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Thermo-Economic Analysis of a Coal-Fired Power Plant (CFPP) Using Turbine Cycle Heat Rate and Plant Net Heat Rates at Various Operating Loads

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ABSTRACT

Evaluating Coal-Fired Power Plant (CFPP) performance is a complex process involving the determination of the turbine cycle Heat Rate (TCHR). This study focuses on determining the TCHR by developing a mathematical model. The model, which incorporates economic analysis of the plant, is developed using energy and mass balance relationships of the turbine cycle, validated using plant commissioning data from a 700MWn CFPP located in Perak, Malaysia. Actual plant data from a 700MWn CFPP is utilized to improve the accuracy and increase the confidence of the results of this study. It was found that at the nominal operating load of 729MWg, there is a Heat Rate (HR) deviation of -1,135 kJ/kWh, leading to daily losses of RM240,447 or USD 60,112. Furthermore, it is possible to utilize the developed model at lower loads as the plant is now being used to operate on "cyclic" loads. The daily losses at a lower load of 431MWg are RM125,767 or USD31,442. Thus, the model is able to compare the plant HR at various loads against commissioning data, and economic analysis is able to be carried out effectively. Valuable information for plant operations and performance engineers could be obtained using this model to determine plant HR.

Keywords: CFPP performance, heat rate, thermo-economic analysis

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INTRODUCTION

Coal-Fired Power Plants (CFPP) are the backbone of the power generation sector in Malaysia, providing close to 40% of the national energy demand (Bujang et al., 2016). With the increasing energy demand in a rapidly developing country, the efficient and optimum operations of the plants are vital to minimize the cost of producing energy per unit to ensure the plant remains profitable and sustainable to operate for the wellbeing of the nation (Zhang et al., 2018).

Actual operational data from a 700 MW CFPP is utilized in this study. The plant has been in operation for approximately 18 years. Therefore, relevant data from the commissioning stages are readily available to carry out a comparative study of performance between the present and commissioning stages. Furthermore, there are three identical units of the 700MW CFPP; thus, the developed model may be utilized for all three units.

The performance of a CFPP has been the subject of several studies by scholars. However, a vast majority of previous research work had only focused on performance modeling using a basic simplified version of the plant thermodynamics instead of focusing comprehensively on the turbine cycle heat rate, which is a more accurate method of determining plant performance (Opris et al., 2020; Almedilla et al., 2018; Gupta & Kumar, 2015a). Furthermore, most of the previous research work has not considered economic analysis, which is crucial for plant operations personnel to determine the amount of profit or loss made by the plant on a particular day while most of the units being investigated are below 500MWn (Neshumayev et al., 2018; Wijaya & Widodo, 2018).

While the investigation of certain parameters of the boiler's operations is appreciated, there is nothing much operations personnel are able to do on a daily basis as most of the recommendations require the unit to be shut down for maintenance works (Gupta & Kumar, 2015b; Pachaiyappan & Prakash, 2015). For instance, the majority of the Rotary Air Heater (RAH) improvements can only be achieved by offline cleaning (Sundaravinayaka & Jayapaul, 2017). Furthermore, although there have been certain studies related to improving the intelligent boiler maintenance interface in boiler trips, such investigations are not focused on the performance of the CFPP (Nistah et al., 2014). Thus, in the present study, it is not viable to consider such areas of CFPP performance, which requires shut down of the unit as there are monetary losses of not producing load (Braun, 2021).

It is evident that most of the previous research work in CFPP did not utilize actual real-life plant data. On the other hand, this study utilizes actual plant data and commissioning plant data to improve the model's accuracy. The commissioning plant data is operational data obtained during the commissioning stage of the plant, during which the plant is tested to meet the design performance standard. Thus, it is possible to compare the present operating data with commissioning data to carry out analysis and highlight gaps by having this commissioning data. Furthermore, the present study focuses on the TCHR, which has not been comprehensively investigated in previous studies. The turbine cycle heat rate (TCHR) is defined as the efficiency of the turbine to convert steam from the boiler to usable rotation energy of the turbine shaft, which is connected to the generator. In addition, while several types of research focus on thermodynamic analysis, there is minimal relation of results obtained with economic analysis. Therefore, this study fills the research gap by utilizing a TCHR model incorporating thermodynamic relationships with economic analysis.

This study focuses on developing a model capable of determining CFPP HR using TCHR as plant operators often face difficulty evaluating the TCHR since the energy and mass balance of the CFPP is not readily available in previous literature or plant operating manuals. Furthermore, the evaluation of CFPP performance is often carried out using a simple input-output method where the total power produced is divided by total energy (fuel) input to determine efficiency, which only provides the overall efficiency of the CFPP without any in-depth analysis of the TCHR. Thus, the CFPP performance evaluation of TCHR based on a 700 MW CFPP unit will benefit the power generation sector as the outcome of this research will assist the operations team in understanding the key concepts behind the evaluation of plant performance. Furthermore, the developed model is able to evaluate the performance of the plant at various loads, which is able to assist operations personnel in understanding the present performance of the plant during cyclic load operations. The ultimate goal of this proposed research is to reduce losses due to negative HR deviation to maintain the profitability and sustainability of the power plant in the challenging power generation sector.

