater heaters system with coal-fired power plant. Furthermore, the influence evaluation of the different coal consumption on the coal-fired power plants in terms of power output and thermal efficiency improvements. As well, this study focuses on the effect of different feedwater heaters' numbers which caused the highest exergy destruction of the coal-fired power plants. For different values of the coal consumption, a parametric study was conducted to determine the efficiency of the coal-fired power plant. The results show that, when the coal consumption increases the power output will increases too. The slight decreases in the efficiencies are due to the small differences in how the mass flow rates of different streams increase. The exergy destruction was increased by about 16% when the consumption of fuel increases by 40 kg/s. It was observed that operating the coal-fired power plant at high coal consumption leads to reduce the effective ness of the feedwater heaters and increases the power output.

1. Introduction

The increase in the global economy comes with increases in fossil fuel prices. There has been a continuous demand for energy, especially the demand for electricity in recent decades [1-11]. Today, fossil fuels remain the major source of energy for electricity generation but as per the International Agency of Energy, it has been predicted that gas-fuelled combined cycle's power plants will contribute majorly to fuel sources by the year 2030 [1,12-21]. One of the major indicators of development and improved standard of living among communities is the level of energy consumption as increases in population, industrialization, and urbanization results in increased energy utilization [22-32]. Currently, more than 80% of global electricity production is contributed by thermal power plants (TPPs) while the remaining 20% comes from different energy sources such as wind, solar, hydraulic, nuclear, biomass, geothermal, etc. The growth of the economy of any nation is directly influenced by the cost and availability of electricity [33-40]. These days, electricity remains a part of normal life; it is so important that electricity consumption per capita is considered today an economic

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development index and a measure of the standard of living of a country. Therefore, it is evident that the level of prosperity of a country is directly dependent on the level of emphasis it places on the continuous development of electrical power, as well as energy and exergy efficiency analysis [41].

Today, power is mainly sourced globally from the burning of fossil fuels such as natural gas and coal [42]. Fossil fuels such as coal, oil, and natural gas are considered the most important energy sources because of their cost and availability [43-59]. The increasing demand for electricity drives the need for more efficient coal-fired power plants [60]. During power generation, the energy losses during the process are of greater concern as it affects the process's net efficiency. Consequently, several studies have been performed on thermal power plants, focusing on the alternative ways of designing and operating the plant to achieve better net efficiency. Thermal power plant analysis is a wide concept that involves the efficient use of energy resources. Before now, the analysis of power plant energy efficiency is dependent on the First Law of Thermodynamics [61]; however, these days, the Second Law analysis is the basis for exergy loss determination; this analysis aims at studying the quality of the energy generated in a system from a wider perspective (this technique is normally referred to as exergy analysis).

This research attempts the development of an integrated model for the analysis and improvement of the overall performance of the coal-fired power plants based on the coal-burning amounts. The exergy analysis is a methodology for assessment of component performance and involves examining the exergy at different feedwater heaters.

2. Methodology

In the present study, Unit 1 of Manjung Coal Fired power plant located in Malaysia is considered for investigation. The process flow diagram (PFD) of this power plant is illustrated in Figure 1. This figure does not show the boiler and economizer sections. To analyze the complete cycle of the powerplant, the continuity, energy and exergy equations governing various components of the cycle are developed and resolved using Engineering Equation Solver (EES) software. The continuity equations are invoked to find the distribution of feed water and steam throughout the cycle.

Table 1 summarizes the energy equations and efficiencies/effectiveness of various components of the thermal cycle; while Table 2 summarizes the exergy supply, exergy destruction and exergy efficiency of those components.

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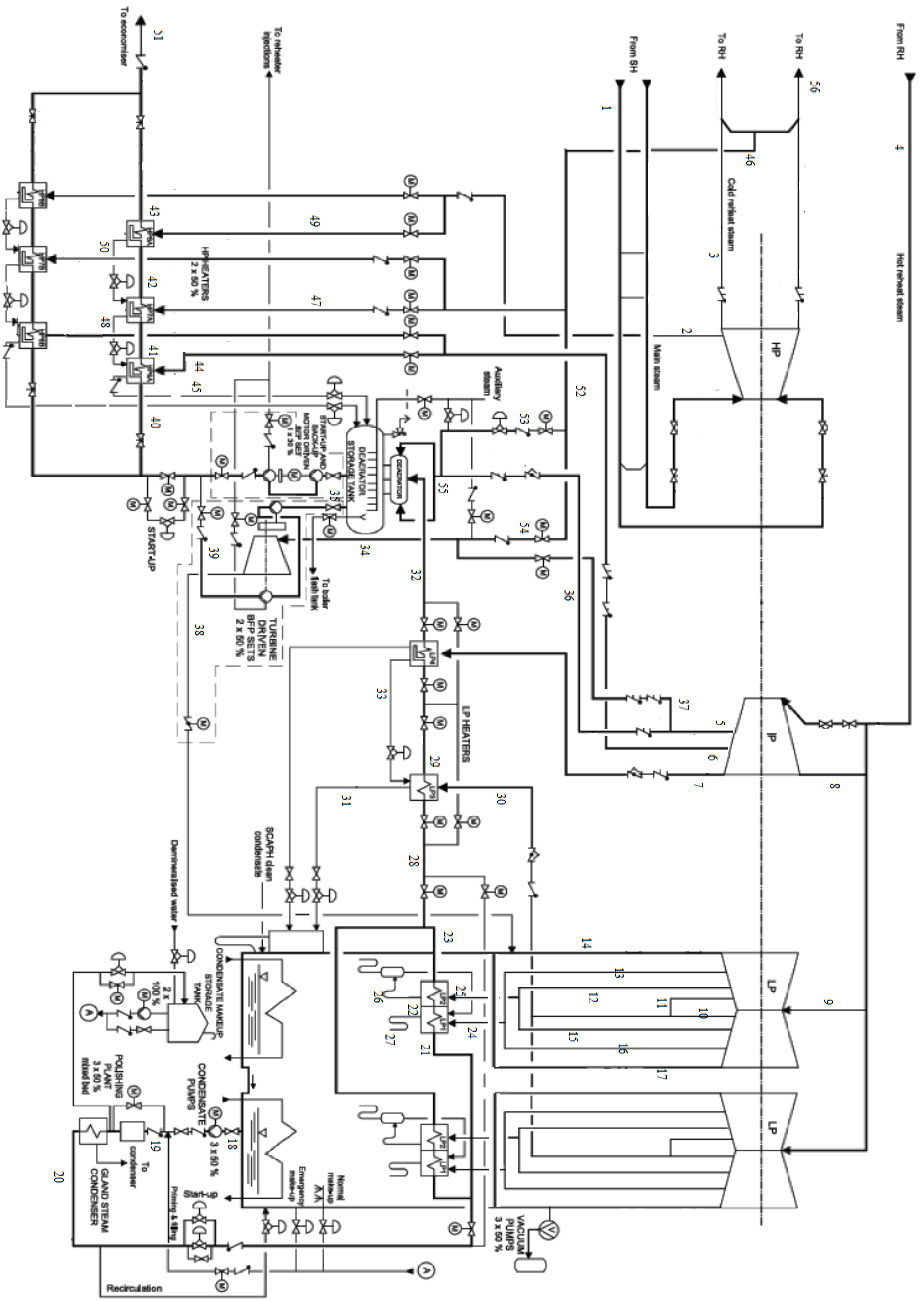

Fig. 1. Process flow diagram of the considered power plant

Table 1
Energy equations and efficiencies/effectiveness of various components of the thermal cycle

