THERMO-ECONOMIC TURBINE CYCLE HEAT RATE PERFORMANCE ANALYSIS OF COAL FIRED POWER PLANT

By

MANMIT SINGH A/L JASBEER SINGH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

November 2022

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

THERMO-ECONOMIC TURBINE CYCLE HEAT RATE PERFORMANCE ANALYSIS OF COAL FIRED POWER PLANT

By

MANMIT SINGH A/L JASBEER SINGH

November 2022

Chair : Associate Professor Ir. Nawal Aswan Bin Abdul Jalil, PhD
Faculty : Engineering

Coal Fired Power Plants (CFPP) are the backbone of the power generation sector in Malaysia, providing approximately 40% of the national energy demand. The efficient and optimum operations of the plants are vital to minimise the cost of producing energy per unit to ensure the plant remains profitable and sustainable to operate. Subcritical CFPP generally have an efficiency of 33-37% during the commissioning performance test. However, as the plant ages, the efficiency and Heat Rate (HR) deteriorate over time due to ageing and operational deviations from design values causing financial losses and since majority of CFPPs are base load plants producing maximum power output, the potential performance improvement is more significant. Since majority of the subcritical CFPP units only have 10 years remaining on Power Purchase Agreement (PPA), it is not viable to consider major retrofitting due to poor return on investment (ROI) thus this study focuses only on economic analysis of the CFPP based on operational aspects. The main objective of this study is to investigate the Turbine Cycle Heat Rate (TCHR) by developing a numerical mathematical model which enables the evaluation of the TCHR which forms the basis for conducting economic analysis of CFPP performance. The model is developed by utilizing energy and mass balance relationships of the turbine cycle which are validated against heat balance diagram of a $700MW_n$ CFPP. The usage of actual plant data improves the accuracy and confidence level of the results. In order to obtain the HR of a CFPP, the TCHR has to be evaluated first by conducting 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 model is able to determine the extraction steam flows of the LPH, HPH and deaerator and subsequently the feedwater flow as these flows are not available on the Distributed Control System (DCS) but are required to evaluate the TCHR. The plant operational data such as pressure and temperature of extraction steam are readily available in the Plant Information (PI) system from which the data is extracted. In essence, the model enables comparison of plant HR

at various operating loads against available commissioning data thus the economic analysis is conducted and it is determined that at the operating baseload of 729 MW_g, there is a HR deviation of -1,135 kJ/kWh which inevitably causes daily losses of RM240,447 or USD 60,112. The developed model is also able to evaluate the daily losses at lower operating loads as the plant is now in transition to cyclic loads operation. At lower loads of 431 MW_g, the daily losses amount to RM 125,767 or USD 31,442. The second objective of this study is to investigate parameters which significantly affect the CFPP performance using HR deviations. The baseline or target values are obtained from the plant commissioning manuals and the Performance Guarantee Test (PGT). It is found that at the operating baseload, the most significant negative HR deviation is for the Rotary Air Heater (RAH) gas exit temperature with a negative HR deviation of -137.9 kJ/kWh leading to an annual loss of RM8.8 million at ACP of RM12/GJ while the superheater and reheater spray flows are contributing least to the HR deviation. The HR deviations analysis highlights the impact of parameters affecting the performance and the ranking of key parameters which affect the HR of the CFPP the most significantly which enables plant operations and maintenance teams to focus on such parameters to mitigate financial losses. The third objective of this study, which is conducting economic analysis of the of the CFPP with regard to TCHR analysis and HR deviation analysis based on the Applicable Coal Price (ACP). The influence of the ACP price towards daily losses or gains has been thoroughly analysed for key performance parameters and it is evident that as the ACP increases, the daily losses increase as well for parameters with negative HR deviation thus it is crucial for plant personnel to be more vigilant on monitoring and mitigating negative HR deviations to minimise monetary losses.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ANALISIS PRESTASI KADAR KITARAN HABA TURBIN TERMO-EKONOMI LOJI JANAKUASA PEMBAKARAN ARANG BATU