The simplified model of a CFPP turbine cycle will determine plant turbine cycle HR. The model is developed using fundamental mass and heat balances of the Low-Pressure Heaters (LPH) and High-Pressure Heaters (HPH) to evaluate the extraction steam flows and determine the main steam and feedwater flow, which are necessary to determine the turbine cycle HR. The model is used to evaluate the turbine cycle HR at present operating condition using actual plant data. The HR Figures may be compared with the expected HR Figures from plant commissioning data. Therefore, it is necessary to use a simplified model so that plant operations personnel are able to understand the principles and utilize the model effectively.

The simplified model is advantageous as the plant operations personnel are able to use it by simply changing the dates of the analysis needed as the built-in PI (Plant Information) Data Link add on is able to automatically extract data from the PI Server connected to the distributed control system (DCS) which is a platform for automated control and operation of the CFPP. In simple words, the DCS screen shows all the important plant parameters live to the operators as the DCS screen is a human-machine interface that has logic solver, historian data, and alarm management while the PI server eases the task of extracting historian operational data (Li & Vani, 2014). Subsequently, economic analysis is carried out to determine the daily losses made due to HR deviation at various operating loads.

Background and CFPP Operations

The plant is a baseload plant that produces maximum power output throughout the day based on the Contractual Available Capacity (CAC), which further emphasizes the importance of the units operating at the maximum possible efficiency (Bisercic & Bugaric, 2021). Furthermore, the potential of performance improvement is more significant for CFPPs operating at baseload as the savings will be significant owing to the fact that there is higher Net Energy Output (NEO) for baseload plants which translates into greater fuel cost savings. Therefore, it is of utmost importance that the units operate at maximum optimal efficiency at all times (Tian et al., 2017).

The CFPP performance is measured by assessing the performance of the main plant, which comprises the boiler and turbine through measurement of prime performance functions such as turbine efficiency, boiler efficiency, and plant heat rate (Umrao et al., 2017; Behbahaninia et al., 2017). In order to maintain high standards of overall performance, it is necessary to continuously monitor these performance parameters at a regular interval (Srinivas et al., 2017).

The overall CFPP processes are described in Figure 1, while Table 1 contains relevant nomenclature for Figure 1. In essence, the treated water, known as “demineralized water,” is supplied to the condenser, a process known as “make-up water,” which replenishes lost operating fluid. Then, the Condensate Extraction Pump (CEP) is responsible for pumping the condensate through the series of LPH. Firstly, the condensate passes through the gland steam cooler and duplex LPH1 and LPH2, after which condensate flows to LPH3 and LPH4 before entering the deaerator with a higher temperature (Buckshumiyanm & Sabarish, 2017).

From the point where the condensate enters the deaerator, the operating fluid is now referred to as “feedwater.” The main function of the feedwater system is to ensure a balanced boiler drum level during the steam evaporation process. The Boiler Feed Pumps (BFP) are responsible for providing suction from the deaerator tank and subsequently provide discharge to a common header that routes feedwater to the high-pressure heaters (Mohammed et al., 2020). The function of the Low-Pressure feedwater (LPH) and High-Pressure Feedwater (HPH) is to increase the temperature of the condensate and feedwater, respectively (Wang et al., 2019).

Table 1
Nomenclature for CFPP process flow as shown in Figure 1

Item	Description
HP Turbine	High-Pressure Turbine
IP Turbine	Intermediate Pressure Turbine
IP Exhaust	Exhaust flow from IP turbine to LP Turbine
LP1/LP2 Turbine	Low-Pressure 1,2 Turbine
LP Exhaust	Exhaust flow from LP turbine to condenser
CEP	Condensate Extraction Pump
LPH3,4	Low-Pressure Heater 3,4
BFP	Boiler Feed Pump
HPH6,7,8	High-Pressure Heater 6,7,8