Component Name	Energy Equation	Energy Efficiency
Boiler	$Q_{Boiler} = m_1 \cdot h_1 + m_4 \cdot h_4 - m_{36} \cdot h_{36} - m_{51} \cdot h_{51}$	$\eta_{Boiler} = \frac{Q_{Boiler}}{m_{Coal} HHV_{Coal}}$
Condenser	$Q_{Cond} = 2m_{14} \cdot h_{14} + 2m_{17} \cdot h_{17} + 2m_{27} \cdot h_{27} + m_{31} \cdot h_{31} - m_{18} \cdot h_{18}$	NA
Deaerator	$m_{32} \cdot h_{32} + m_{34} \cdot h_{34} + 2m_{45} \cdot h_{45} - m_{35} \cdot h_{35} = 0$	NA
HPT	$W_{HPT} = m_1 \cdot h_1 - m_2 \cdot h_2 - m_3 \cdot h_3$	$\eta_{s,HP,i} = \frac{h_1 - h_i}{h_1 - h_{i,s}}$ $i = 2, 3$
IPT	$W_{IPT} = m_4 \cdot h_4 - m_5 \cdot h_5 - m_6 \cdot h_6 - m_7 \cdot h_7 - m_8 \cdot h_8$	$\eta_{s,IP,i} = \frac{h_4 - h_i}{h_4 - h_{i,s}}$ $i = 5, \ldots, 8$
LPT	$W_{LPT} = 2\left(m_9 \cdot h_9 - \sum_{i=10}^{17} m_i \cdot h_i \right)$	$\eta_{s,LP,i} = \frac{h_9 - h_i}{h_9 - h_{i,s}}$ $i = 10, \ldots, 17$
BFP	$W_{BFP} = m_{35} \cdot \left(h_{35} - h_{39} \right)$	$\eta_{s,BFP} = \frac{v_{35} \cdot \left(p_{39} - p_{35} \right)}{h_{39} - h_{35}}$
FWH #1	$m_{21} \cdot h_{21} + m_{24} \cdot h_{24} + m_{26} \cdot h_{26} - m_{22} \cdot h_{22} - m_{27} \cdot h_{27} = 0$	$\varepsilon = \frac{T_{22} - T_{21}}{T_{24} - T_{21}}$
FWH's #2, #4, #8	$m_{c,in} \cdot h_{c,in} + m_{h,in} \cdot h_{h,in} - m_{c,out} \cdot h_{c,out} - m_{h,out} \cdot h_{h,out} = 0$	$\varepsilon = \varepsilon' \cdot \frac{T_{c,out} - T_{c,in,b}}{T_{c,out} - T_{c,in}} + \varepsilon'' \cdot \frac{T_{c,in,b} - T_{c,in}}{T_{c,out} - T_{c,in}}$ $\varepsilon' = \frac{T_{h,in} - T_{h,sat}}{T_{h,in} - T_{c,in,b}}$, $\varepsilon'' = \frac{T_{c,in,b} - T_{c,in}}{T_{h,sat} - T_{c,in}}$
FWH's #3, #6, #7	$m_{h,in} \cdot h_{h,in} + m_{c,in} \cdot h_{c,in} + m_{con,dis} \cdot h_{con,dis} - m_{c,out} \cdot h_{c,out} - m_{h,out} \cdot h_{h,out} = 0$	$\varepsilon = \varepsilon' \cdot \frac{T_{c,out} - T_{c,in,b}}{T_{c,out} - T_{c,in}} + \varepsilon'' \cdot \frac{T_{c,in,b} - T_{c,in}}{T_{c,out} - T_{c,in}}$ $\varepsilon' = \frac{T_{h,in} - T_{h,sat}}{T_{h,in} - T_{c,in,b}}$ **&** $\varepsilon'' = \frac{T_{c,in,b} - T_{c,in}}{T_{h,sat} - T_{c,in}}$

Table 2
Exergy supply, destruction and efficiency of various components of the thermal cycle

Component Name	Exergy Supply	Exergy Destruction	Exergy Efficiency
Boiler	$Exs_{Boiler} = Ex_{Chem,Coal}$ $Ex_{Chem,Coal} = \varphi LHV$ $\varphi = 1.0437 + 0.1896(h/c) + 0.2499(o/c) + 0.0428(n/c)$	$Exd_{Boiler} = Ex_{Chem,Coal} - \begin{pmatrix} Ex_1 + Ex_4 - Ex_{51} \\ -Ex_{36} \end{pmatrix}$	$\eta_{2,Boiler} = \frac{Ex_1 + Ex_4 - Ex_{51} - Ex_{36}}{Ex_{Chem,Coal}}$
Condenser	$Exs_{cond} = Ex_{27} + 2Ex_{14} + 2Ex_{17} + Ex_{31} + Ex_{52}$	$Exd_{condenser} = Exs_{condenser} - (Ex_{53} - Ex_{18})$	$\eta_{2,condenser} = 1 - \frac{Exd_{condenser}}{Exs_{condenser}}$
Deaerator	$Exs_{deaerator} = Ex_{32} + Ex_{34} + 2Ex_{45}$	$Exd_{deaerator} = T_0 S_{gen} = T_0 \begin{pmatrix} m_{35}s_{35} - m_{32}s_{32} - \\ m_{34}s_{34} - 2m_{45}s_{45} \end{pmatrix}$	$\eta_{2,deaerator} = 1 - \frac{Exd_{deaerator}}{Exs_{deaerator}}$
HPT	$Exs_{HPT} = Ex_1 - Ex_2 - Ex_3$	$exd_{HPT} = Exs_{HPT} - W_{HPT}$	$\eta_{2s,HPT} = \frac{W_{HPT}}{Exs_{HPT}}$
IPT	$Exs_{IPT} = Ex_4 - Ex_5 - Ex_6 - Ex_7 - Ex_8$	$Exd_{IPT} = Exs_{IPT} - W_{IPT}$	$\eta_{2s,IPT} = \frac{W_{IPT}}{Exs_{IPT}}$
LPT	$Exs_{LPT} = 2Ex_9 - 2\left(\sum_{i=10}^{17} Ex_i\right)$	$Exd_{LPT} = Exs_{LPT} - W_{LPT}$	$\eta_{2s,LPT} = \frac{W_{LPT}}{Exs_{LPT}}$
BFP	$Exs_{BFP} = W_{BFP}$	$Exd_{BFP} = W_{BFP} - (Ex_{39} - Ex_{35})$	$\eta_{2s,BFP} = \frac{Ex_{39} - Ex_{35}}{W_{BFP}}$
FWH #1	$Exs_{FWH1} = Ex_{24} + Ex_{26b} - Ex_{27}$	$Exd_{FWH1} = Exs_{FWH1} - (Ex_{22} - Ex_{21})$	$\eta_{2,FWH1} = \frac{Ex_{22} - Ex_{21}}{Ex_{24} + Ex_{26b} - Ex_{27}}$
FWH's #2, #4, #8	$Exs = Ex_{h,in} - Ex_{h,out}$	$Exd = Exs - (Ex_{c,out} - Ex_{c,in})$	$\eta_2 = \frac{Ex_{c,out} - Ex_{c,in}}{Ex_{h,in} - Ex_{h,out}}$
FWH's #3, #6, #7	$Exs = Ex_{h,in} + Ex_{con,dis} - Ex_{h,out}$	$Exd = Exs - (Ex_{c,out} - Ex_{c,in})$	$\eta_2 = \frac{Ex_{c,out} - Ex_{c,in}}{Ex_{h,in} + Ex_{con,dis} - Ex_{h,out}}$

In this investigation, Unit 1 of Manjung Coal Fired Power plant located in Malaysia is considered for analysis. This unit produces 700 MW nominally; while according to the acquired data, its actual output is around 590 MW. To have a solid ground for comparison and analysis, a baseline case is assumed. Solving the governing equations developed, different parameters of the powerplant are evaluated for the baseline case. Table 3 presents the actual input data for the mass flow rates of the water and steam flows of the baseline case which are furnished to the computational code. The mass flow rates of other lines are calculated using the continuity equations. Table 4 shows the pressure and temperature data giving to the code. These data are collected from the instruments of the powerplant.