Oleh

MANMIT SINGH A/L JASBEER SINGH

November 2022

Pengerusi : Profesor Madya Ir. Nawal Aswan Bin Abdul Jalil, PhD
Fakulti : Kejuruteraan

Loji Kuasa Arang Batu (CFPP) adalah tulang belakang sektor penjanaan kuasa di Malaysia, menyediakan kira-kira 40% daripada permintaan tenaga negara. Operasi loji yang cekap dan optimum adalah penting untuk meminimumkan kos pengeluaran tenaga seunit bagi memastikan loji kekal menguntungkan dan mampan untuk beroperasi. CFPP subkritikal umumnya mempunyai kecekapan 33-37% semasa ujian prestasi pentauliahan. Walau bagaimanapun, apabila loji semakin tua, kecekapan dan kadar haba (HR) merosot dari semasa ke semasa disebabkan oleh penuaan dan sisihan operasi daripada nilai reka bentuk yang menyebabkan kerugian kewangan dan memandangkan majoriti CFPP adalah loji beban asas yang menghasilkan output kuasa maksimum, potensi peningkatan prestasi adalah lebih ketara. Memandangkan majoriti unit CFPP subkritikal hanya mempunyai baki 10 tahun dalam Perjanjian Pembelian Kuasa (PPA), adalah tidak wajar untuk mempertimbangkan pengubahsuaian besar kerana pulangan pelaburan (ROI) yang lemah, justeru kajian ini hanya tertumpu pada analisis ekonomi CFPP berdasarkan aspek operasi. Objektif utama kajian ini adalah untuk menyiasat HR Kitaran Turbin (TCHR) dengan membangunkan model matematik mudah yang membolehkan penilaian TCHR yang menjadi asas menjalankan analisis ekonomi prestasi CFPP. Model ini dibangunkan menggunakan hubungan tenaga dan imbangan jisim kitaran turbin yang disahkan terhadap rajah imbangan haba daripada CFPP 700 MW_n. Penggunaan data tumbuhan sebenar meningkatkan ketepatan dan tahap keyakinan keputusan. Untuk mendapatkan HR CFPP, TCHR perlu dinilai terlebih dahulu dengan menjalankan tenaga dan keseimbangan jisim komponen utama dalam kitaran turbin seperti Pemanas Tekanan Rendah (LPH), Pemanas Tekanan Tinggi (HPH) dan deaerator. Model ini dapat menentukan aliran wap pengekstrakan LPH, HPH dan deaerator dan seterusnya aliran air suapan kerana aliran ini tidak tersedia pada Sistem Kawalan Teragih (DCS) tetapi diperlukan untuk menilai TCHR. Data operasi loji seperti tekanan dan suhu stim pengekstrakan sedia tersedia dalam sistem Maklumat Loji (PI) dari mana data diekstrak. Pada asasnya, model ini membolehkan perbandingan HR loji pada