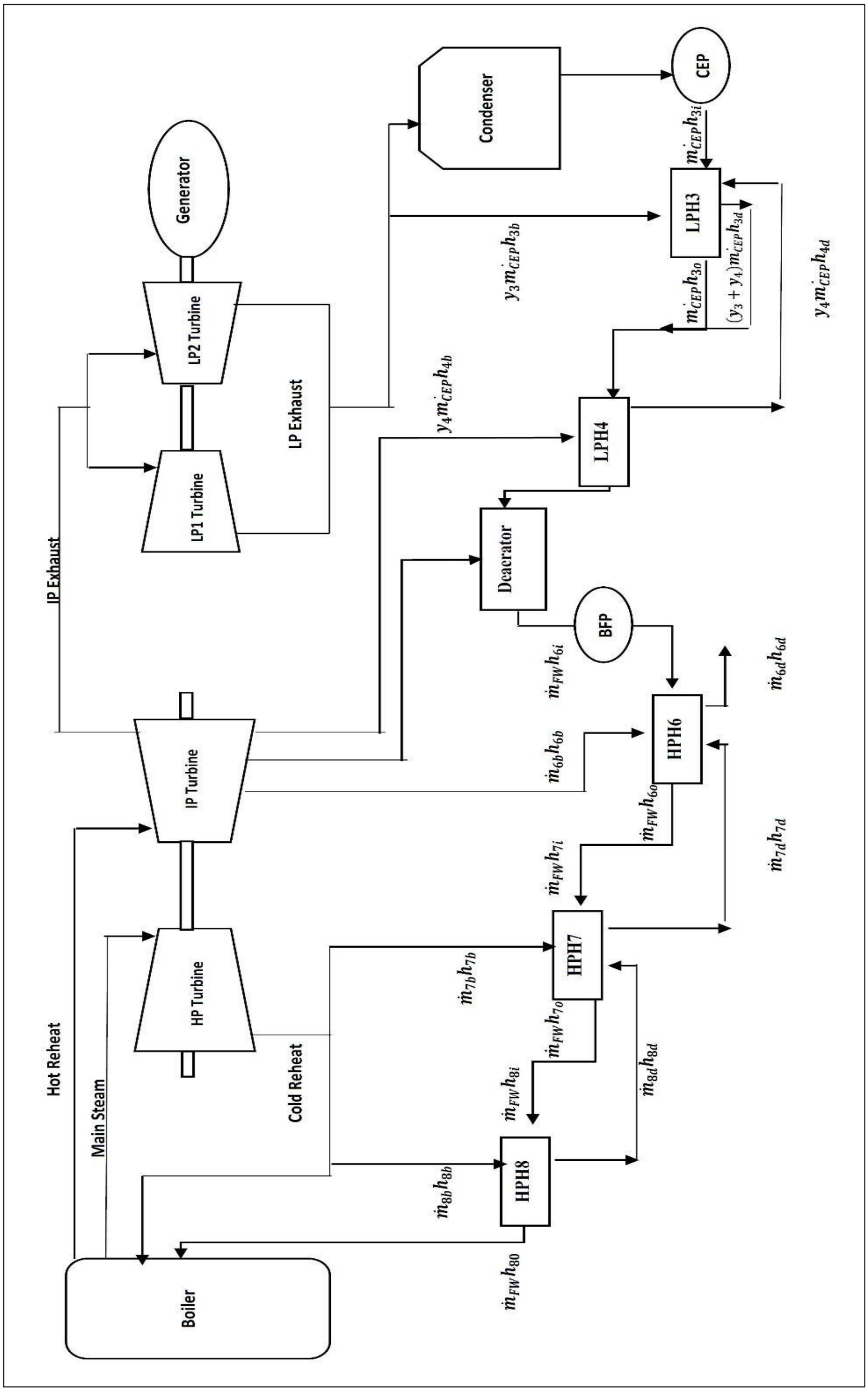

Figure 1. CFPP process flow

From the outlet of HPH8, the feedwater flows to the boiler drum via the economizer, which absorbs heat from flue gas to increase feedwater temperature (Fuzi et al., 2020). The operating fluid continuously circulates from the boiler drum through the downcomers before rising through the water walls of the boiler. It enters the boiler drum again, where a portion of the operating fluid is converted into steam. The function of the boiler drum is to separate vapor from the liquid while supplying the vapor to the superheaters, after which the steam enters the high-pressure turbine, rotating the shaft coupled to the electrical generator (conversion of mechanical rotational energy to electrical energy), producing electricity. After expansion in the turbine, the exhaust steam is condensed in the condenser and is circulated through the CEP to complete the cycle (Devandiran et al., 2016).

METHODOLOGY

In order to determine the heat rate and efficiency of a CFPP, the turbine cycle heat rate (TCHR) has to be determined. The process of evaluating the TCHR involves calculating the energy and mass balance of key components in the turbine cycle, such as the Low-Pressure Heaters (LPH), High-Pressure Heaters (HPH), and deaerator. The parameters such as pressure and temperature of extraction steam are readily available in the Distributed Control System (DCS). The extraction steam flow is the bled steam extracted from the various turbine stages, which is used to preheat the condensate and feedwater, respectively, in the feedwater heaters (FWH). In order the ease the plant personnel to utilize the developed model, an excel spreadsheet or any other similar tool is utilized.

The main aim of carrying out the energy and mass balance is to determine the extraction steam flows of the LPH, HPH, and deaerator and subsequently the feedwater flow as these steam flows are not available on the DCS. Comparison of the extraction steam flows can then be made with the operating TCHR provided in the commissioning and performance test stage of the plant for plant operation engineers to understand the present operating situation of the plant. Furthermore, the feedwater flow is one of the main parameters determined through this energy and mass balance calculations, and the feedwater flow is vital in determining the TCHR.