Table 3
The input data for the mass flow rates of water/steam in the power plant

State	Mass flow rate [kg/s]
1	480.50
2	16.71
6	20.20
7	26.60
10	2.33
11	2.33
12	3.34
13	3.34
46	26.82

Table 4
The input data for the pressure and temperature of the water/steam flows in different stations of the powerplant

State	Pressure[bar]	Temperature [℃]	State	Pressure[bar]	Temperature [℃]
1	148.1	539.8	27	0.23	NA
2	43	362	28	20	82.2
3	33	321	29	18	NA
4	28.2	534.3	30	1.1	NA
5	8.3	351.5	31	1.1	NA
6	18	464	32	16	NA
7	3.8	262.4	33	3.8	NA
8	3.8	262.4	34	8.3	345.3
9	3.8	262.4	35	8.3	NA
10	1.1	146.3	36	33	NA
11	1.1	146.3	37	155.7	300
12	0.59	91	38	155.7	NA
13	0.23	102	39	175.2	NA
14	0.073	NA	40	173.2	NA
15	0.59	91	41	170.2	NA
16	0.23	102	42	167.2	NA
17	0.073	NA	43	164.2	NA
18	0.073	NA	44	18	NA
19	27	NA	45	18	NA
20	26	NA	46	33	NA
21	25	41.4	47	33	NA
22	23	NA	48	33	NA
23	21	NA	49	43	NA
24	0.23	NA	50	43	NA
25	0.59	NA	51	160.3	256.8
26	0.59	NA			

The effectiveness of various closed boiler feed water heaters at the baseline case are calculated and presented in Table 5. The data will be used in the predictive mode to anticipate the behavior of the boiler feed water heaters when the mass flow rates are varied. From this table, it is clear that the best thermal performance of the heaters belongs to heater #6 while the worst performance is for heaters #2 and #3. This can be attributed to the structure of the heaters.

Table 5
The effectiveness of closed boiler feed water heaters

Boiler feed water heater No.	Effectiveness
1	0.84
2	0.77
3	0.77
4	0.81
6	0.87
7	0.81
8	0.79

To find the properties of steam leaving different stages of the turbines, we need to know the isentropic efficiencies of the stages. For this purpose, for the baseline case, the isentropic efficiencies of various expansion stages of the turbines are evaluated and presented in Table 6.

Table 6
Isentropic efficiencies of various expansion stages through the turbines

Stage number	Isentropic efficiency
HP2	0.84
HP3	0.89
IP5	0.95
IP6	0.92
IP7	0.92
IP8	0.92
LP10, LP11	0.85
LP12, LP15	0.89
LP13, LP16	0.74
LP14, LP17	0.84

Table 7 gives the main parameters of the thermal cycle and powerplant. Using this table, we can be assured that the code works properly and we can rely on the results. As is seen from this table, the net power delivered by the cycle is 590 MW which is close to the data acquired from the powerplant. The thermal efficiency of the cycle is 43.71%, the efficiency of boiler is about 69.67% and the efficiency of the powerplant is 30.45%. To achieve these data, according to the data of the powerplant, it is assumed that 7618 Ton/day (88.17 kg/s) coal with CV of 21982 kJ.kg is consumed.

Table 7
Main parameters of the thermal cycle and powerplant

Parameter	Value
Heat transfer rate of the condenser, $Q_{Cond.}$	759.811 MW
Power consumed by the boiler feed pump, W_{BFP}	16.964 MW
Power generated by the high pressure turbine, W_{HPT}	184.283 MW
Power generated by the intermediate pressure turbine, W_{IPT}	226.293 MW
Power generated by the low pressure turbine, W_{LPT}	196.964 MW
Net power generated by the thermal cycle, W_{net}	590.234 MW
Heat rate of the thermal cycle, HR_{Cycle}	2.288
Heat transfer rate of the boiler, Q_{Boiler}	1220 MW
Heat transfer rate of the economizer, $Q_{Eco.}$	130.006 MW
Thermal efficiency of the cycle, $\eta_{th,cycle}$	43.71%
Efficiency of the boiler, η_{Boiler}	69.67%
Efficiency of the powerplant, η_{pp}	30.45%

The supplied and destroyed exergies to/at different turbine stages and various heaters of the thermal cycle at the baseline case are presented in Table 8. Also, included in this table is the total supplied exergy to the cycle as well as the total destroyed exergy throughout the cycle.

Table 8
The supplied and destroyed exergies to/at various components of the thermal cycle

Component	Supplied exergy rate [kW]	Destroyed exergy rate [kW]
HPT	195630	11347
IPT	232740	6447
LPT	234366	37402
FWH #1	3706	1312
FWH #2	5203	1330
FWH #3	5440	1041
FWH #4	18500	4057
FWH #5	57703	3255
FWH #6	11545	1364
FWH #7	11618	870.4
FWH #8	7421	480.1
Total cycle	744410	154176

Table 9 represents the second law efficiencies of various turbines and feed water heaters of the cycle for the baseline case. In fact, this table shows the strong and weak points of the power plant. Going through the table it is seen that IPT has the best performance regarding the second law of thermodynamics; while, LPT performs as the weakest. For the feed water heaters, we see that FWH #1 has the worst condition while heaters #5 and #8 have the best second law efficiencies. The low second law efficiency of first feed water heater is contributed to this fact that the extracted steam entering this heater is saturated steam having less thermal potential in heating the feed water stream.

Table 9
Second law efficiencies of the turbines, the FWH's of the cycle and total cycle

Component	Second law efficiency [%]
HPT	94.2
IPT	97.23
LPT	84.04
FWH #1	64.59
FWH #2	74.44
FWH #3	80.86
FWH #4	78.07
FWH #5	94.36
FWH #6	88.19
FWH #7	92.51
FWH #8	93.53
Total cycle	79.29

3. Results and Discussion
3.1 Main Steam Mass Flow Rate

To see the effect of main steam mass flow rate (at the exit of the superheater) on different parameters of the cycle, five distinct mass flow rates are considered; that is, 360, 420, 480.5, 540 and

600 kg/s. In fact, the mass flow rate of 480.5 kg/s is the baseline mass flow rate, while two lower and two higher mass flow rates are also considered to examine its impact on the cycle.

Figure 2 illustrates the variations of the mass flow rates of the bled steam of turbines for heating different feed water heaters at the aforementioned main steam mass flow rates. From this figure, it is seen that the steam extracted for feed water heaters #4 and #5 have the highest mass flow rates, while the least amount of steam is bled for feed water heaters #1 and #2. It needs notice that feed water heaters #1, #2, #6, #7 and #8 are in pair; that is, there are two heaters #1 in parallel and so on. Considering this matter, the least amount of steam invoked by the feed water heaters, is the steam devoted to feed water heater #3.

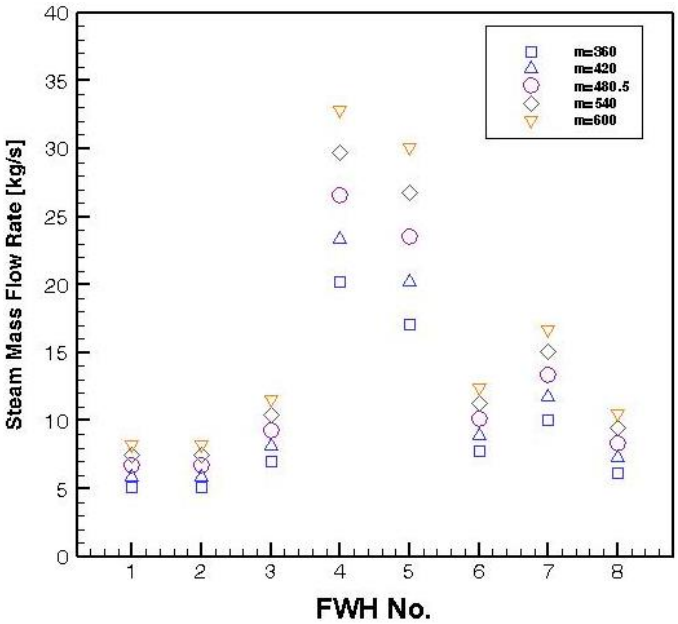

Fig. 2. Effect of the mass flow rate of the main steam on the mass flow rate of the steam extracted for various feed water heaters

The other important notion of this figure is that heaters #4 and #5 are most sensible to the variations of the mass flow rate of the main steam. When this mass flow rate increases, the flow rate of water going through all the way down to the condenser will increase. However, as the mass flow rate of the feed water stream through the heaters ramps up, the required steam for compensating this increased energy requirement would also rise. This matter is reflected in this graph.

The variations of the effectiveness of feed water heaters versus the main steam mass flow rate is plotted in Figure 3. It is observed that by increasing the main steam mass flow rate, the effectiveness of the heaters reduces. This is due to the fact that at higher mass flow rates, the velocity of the fluids grows which hinders the perfect contact between the fluids and the heat transfer surfaces. This happens for both of the in-tube and shell-side streams. This issue is more pronounced in feed water heater #3 which accommodates the highest increase in the mass flow rate of the extracted steam (referring to Figure 2). That is, the more growth in the streams mass flow rate leads to steeper fall in the heater effectiveness.

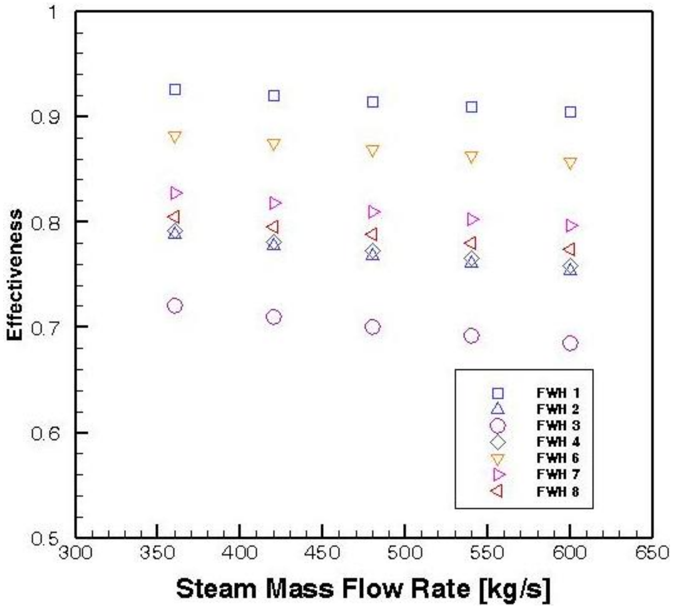

Fig. 3. Variations of FWH's effectiveness with the mass flow rate of the main steam

The impact of the change in the mass flow rate of the main steam on the thermal and second law efficiencies of the cycle as well as the efficiency of the powerplant is slight as is seen in Figure 4. In fact, as there are little deviations in increments of different streams, the aforementioned efficiencies vary slightly. Otherwise, we expect that the efficiencies do not vary with the change in the main steam mass flow rate. Although it is not conceivable from the figure, all of the efficiencies decrease with the increase of the main steam mass flow rate. The maximum variations of thermal efficiency, powerplant efficiency and second law efficiency are 0.04, 0.03 and 0.07%, respectively.

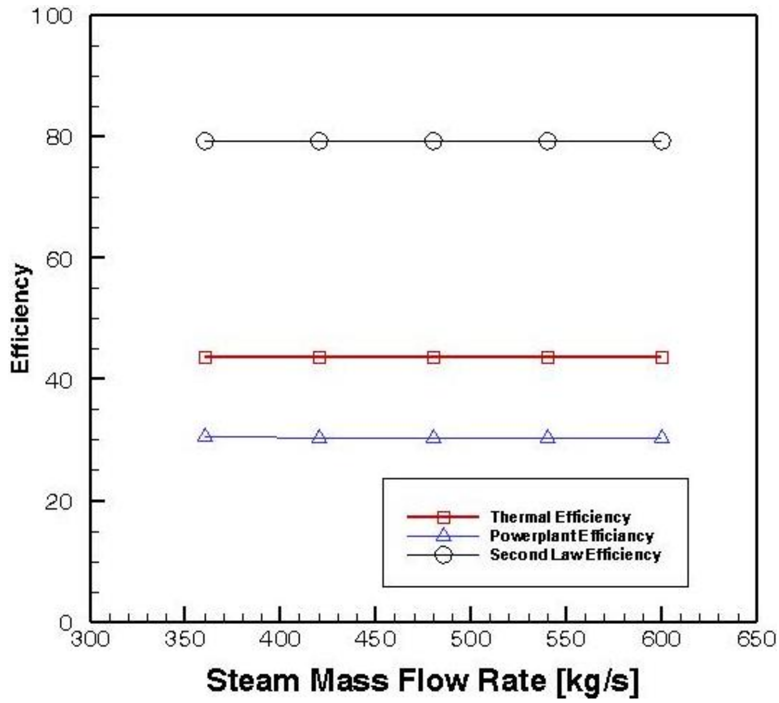

Fig. 4. The effect of mass flow rate of the main steam on different efficiencies of the cycle and powerplant

Presented in Table 10 are the coal consumption rate, the values of the heat rate of the cycle and net power delivered by the cycle at different mass flow rates of the main steam. It is seen that the fuel consumption rate and the net power of the cycle are proportional to the mass flow rate of steam provided by the boiler, expectedly; however, the effect of this mass flow rate on the heat rate is negligible. This is in agreement with what we have seen in Figure 4.

Table 10
The effect of steam mass flow rate produced in boiler on the Heat Rate of the cycle, net power delivered by the cycle and mass flow rate of coal consumed in the boiler

Steam Mass Flow Rate [kg/s]	$\dot{m}_{Coal}$ [kg/s]	HR_{cycle}	$\dot{W}_{net}$ [MW]
360	66.01	2.287	442.138
420	77.04	2.287	515.873
480.5	88.17	2.288	590.234
540	99.12	2.288	663.377
600	110.20	2.289	737.145

The exergy efficiencies of the high, intermediate and low pressure turbines are calculated at different values of the main steam mass flow rates, Figure 5. Here again, it is observed that the variations are slight. However, it needs caution that the turbines should be capable of accommodating these amounts of mass flow rates. In fact, when less steam passes through the turbine, the powerplant will work in partial load; and when higher flow rates of steam passes, the system will work in overload. The latter needs more detailed examination prior to put in practice.