Due to the complexity of energy and mass balance, the relations for pressure, temperature, and mass flow must be computed to determine the extraction steam flows, hot reheat flow, cold reheat flow, and feedwater flow from the given DCS input parameters. The flowchart of the methodology is illustrated in Figure 2.

The energy and mass balance of the individual HPH6, 7, and 8 are conducted based on Figure 3. The nomenclature for the variables is available in Tables 2 and 4. For HPH8, the energy balance is done by using the principle of mass input is equal to mass output (for both tubes and shell), as shown in Equation 1:

$$\dot{m}_{FW}h_{8i}+\dot{m}_{8b}h_{8b}=\dot{m}_{FW}h_{8o}+\dot{m}_{8d}h_{8d} \quad [1]$$

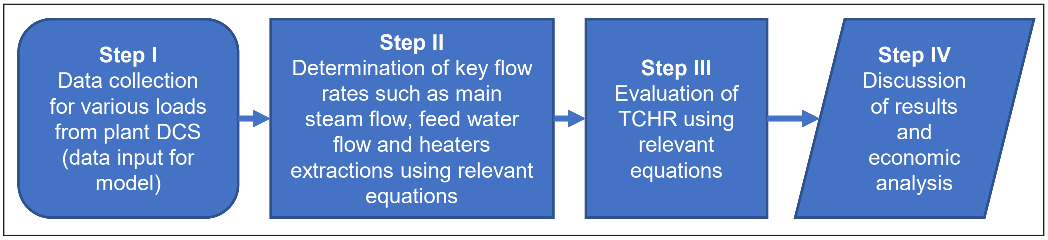

Figure 2. Simplified methodology flowchart

The mass balance of the shell alone is shown in Equation 2:

$$\dot{m}_{8b} = \dot{m}_{8d} \quad [2]$$

Equation 1 can be rearranged by substituting Equation 2, as shown in Equation 3. Equation 3 is arranged with bled steam ($m8b$) as the subject, as shown in Equation 4.

$$\dot{m}_{8b}(h_{8b} - h_{8d}) = \dot{m}_{FW}h_{8o} - \dot{m}_{FW}h_{8i} \quad [3]$$

$$\dot{m}_{8b} = \frac{h_{8o}-h_{8i}}{h_{8b}-h_{8d}} \,.\, \dot{m}_{FW} \quad [4]$$

For HPH7, the energy and mass balance are applied to both tube and shell as shown in Equation 5:

$$\dot{m}_{FW}h_{7i} + \dot{m}_{7b}h_{7b} + \dot{m}_{8d}h_{8d} = \dot{m}_{FW}h_{7o} + \dot{m}_{7d}h_{7d} \quad [5]$$

The mass balance of the shell alone is shown in Equation 6:

$$\dot{m}_{7d} = \dot{m}_{7b} + \dot{m}_{8b} \quad [6]$$

Equation 5 is rearranged by substituting Equation 6. Finally, the equation is arranged with bled steam ($m7b$) as the subject in Equation 7:

$$\dot{m}_{7b} = \frac{h_{7o}-h_{7i}}{h_{7b}-h_{7d}} \,.\, \dot{m}_{FW} + \frac{h_{7d}-h_{8d}}{h_{7b}-h_{7d}} \,.\, \dot{m}_{8b} \quad [7]$$

For HPH6, the energy and mass balance are applied to both tube and shell as shown in Equation 8:

$$\dot{m}_{FW}h_{6i} + \dot{m}_{6b}h_{6b} + \dot{m}_{7d}h_{7d} = \dot{m}_{6d}h_{6d} + \dot{m}_{FW}h_{6o} \quad [8]$$

The mass balance of the shell alone is shown in Equation 9:

$$\dot{m}_{6d} = \dot{m}_{8b} + \dot{m}_{7b} + \dot{m}_{6b} \quad [9]$$

Equation 8 can be rearranged by substituting Equation 9. The equation is arranged with bled steam ($m6b$) as the subject in Equation 10:

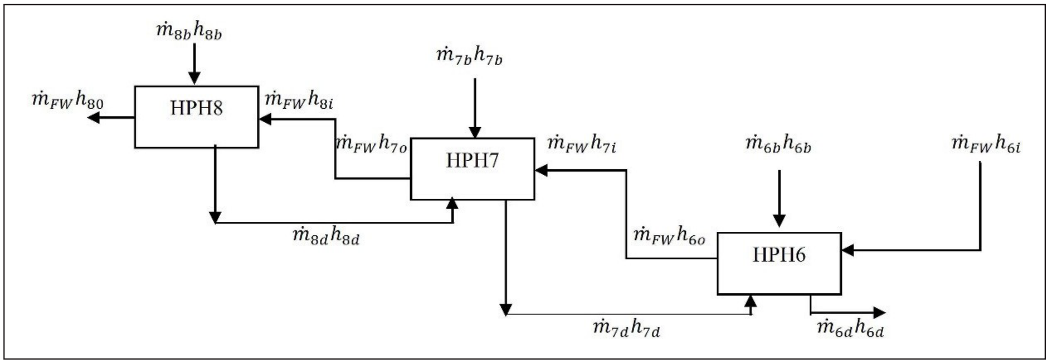

Figure 3. Energy and Mass balance for HPH 6, 7 and 8

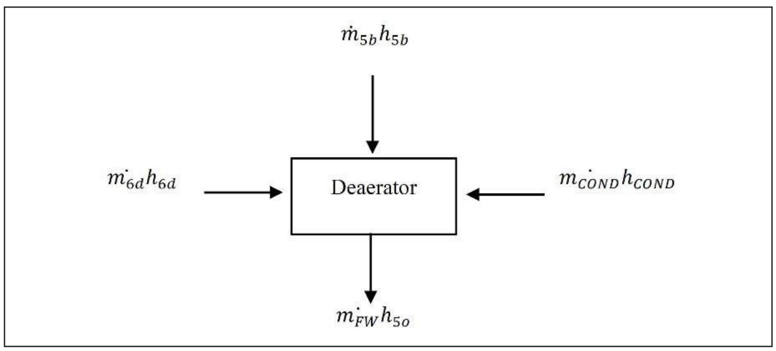

Figure 4. Energy and Mass balance for HPH 5 (Deaerator)

$$\dot{m}_{6b} = \frac{h_{6d}-h_{7d}}{h_{6b}-h_{6d}}.\dot{m}_{8b} + \frac{h_{6d}-h_{7d}}{h_{6b}-h_{6d}}.\dot{m}_{7b} + \frac{h_{6o}-h_{6i}}{h_{6b}-h_{6d}}.\dot{m}_{FW} \quad [10]$$

Based on Figure 4, the energy balance of the deaerator (HPH5) is shown in Equation 11:

$$\dot{m}_{FW}h_{5o} = \dot{m}_{cond}h_{cond} + \dot{m}_{5b}h_{5b} + \dot{m}_{6d}h_{6d} \quad [11]$$

The mass of balance of the deaerator (HPH5) in terms of $\dot{m}_{FW}$ in Equation 12:

$$\dot{m}_{FW} = \dot{m}_{cond} + \dot{m}_{5b} + \dot{m}_{6d} \quad [12]$$

The energy and mass balance of the individual LPH is shown below based on Figure 5. For example, the energy balance for LPH4 is shown in Equation 13:

$$y_4\dot{m}_{CEP}h_{4b} + [\dot{m}_{CEP} + \dot{m}_{CEP}(y_3 + y_4)]h_{4i} = y_4\dot{m}_{CEP}h_{4d} + [\dot{m}_{CEP} + \dot{m}_{CEP}(y_3 + y_4)]h_{4o} \quad [13]$$

Equation 13 is simplified in terms of extraction flow of LPH4 (y_4) as shown in Equation 14:

$$y_4 = \frac{(h_{4o}-h_{4i})y_3+h_{40}-h_{4i}}{h_{4b}+h_{4i}-h_{4d}-h_{40}} \quad [14]$$

Based on Figure 4, the energy balance for LPH3 is shown in Equation 15:

$$\boldsymbol{y_3 \dot{m}_{CEP} h_{3b} + \dot{m}_{CEP} h_{3i} + y_4 \dot{m}_{CEP} h_{4d} = \dot{m}_{CEP}(y_3 + y_4) h_{3d} + \dot{m}_{CEP} h_{3o}} \quad [15]$$

Equation 15 is simplified in terms of extraction flow of LPH3 (y_3) as shown in Equation 16:

$$\boldsymbol{y_3 = \frac{(h_{3o} - h_{3i}) + (h_{3d} - h_{4d}) y_4}{h_{3b} - h_{3d}}} \quad [16]$$

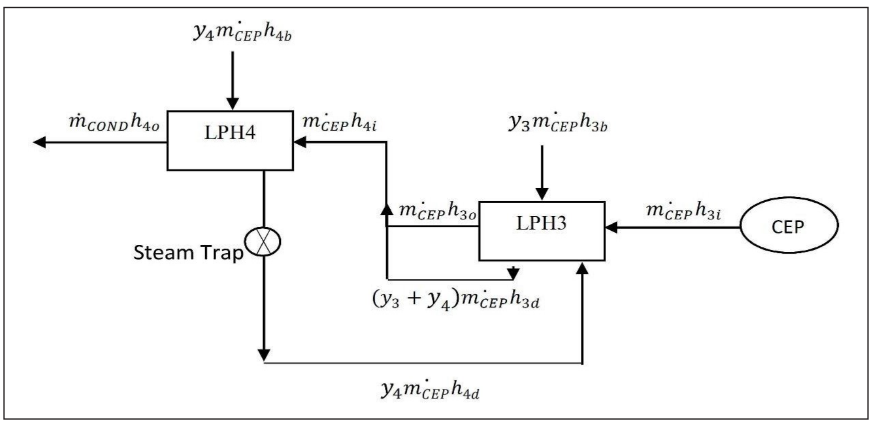

Figure 5. Energy and Mass balance for LPH3 and LPH4

In essence, the TCHR is obtained by adding energy input of main steam and energy input of hot reheat steam from the reheater divided by the net power (load) of the unit. Then, the net TCHR is evaluated using the following Equation 17:

$$\boldsymbol{Net\ Turbine\ Cycle\ HR = \frac{\dot{m}_{Main\ Steam}(h_{MS} - h_{FW}) + \dot{m}_{Hot\ Reheat}(h_{Hot\ Reheat} - h_{Cold\ Reheat})}{Net\ Power}} \quad [17]$$

Furthermore, the net plant HR may be obtained by dividing the Net Turbine cycle HR with the boiler efficiency as shown in Equation 18:

$$\boldsymbol{Net\ Plant\ HR = \frac{Net\ Turbine\ Cycle\ HR}{Boiler\ Efficiency}} \quad [18]$$

The available data from the plant DCS is extracted and shown in a simplified form in Table 2. This data, referred to as the "input data," includes relevant pressures, temperature, and the corresponding enthalpy values. These values are important to determine extraction steam flows for the HPH and deaerator, which are not available in the DCS but are required to evaluate the TCHR. These parameters include pressure and temperature for the inlet and outlet of the deaerator, HPH, and the drains of the HPH, as shown in Table 2. In addition, these values are crucial to determine the respective mass flow rate of the extraction steam of the HPH, feedwater flowrate, condensate flowrate, cold reheat steam flowrate, and hot reheat steam flowrate values, which are required to determine the TCHR as these flow rates are not available in the DCS and these important flowrates may be determined by the model for which the results are summarized in Table 4. The values shown in Table 2 are extracted at a load of 729MWg, which is the normal operating load of the plant. In addition, data has also been extracted for two other loads, 503MWg and 431MWg, which are the cyclic loading pattern for the plant representing 70% and 60% Maximum Continuous Rating (MCR), respectively. However, the input data is not shown in Table 2, although the results are shown in the proceeding section.

Table 2
Pressures, temperature and enthalpy at load 729 MWg including nomenclature

Item	Nomenclature	Pressure(bara)	Temperature(^{O}C)	Enthalpy(kJ/kg)
A) Condensate				
Deaerator Inlet	h_{5i}	25.1	146.0	614.9
Deaerator Outlet	h_{5o}	-	186.7	793.0
B) FeedWater				
HPH6 Inlet	h_{6i}	209.0	189.7	815.8
HPH6 Outlet	h_{6o}	208.5	217.8	939.6
HPH7 Outlet	h_{7o}	207.5	251.3	1092.6
HP8 Outlet	h_{8o}	206.0	268.7	1175.7
C) Drains				
HPH6	h_{6d}	-	191.5	814.4
HPH 7	h_{7d}	-	214.9	920.1
HPH 8	h_{8d}	-	252.2	1096.5
D) Extraction Steam				
Deaerator	h_{5b}	12.0	353.7	3384.1
HPH 6	h_{6b}	19.1	461.4	3384.1
HPH 7	h_{7b}	37.0	312.2	3004.5
HPH 8	h_{8b}	50.3	352.8	3075.9
E) Main Steam				
Throttle Steam	h_{MS}	177.8	527.9	3356.8
Cold Reheat Steam	h_{CRH}	36.3	300.5	2975.3
Hot Reheat Steam	h_{HRH}	34.8	541.2	3545.1
Make-Up water	h_{MUW}	-	30.0	125.7

RESULTS AND DISCUSSIONS

The model obtains various parameters such as heaters extraction flow, condensate flow, and feedwater flow. These values are crucial to determine the gross turbine HR at various operating loads of interest.

Based on Figure 6, the gross turbine HR at present and during commissioning are plotted to compare the deviating in the turbine HR. It is evident that the present turbine HR is significantly higher than the designed turbine HR at commissioning, which is the main contributory reason for the poor HR and losses at the plant. The main contributory causes of higher turbine HR are the higher main steam and feedwater flows at the same load compared with commissioning data. Furthermore, the extraction steam flows for the HPH and LPH are also higher, which signifies that the performance of the feedwater heater is not satisfactory as more energy input in terms of extraction steam is required to achieve the target feedwater temperature. Although Devandiran et al. (2016) have clearly mentioned a few possible reasons for poor FWH performance, there is no evidence of determining the extraction steam flow determined in this study. At a load of 729 MWg, which is the normal operating load of the plant, the gross turbine HR is 8,888 kJ/kWh, which is much higher than the designed HR of 7,753 kJ/kWh. The deviation of -1,135 kJ/kWh leads to daily losses of RM240,447.