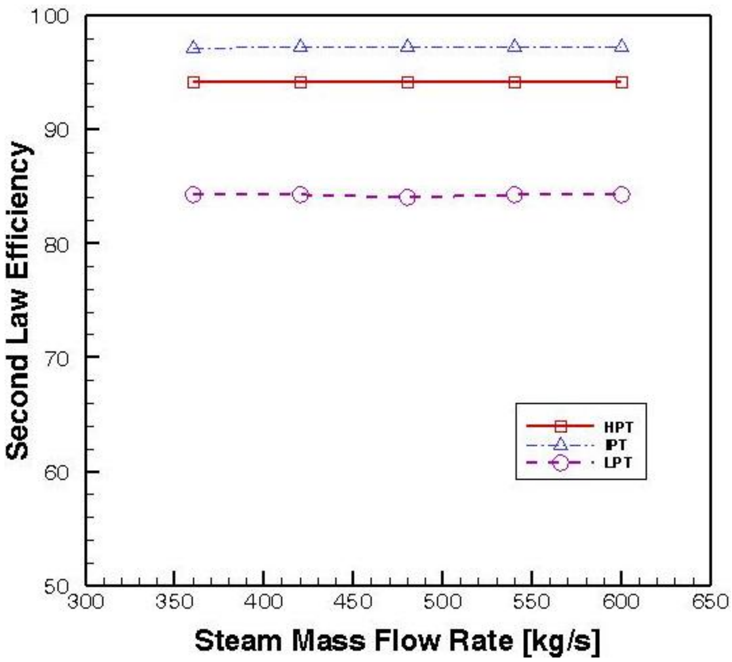

Fig. 5. Effect of the main steam mass flow rate on the second law efficiencies of different turbines

The variations of the second law efficiencies of various feed water heaters versus the mass flow rate of the main steam are depicted in Figure 6. From this figure, it is evident that the highest exergy efficiency belongs to heater #5 which is a direct type heater. As the heat transfer occurs more perfectly in this heat exchanger, its exergy efficiency is higher than its peers. Moreover, it is seen that among the closed type heat exchangers, heaters #1 and #8 have the lowest and highest exergy efficiencies, respectively. This can be reasoned by this fact that these heaters have the largest and smallest temperature differences between the streams. Also, it is notable that the exergy efficiency of the heaters is not sensitive to the main steam mass flow rate.

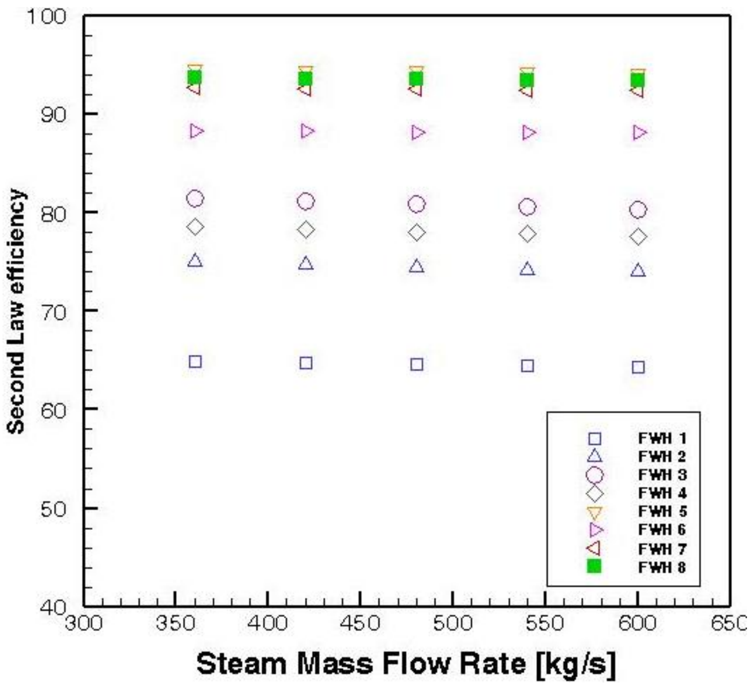

Fig. 6. Effect of the main steam mass flow rate on the exergy efficiencies of the heaters

3.2 Coal Consumption Rate

The variations of the effectiveness of feed water heaters versus the coal consumption rate is plotted in Figure 7. It is observed that by increasing the coal consumption rate, the effectiveness of the heaters is reduced. This is due to the fact that at higher coal consumption rates, more steam will be produced (while the state of the produced superheated steam is fixed). Similar to what has been observed in Figure 3, this issue leads to lower values of heater effectiveness.

The impact of change in the coal consumption rate on the thermal and second law efficiencies of the cycle as well as the efficiency of the powerplant is negligible as is seen in Figure 8. The slight changes in the efficiencies are due to the small differences in how the mass flow rates of different streams increase.

From Table 11 it is observable when more coal is burnt in the boiler, more power is delivered by the powerplant. This is totally expectable as burning more fuel means producing more steam. Also, it is seen that the heat rate of the cycle is not so sensitive to the coal consumption rate.

The variations of the second law efficiencies of various feed water heaters versus the coal consumption rate are presented in Figure 9. From this figure, it is evident that the exergy efficiency of the heaters is not sensitive to the coal consumption rate.

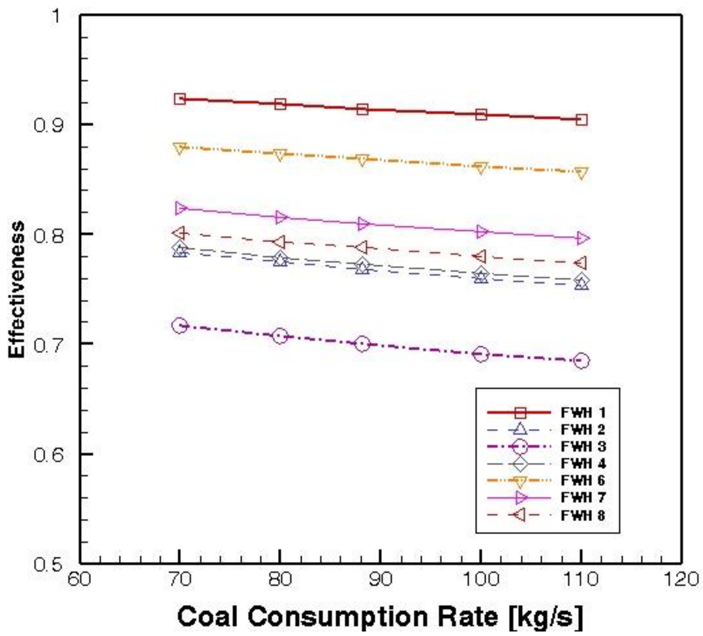

Fig. 7. Variations of FWH's effectiveness with the coal consumption rate

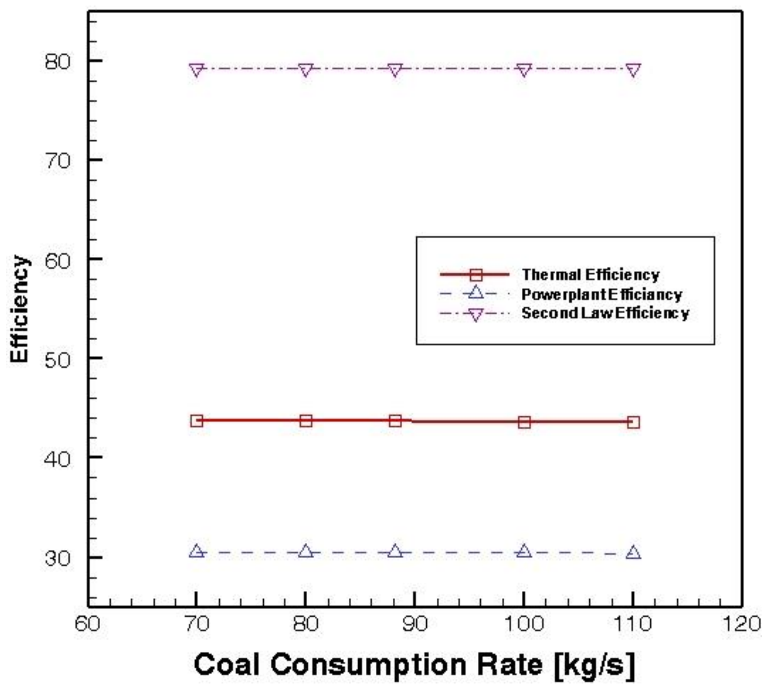

Fig. 8. Variations of the efficiencies of the cycle and powerplant with the coal consumption rate

Table 11
The effect of coal consumption rate on the Heat Rate and net power delivered by the cycle

$\dot{m}_{Coal}$ [kg/s]	HR_{cycle}	$\dot{W}_{net}$ [MW]
70	2.287	468.800
80	2.287	535.640
88.17	2.288	590.234
100	2.288	669.264
110	2.289	736.052

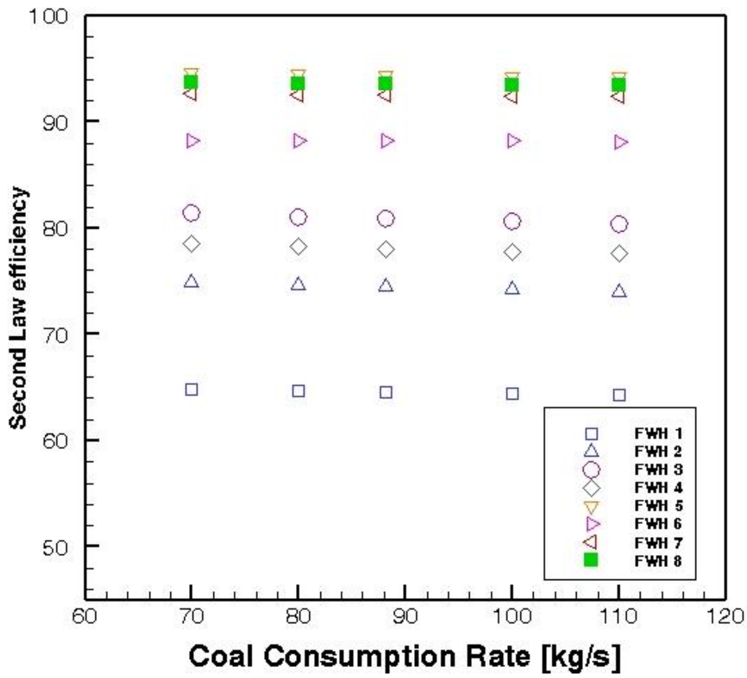

Fig. 9. Variations of exergy efficiency of the FWH's with the coal consumption rate

5. Conclusions

To analyze the coal-fired power plant, a computational code was developed. The most important findings of this study are stated under the following subsections.

i. By increasing the main steam mass flow rate, the effectiveness of the heaters reduces.
ii. The net power of the cycle is linearly proportional to the mass flow rate of the steam generated in the boiler.
iii. Increasing the mass flow rate intensifies the exergy destruction of different components of the power plant.
iv. The mass flow rate of superheated steam has slight impact on the exergy efficiencies of various equipment of the cycle.
v. By increasing the coal consumption rate, the effectiveness of the heaters is reduced.
vi. Increasing the fuel consumption rate will increase the exergy destruction at the main components of the thermal cycle in the range of 52 ~ 68%.

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References

[1] Deng, Chao, Ahmed T. Al-Sammarraie, Thamir K. Ibrahim, Erfan Kosari, Firdaus Basrawi, Firas B. Ismail, and Ahmed N. Abdalla. "Air cooling techniques and corresponding impacts on combined cycle power plant (CCPP) performance: A review." *International Journal of Refrigeration* 120 (2020): 161-177. https://doi.org/10.1016/j.ijrefrig.2020.08.008
[2] Zaidan, Maki H., Aadel AR Alkumait, and Thamir K. Ibrahim. "Assessment of heat transfer and fluid flow characteristics within finned flat tube." *Case Studies in Thermal Engineering* 12 (2018): 557-562. https://doi.org/10.1016/j.csite.2018.07.006

[3] Awad, Omar I., R. Mamat, Thamir K. Ibrahim, Ftwi Y. Hagos, M. M. Noor, I. M. Yusri, and A. M. Leman. "Calorific value enhancement of fusel oil by moisture removal and its effect on the performance and combustion of a spark ignition engine." *Energy Conversion and Management* 137 (2017): 86-96. https://doi.org/10.1016/j.enconman.2017.01.009

[4] Ibrahim, Thamir K., Mohammed Kamil Mohammed, Omar I. Awad, Ahmed N. Abdalla, Firdaus Basrawi, Marwah N. Mohammed, G. Najafi, and Rizalman Mamat. "A comprehensive review on the exergy analysis of combined cycle power plants." *Renewable and Sustainable Energy Reviews* 90 (2018): 835-850. https://doi.org/10.1016/j.rser.2018.03.072

[5] Mhamuad, Aziz7 M., Thamir Kh Ibrahim, and Raid R. Jasim. "Determination of the temperature distribution the perforated fins under." *Tikrit Journal of Engineering Sciences* 15, no. 2 (2008): 63-78.

[6] Ibrahim, Thamir K., and M. M. Rahman. "Effect of compression ratio on the performance of different strategies for the gas turbine." *International Journal of Automotive and Mechanical Engineering* 9 (2014): 1747. https://doi.org/10.15282/ijame.9.2013.23.0145

[7] Basrawi, Firdaus, Thamir K. Ibrahim, Khairul Habib, and Takanobu Yamada. "Effect of operation strategies on the economic and environmental performance of a micro gas turbine trigeneration system in a tropical region." *Energy* 97 (2016): 262-272. https://doi.org/10.1016/j.energy.2015.12.117

[8] Basrawi, Firdaus, Thamir K. Ibrahim, Giok Chui Lee, Khairul Habib, and Hassan Ibrahim. "Effect of solar fraction on the economic and environmental performance of solar air-conditioning by adsorption chiller in a tropical region." *Journal of Solar Energy Engineering* 137, no. 6 (2015). https://doi.org/10.1115/1.4031707

[9] Ibrahim, Thamir K., and M. M. Rahman. "Effective Parameters on Performance of Multipressure Combined Cycle Power Plants." *Advances in Mechanical Engineering (Hindawi Publishing Corporation)* (2014). https://doi.org/10.1155/2014/781503

[10] Ibrahim, Thamir K., and M. M. Rahman. "Effects of cycle peak temperature ratio on the performance of combined cycle power plant." *International Journal of Automotive & Mechanical Engineering* 13, no. 2 (2016). https://doi.org/10.15282/ijame.13.2.2016.8.0280

[11] Awad, Omar I., Rizalman Mamat, Thamir K. Ibrahim, Maurice Kettner, K. Kadirgama, A. M. Leman, and A. I. M. Saiful. "Effects of fusel oil water content reduction on fuel properties, performance and emissions of SI engine fueled with gasoline-fusel oil blends." *Renewable Energy* 118 (2018): 858-869. https://doi.org/10.1016/j.renene.2017.11.071

[12] Panos, Evangelos, Martin Densing, and Kathrin Volkart. "Access to electricity in the World Energy Council's global energy scenarios: An outlook for developing regions until 2030." *Energy Strategy Reviews* 9 (2016): 28-49. https://doi.org/10.1016/j.esr.2015.11.003

[13] Ibrahim, Thamir K., and M. M. Rahman. "Effects of isentropic efficiencies on the performance of combined cycle power plants." *International Journal of Automotive & Mechanical Engineering* 12 (2015). https://doi.org/10.15282/ijame.12.2015.9.0244

[14] Ibrahim, Thamir K., and M. M. Rahman. "Effects of isentropic efficiency and enhancing strategies on gas turbine performance." *Journal of Mechanical Engineering and Sciences* 4 (2013): 383-396. https://doi.org/10.15282/jmes.4.2013.3.0036

[15] Ibrahim, Thamir K., and M. M. Rahman. "Effects of operation conditions on performance of a gas turbine power plant." In *National Conference in Mechanical Engineering Research and Postgraduate Studies (2nd NCMER 2010)*, pp. 135-144. Kuantan: Faculty of Mechanical Engineering, UMP Pekan, 2010.