A summary of the economic analysis is shown in Table 3, which illustrates the daily losses at the normal operating load, 729 MWg, as well as the two cyclic operating loads, 503 and 431 MWg, respectively. The HR deviation is the difference between expected gross turbine HR based on commissioning data with the present gross turbine HR. This deviation may be converted to daily monetary losses by assuming the capacity factor of 0.85, which is the nominal capacity factor of the plant as required by the regulatory body. It is evident that the plant is operating at negative HR or, in other words, negative HR deviation is when the actual plant HR is higher than the expected plant HR. The negative HR adversely affects the monetary performance of the plant leading to daily monetary losses, as seen in Table 3. In essence, the economic analysis of the plant is crucial for plant

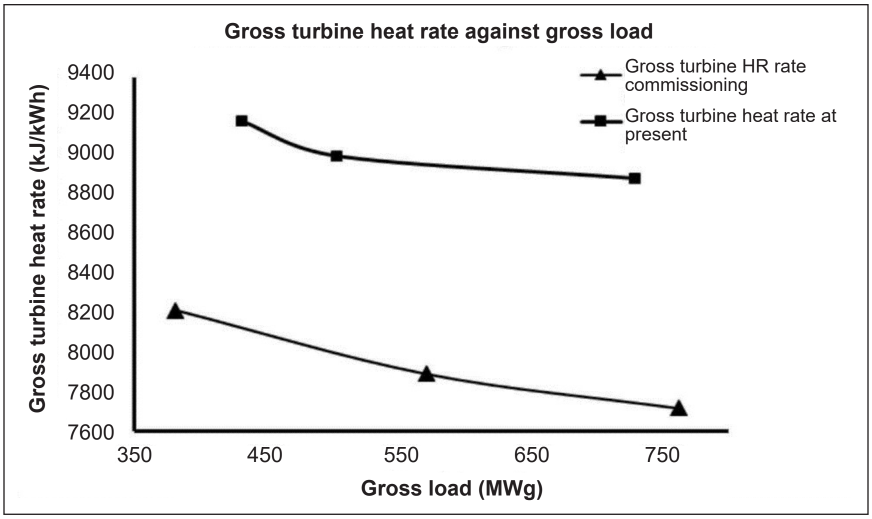

Figure 6. Gross turbine HR again gross load

operators to determine the actual operating performance of the plant at particular loads to identify areas of loss. It is important to note that the largest daily losses occur at a baseload of 729MWg. Therefore, it is crucial to ensure the plant operators pay more attention to the performance of the plant when operating at baseload as the losses are more significant at baseload than other cyclic loads. Furthermore, several other studies have not attempted to evaluate the economic performance of the plants, such as Wang et al. (2019) and Umrao et al. (2017); thus, one of the significant benefits of this model is the ability to carry out the economic analysis.

Table 3
Summary of economic analysis at various operating loads

Item	Unit	Values		
Gross load	MWg	729	503	431
Expected Gross Turbine HR basedon commissioning data	kJ/kWh	7,753	8,032	8,121
Gross Turbine HR at Present	kJ/kWh	8,888	9,002	9,179
HR Deviation (expected-presentHR)	kJ/kWh	-1135	-970	-1058
Daily Losses with capacity factor0.85	RM/day	240,447	137,096	125,767
	USD/day*	60,112	34,274	31,442

*The exchange rate used is 1 USD = RM 4

Based on Figure 7, it is evident that the plant net heat rate decreases as the boiler efficiency increases for a constant turbine net heat rate; thus, one of the possible methods to improve plant heat rate is through improving the boiler efficiency and this particular trend has also been observed by Gupta and Kumar (2015a & 2015b) The net plant HR profile is based on Equation 18. The boiler efficiency is varied to illustrate the effect of boiler efficiency on net plant HR.