[16] Mohammed, Mohammed Kamil, Wadhah Hussein Al Doori, Ataalah Hussain Jassim, Thamir Khalil Ibrahim, and Ahmed Tawfeeq Al-Sammarraie. "Energy and exergy analysis of the steam power plant based on effect the numbers of feed water heater." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 56, no. 2 (2019): 211-222.

[17] Elghool, Ali, Firdaus Basrawi, Hassan Ibrahim, Thamir Khalil Ibrahim, M. Ishak, T. M. Yusof, and Salem Abdullah Bagaber. "Enhancing the performance of a thermo-electric generator through multi-objective optimisation of heat pipes-heat sink under natural convection." *Energy Conversion and Management* 209 (2020): 112626. https://doi.org/10.1016/j.enconman.2020.112626

[18] Basrawi, Firdaus, Yeong C. Leon, Thamir K. Ibrahim, Mohd Hazwan Yusof, A. A. Razak, Shaharin Anuar Sulaiman, and Takanobu Yamada. "Experimental Analysis on the Effect of Area of Surface Cooling for a Water-Cooled Photovoltaic." In *MATEC Web of Conferences*, vol. 225, p. 01011. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201822501011

[19] Ibrahim, Thamir K., Ahmed T. Al-Sammarraie, Wadhah H. Al-Taha, Mohammad Reza Salimpour, Manar Al-Jethelah, Ahmed N. Abdalla, and Hai Tao. "Experimental and numerical investigation of heat transfer augmentation in heat sinks using perforation technique." *Applied Thermal Engineering* 160 (2019): 113974. https://doi.org/10.1016/j.applthermaleng.2019.113974

[20] Mohammed, Mohammed K., M. Kh Abdolbaqi, Thamir K. Ibrahim, Rizalman Bin Mamat, and Omar I. Awad. "Experimental and Numerical investigation of Heat transfer enhancement using Al2O3-Ethylene Glycol/Water nanofluids in straight channel." In *MATEC Web of Conferences*, vol. 225, p. 01019. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201822501019

[21] Basrawi, Firdaus, Thamir K. Ibrahim, Surendran S. Sathiyaseelan, and A. A. Razak. "Experimental investigation on performance of solar-powered attic ventilation." In *Sustainable Thermal Power Resources Through Future Engineering*, pp. 1-19. Springer, Singapore, 2019. https://doi.org/10.1007/978-981-13-2968-5_1

[22] Ibrahim, Thamir K., Marwah N. Mohammed, Mohammed Kamil Mohammed, G. Najafi, Nor Azwadi Che Sidik, Firdaus Basrawi, Ahmed N. Abdalla, and S. S. Hoseini. "Experimental study on the effect of perforations shapes on vertical heated fins performance under forced convection heat transfer." *International Journal of Heat and Mass Transfer* 118 (2018): 832-846. https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.047

[23] Ibrahim, Thamir K., Ahmed T. Al-Sammarraie, Manar SM Al-Jethelah, Wadhah H. Al-Doori, Mohammad Reza Salimpour, and Hai Tao. "The impact of square shape perforations on the enhanced heat transfer from fins: Experimental and numerical study." *International Journal of Thermal Sciences* 149 (2020): 106144. https://doi.org/10.1016/j.ijthermalsci.2019.106144

[24] Awad, Omar I., Rizalman Mamat, M. M. Noor, Thamir K. Ibrahim, I. M. Yusri, and A. F. Yusop. "The impacts of compression ratio on the performance and emissions of ice powered by oxygenated fuels: A review." *Journal of the Energy Institute* 91, no. 1 (2018): 19-32. https://doi.org/10.1016/j.joei.2016.09.003

[25] Deng, Chao, Ahmed N. Abdalla, Thamir K. Ibrahim, MingXin Jiang, Ahmed T. Al-Sammarraie, and Jun Wu. "Implementation of Adaptive Neuro-fuzzy Model to Optimize Operational Process of Multiconfiguration Gas-Turbines." *Advances in High Energy Physics* 2020 (2020). https://doi.org/10.1155/2020/6590138

[26] Ibrahim, Thamir K., M. M. Rahman, and Ahmed N. Abdalla. "Improvement of gas turbine performance based on inlet air cooling systems: A technical review." *International Journal of Physical Sciences* 6, no. 4 (2011): 620-627.

[27] Ibrahim, Thamir K., M. Rahman, and K. Sharma. "Influence of operation conditions on performance of combined cycle gas turbine." In *International Conference on Mechanical and Electrical Technology*, 3rd,(ICMET-China 2011), vol. 1, pp. 9-15. 2011.

[28] Elghool, Ali, Firdaus Basrawi, Hassan Ibrahim, and Thamir Ibrahim. "Investigation on the performance of a prototype of thermo-electric generation with heat pipe-heat sink." In *MATEC Web of Conferences*, vol. 131, p. 01005. EDP Sciences, 2017. https://doi.org/10.1051/matecconf/201713101005

[29] Ibrahim, Thamir K. "The Life cycle assessments of gas turbine using inlet air cooling system." *Tikrit Journal of Engineering Sciences* 22, no. 1 (2015): 69-75. https://doi.org/10.25130/tjes.22.1.07

[30] Al-Sammarraie, Ahmed Tawfeeq Ahmed, Raaid Rashad Jassem, and Thamir K. Ibrahim. "Mixed convection heat transfer in inclined tubes with constant heat flux." *European Journal of Scientific Research* 97, no. 1 (2013): 144-158.

[31] Elghool, Ali, Firdaus Basrawi, Thamir Khalil Ibrahim, Hassan Ibrahim, M. Ishak, Mohd Hazwan bin Yusof, and Salem Abdullah Bagaber. "Multi-objective optimization to enhance the performance of thermo-electric generator combined with heat pipe-heat sink under forced convection." *Energy* 208 (2020): 118270. https://doi.org/10.1016/j.energy.2020.118270

[32] Alkumait, Aadel Abdul Razzaq, Maki Haj Zaidan, and Thamir Khalil Ibrahim. "Numerical Investigation of Forced Convection Flow over Backward Facing Step Affected By A Baffle Position." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 52, no. 1 (2018): 33-45.

[33] Ibrahim, Thamir K., M. M. Rahman, Obed M. Ali, Firdaus Basrawi, and Rizalman Mamat. "Optimum performance enhancing strategies of the gas turbine based on the effective temperatures." In *MATEC Web of Conferences*, vol. 38, p. 01002. EDP Sciences, 2016. https://doi.org/10.1051/matecconf/20163801002

[34] Ibrahim, Thamir K., and M. M. Rahman. "Optimum performance improvements of the combined cycle based on an intercooler-reheated gas turbine." *Journal of Energy Resources Technology* 137, no. 6 (2015). https://doi.org/10.1115/1.4030447

[35] Mohammed, Mohammed Kamil, Omar I. Awad, M. M. Rahman, G. Najafi, Firdaus Basrawi, Ahmed N. Abd Alla, and Rizalman Mamat. "The optimum performance of the combined cycle power plant: A comprehensive review." *Renewable and Sustainable Energy Reviews* 79 (2017): 459-474. https://doi.org/10.1016/j.rser.2017.05.060

[36] Awad, Omar I., R. Mamat, Thamir K. Ibrahim, Ali Thaeer Hammid, I. M. Yusri, Mohd Adnin Hamidi, Ali M. Humada, and A. F. Yusop. "Overview of the oxygenated fuels in spark ignition engine: Environmental and performance." *Renewable and Sustainable Energy Reviews* 91 (2018): 394-408. https://doi.org/10.1016/j.rser.2018.03.107