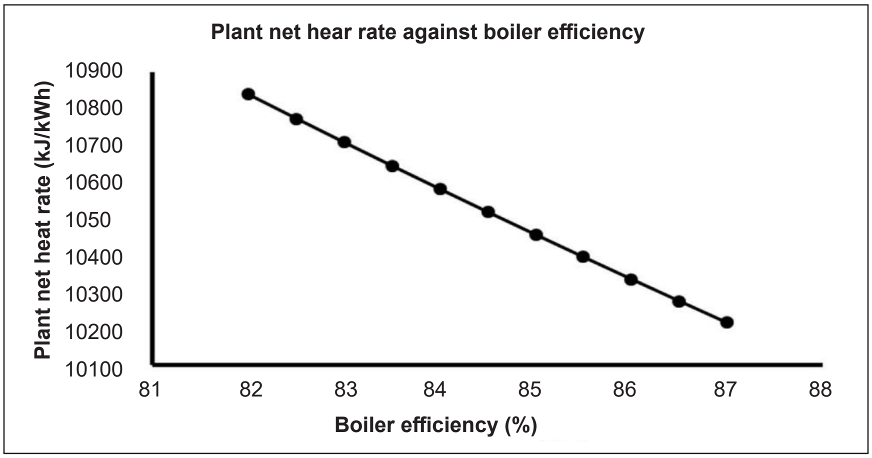

Figure 7. Plant net heat rate against boiler efficiency

The heat balance summary is illustrated in Table 4. In essence, the mass flow rates of all the HPH steam flows and drain flows are obtained after utilizing the energy and mass balance as previously explained in the methodology section (Equations 1–15). Furthermore, the main steam flow, feedwater flow, hot reheat flow, and cold reheat flow have also been evaluated and will be used to determine the TCHR. At the same time, this is advantageous as previously, and these crucial flows are not available in the DCS, making it difficult for plant operators to appreciate the actual operating parameters of the plant. It is important to note a significant difference between the DCS and calculated values of the main steam and feedwater flow. For instance, the calculated feedwater flow is much higher than the DCS feedwater flow, which suggests potential water losses in the cycle, which could be due to passing valves, such as drain valves and leakages, and this may prompt the operations personnel to tighten drain valves and related valves by carrying out the valve line up procedure followed by continuous monitoring on the model to ensure that both the calculated and DCS feedwater flow value are as close as possible to prevent water losses. It is a significant benefit of this particular study as the model can provide an indicator of the main reasons for losses in the plant that have not been investigated by other studies such as those by Tian et al. (2017) and Sundaravinayaka and Jayapaul (2017).

Table 4
Heat balance calculations summary including nomenclature

Item	Nomenclature	Flowrate (kg/h)		
Gross Load	MWg	729	503	431
Feedwater flow (DCS)	$\dot{m}_{FW,DCS}$	2,039,944	1,246,630	1,098,308
FeedWater flow (calculated)	$\dot{m}_{FW}$	2,323,924	1,419,216	1,243,143
HPH6 drain flow	$\dot{m}_{6d}$	361,155	194,836	164,359
HPH7 drain flow	$\dot{m}_{7d}$	259,919	132,493	113,051
HPH8 Steam Extraction	$\dot{m}_{8b}$	97,623	46,624	38,517
HPH7 Steam Extraction	$\dot{m}_{7b}$	162,296	85,869	74,535
HPH6 Steam Extraction	$\dot{m}_{6b}$	101,237	62,343	51,308
HPH5 Steam Extraction	$\dot{m}_{5b}$	127,917	72,606	57,859
Condensate Flow	$\dot{m}_{cond}$	1,904,487	1,311,096	1,140,652
Make-Up Flow	$\dot{m}_{MUW}$	44,759	26,272	31,593
Main Steam Flow (calculated)	$\dot{m}_{MS}$	2,399,521	1,581,256	1,365,285
Main Steam Flow (DCS)	$\dot{m}_{MS,DCS}$	2,070,626	1,403,243	1,217,265
Cold Reheat Steam flow	$\dot{m}_{CRH}$	2,134,102	1,443,263	1,246,734
Hot Reheat Steam flow	$\dot{m}_{HRH}$	2,134,153	1,443,776	1,246,821

The net turbine HR at various operating loads is shown in Table 5. As previously discussed, the measured net heat rate is obtained by utilizing Equation 17. The key input required to evaluate the turbine cycle HR is obtained from Table 4. It is important to note that the gross turbine HR is obtained by using "Gross Load" instead of "Net Load" in Equation 17.

Table 5
Summary of measured turbine heat rate at various operating loads

Item		**Unit**	**Value**		
Gross Load	$LOAD_{GROSS}$	MWg	729	503	431
Net Load	$LOAD_{NET}$	MWn	675	460	391
Measured Gross Turbine Heat Rate	HR_{GROSS}	kJ/kWh	8,888	9,002	9,179
Measured Net Turbine Heat Rate	HR_{NET}	kJ/kWh	9,557	9,705	10,016

CONCLUSIONS

A model to determine CFPP performance through TCHR has been developed. The basis of the model emphasizes evaluating the TCHR, which is a crucial aspect of CFPP performance, yet not much importance is shown in previous studies. Determination of the TCHR involves actual plant data, which improves the accuracy of the model, which is also validated using commissioning data that is readily available for this particular plant. The economic analysis of the plant shows that there is a negative HR deviation which is causing monetary losses as the present turbine HR is higher than the baseline commissioning turbine HR. The model is also able to quantify the monetary losses at cyclic loads, which is important since the new operating regime of the plant is cyclic loads. The HR deviation figures are vital to prioritize important plant maintenance activities to improve financial performance. Furthermore, the extraction steam flows of the LPH and HPH may also be determined using energy and mass balance equations which are not available on the DCS; thus, the operations personnel may use the figures to compare present values with designed values to determine the performance of feedwater heaters and leakages due to passing valves.

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