[37] Ibrahim, Thamir K., and M. M. Rahman. "Parametric simulation of triple-pressure reheat combined cycle: A case study." *Advanced Science Letters* 13, no. 1 (2012): 263-268. https://doi.org/10.1166/asl.2012.3844

[38] Ibrahim, Thamir K., and M. M. Rahman. "Parametric study of a two-shaft gas turbine cycle model of power plant." In *IOP Conference Series: Materials Science and Engineering*, vol. 36, no. 1, p. 012024. IOP Publishing, 2012. https://doi.org/10.1088/1757-899X/36/1/012024

[39] Zulkepli, Afzam, M. R. R. Chand, Thamir K. Ibrahim, Hamzah Sakidin, Firdaus Basrawi, and Mohd Hazwan Yusof. "Performance analysis of a Copper Indium Gallium Selenide (CIGS) based Photovoltaic Thermal (PV/T) water collector." In *MATEC Web of Conferences*, vol. 225, p. 04023. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201822504023

[40] Awad, Omar I., Rizalman Mamat, Thamir K. Ibrahim, Obed M. Ali, K. Kadirgama, and A. M. Leman. "Performance and combustion characteristics of an SI engine fueled with fusel oil-gasoline at different water content." *Applied Thermal Engineering* 123 (2017): 1374-1385. https://doi.org/10.1016/j.applthermaleng.2017.05.132

[41] Dudley, Bob. "BP statistical review of world energy." *World Petroleum Congress*, London. 2019.

[42] Petrakopoulou, Fontina, Alexander Robinson, and Marina Olmeda-Delgado. "Impact of climate change on fossil fuel power-plant efficiency and water use." *Journal of Cleaner Production* 273 (2020): 122816. https://doi.org/10.1016/j.jclepro.2020.122816

[43] Sieminski, Adam. "International energy outlook 2013." *US Energy Information Administration (EIA) Report Number: DOE/EIA-0484* (2013).

[44] Abdalla, Ahmed N., Omar I. Awad, Hai Tao, Thamir K. Ibrahim, Rizalman Mamat, and Ali Thaeer Hammid. "Performance and emissions of gasoline blended with fusel oil that a potential using as an octane enhancer." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 41, no. 8 (2019): 931-947. https://doi.org/10.1080/15567036.2018.1521889

[45] Zaidan, Maki H., Thamir K. Ibrahim, and Aadel AR Alkumait. "Performance enhancement by using wet pad in vapor compression cooling system." *Journal of Engineering and Technological Sciences* 51, no. 1 (2019): 48-63. https://doi.org/10.5614/j.eng.technol.sci.2019.51.1.4

[46] Elghool, Ali, Firdaus Basrawi, Thamir Khalil Ibrahim, Khairul Habib, Hassan Ibrahim, and Daing Mohamad Nafiz Daing Idris. "A review on heat sink for thermo-electric power generation: Classifications and parameters affecting performance." *Energy Conversion and Management* 134 (2017): 260-277. https://doi.org/10.1016/j.enconman.2016.12.046

[47] Ibrahim, Thamir K., M. M. Rahman, M. K. Mohammed, and Firdaus Basrawi. "Statistical analysis and optimum performance of the gas turbine power plant." *International Journal of Automotive and Mechanical Engineering* 13 (2016): 3215. https://doi.org/10.15282/ijame.13.1.2016.8.0268

[48] Ibrahim, Thamir K., and Mustafizur M. Rahman. "Study on effective parameter of the triple-pressure reheat combined cycle performance." *Thermal Science* 17, no. 2 (2013): 497-508. https://doi.org/10.2298/TSCI111016143I

[49] Elghool, Ali, Firdaus Basrawi, Hassan Ibrahim, Thamir K. Ibrahim, Shaharin A. Sulaiman, and M. Ishak. "Study on the Performance of a Thermo-Electric Generation Model with Two Different Materials of Heat Pipe-Heat Sink." In *MATEC Web of Conferences*, vol. 225, p. 04009. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201822504009

[50] Basrawi, Firdaus, Izwan Ismail, Thamir Khalil Ibrahim, Daing Mohamad Nafiz Daing Idris, and Shahrani Anuar. "A study on the power generation potential of mini wind turbine in east coast of Peninsular Malaysia." In *AIP Conference Proceedings*, vol. 1826, no. 1, p. 020023. AIP Publishing LLC, 2017. https://doi.org/10.1063/1.4979239

[51] Basrawi, Firdaus, Thamir K. Ibrahim, Khairul Habib, Takanobu Yamada, and Daing Mohamad Nafiz Daing Idris. "Techno-economic performance of biogas-fueled micro gas turbine cogeneration systems in sewage treatment plants: Effect of prime mover generation capacity." *Energy* 124 (2017): 238-248. https://doi.org/10.1016/j.energy.2017.02.066

[52] Basrawi, Firdaus, M. R. R. Chand, K. H. Koo, and Thamir K. Ibrahim. "Theoretical analysis on the economic performance of micro gas turbine-trigeneration system with different operation strategies for residential building in a tropical region." In *MATEC Web of Conferences*, vol. 38, p. 01003. EDP Sciences, 2016. https://doi.org/10.1051/matecconf/20163801003

[53] Rahman, M. M., Thamir K. Ibrahim, M. Y. Taib, M. M. Noor, and Rosli A. Bakar. "Thermal analysis of open-cycle regenerator gas-turbine power-plant." *Fuel* 200, no. 4 (2010): 811-816.

[54] Ibrahim, Thamir K., Mohammed K. Mohammed, Omar I. Awad, Rizalman Mamat, and M. Kh Abdolbaqi. "Thermal and Economic Analysis of Gas Turbine Using Inlet Air Cooling System." In *MATEC Web of Conferences*, vol. 225, p. 01020. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201822501020

[55] Alkumait, Aadel AR, Thamir K. Ibrahim, Maki H. Zaidan, and Ahmed T. Al-Sammarraie. "Thermal and hydraulic characteristics of TiO2/water nanofluid flow in tubes possessing internal trapezoidal and triangular rib shapes." *Journal of Thermal Analysis and Calorimetry* (2020): 1-14. https://doi.org/10.1007/s10973-020-10289-7

[56] Ibrahim, Thamir K., and M. M. Rahman. "Thermal impact of operating conditions on the performance of a combined cycle gas turbine." *Journal of Applied Research and Technology* 10, no. 4 (2012): 567-577. https://doi.org/10.22201/icat.16656423.2012.10.4.377
[57] Hussein, Omar A., Khairul Habib, Ali S. Muhsan, R. Saidur, Omer A. Alawi, and Thamir K. Ibrahim. "Thermal performance enhancement of a flat plate solar collector using hybrid nanofluid." *Solar Energy* 204 (2020): 208-222. https://doi.org/10.1016/j.solener.2020.04.034
[58] Ibrahim, Thamir K., Firdaus Basrawi, Omar I. Awad, Ahmed N. Abdullah, G. Najafi, Rizlman Mamat, and F. Y. Hagos. "Thermal performance of gas turbine power plant based on exergy analysis." *Applied Thermal Engineering* 115 (2017): 977-985. https://doi.org/10.1016/j.applthermaleng.2017.01.032
[59] Ibrahim, Thamir K., and Marwah N. Mohammed. "Thermodynamic evaluation of the performance of a combined cycle power plant." *International Journal of Energy Science and Engineering* 1, no. 11 (2015).
[60] Khatib, Hisham. "IEA world energy outlook 2011-A comment." *Energy Policy* 48 (2012): 737-743. https://doi.org/10.1016/j.enpol.2012.06.007
[61] Dunham, Marc T., and Brian D. Iverson. "High-efficiency thermodynamic power cycles for concentrated solar power systems." *Renewable and Sustainable Energy Reviews* 30 (2014): 758-770. https://doi.org/10.1016/j.rser.2013.11.010