pelbagai tahap beban dengan data pentauliahan loji yang tersedia, oleh itu analisis ekonomi dijalankan dan ditentukan bahawa pada beban asas operasi 729 MW_g, terdapat sisihan HR berjumlah -1,135 kJ/kWj yang pasti menyebabkan kerugian RM240,447 atau USD 60,112 setiap hari. Model yang dihasilkan juga mampu menilai kerugian harian pada beban operasi yang lebih rendah kerana loji kini beralih kepada operasi beban kitaran. Pada beban lebih rendah 431 MW_g, kerugian harian berjumlah RM 125,767 atau USD 31,442. Objektif kedua kajian ini adalah untuk menyiasat parameter yang secara signifikan mempengaruhi prestasi CFPP menggunakan sisihan HR. Nilai asas atau sasaran diperoleh daripada manual pentauliahan loji dan Ujian Jaminan Prestasi (PGT). Didapati bahawa pada beban asas operasi, sisihan HR negatif yang paling ketara adalah untuk suhu keluar gas Rotary Air Heater (RAH) dengan sisihan HR negatif -137.9 kJ/kWj membawa kepada kerugian tahunan sebanyak RM8.8 juta pada ACP sebanyak RM12/GJ manakala aliran semburan pemanas super dan pemanas semula menyumbang paling sedikit kepada sisihan HR. Analisis sisihan HR menyerlahkan kesan parameter yang mempengaruhi prestasi dan penarafan parameter utama yang paling ketara memberi kesan kepada HR CFPP yang membolehkan operasi loji dan pasukan penyelenggaraan menumpukan pada parameter tersebut untuk mengurangkan kerugian kewangan. Objektif ketiga kajian ini, iaitu menjalankan analisis ekonomi CFPP berkenaan dengan analisis TCHR dan analisis sisihan HR berdasarkan Harga Arang Gunaan (ACP). Pengaruh harga ACP terhadap kerugian atau keuntungan harian telah dianalisis secara menyeluruh untuk parameter prestasi utama dan terbukti bahawa apabila ACP meningkat, kerugian harian meningkat juga untuk parameter dengan sisihan HR negatif oleh itu adalah penting bagi kakitangan loji untuk lebih berhati-hati dalam memantau dan mengurangkan penyelewengan HR negatif untuk meminimumkan kerugian kewangan.

ACKNOWLEDGEMENT

To my beloved grandmother, single mother and aunty for their invaluable sacrifices, encouragement and continuous support throughout my life. This would not have been possible without your love and blessings

&

To my awesome lecturers for guiding and supporting me when I needed it the most

&

To all my friends and colleagues at Tenaga Nasional for always warmly supporting and encouraging me

Praises to the almighty l Love *all, Serve All*

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Nawal Aswan bin Abdul Jalil, PhD
Associate Professor, Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Sharafiz bin Abdul Rahim, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Zamir Aimaduddin bin Zulkefli, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Hasril bin Hasini, PhD
Associate Professor, Ir.
Department of Mechanical Engineering
University Tenaga Nasional
(Member)

____

ZALILAH MOHD SHARIFF, PHD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 12 January 2023

Declaration by Graduate Student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and the copyright of the thesis are fully-owned by Universiti Putra Malaysia, as stipulated in the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from the supervisor and the office of the Deputy Vice-Chancellor (Research and innovation) before the thesis is published in any written, printed or electronic form (including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials) as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld in accordance with the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2015-2016) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: ________________________ Date: _____________

Name and Matric No.: Manmit Singh A/L Jasbeer Singh

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research and the writing of this thesis were done under our supervision;
- supervisory responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2015-2016) are adhered to.

Signature: ______________________________
Name of Chairman of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACP	Applicable Coal Price
BFP	Boiler Feed Pump
CAC	Contractual Available Capacity
CEP	Condensate Extraction Pump
CFPP	Coal Fired Power Plant
CO2	Carbon Dioxide
DCA	Drain Cooler Approach
DCS	Distributed Control System
FWH	Feedwater Heaters
HBD	Heat Balance Diagram
HPH	High Pressure Heater
HPT	High Pressure Turbine
HTS	High Temperature Superheater
HR	Heat Rate
IPT	Intermediate Pressure Turbine
LPH	Low Pressure Heater
LPT	Low Pressure Turbine
PGT	Performance Guarantee Test
PI	Plant Information
PPA	Power Purchase Agreement
RAH	Rotary Air Heater
ROI	Returns on Investment
ST	Steam Turbine
TCHR	Turbine Cycle Heat Rate

TMCR	Turbine Maximum Continuous Rating
TR	Temperature Rise
TTD	Terminal Temperature Difference

CHAPTER 1

INTRODUCTION

1.1 Background

Coal-Fired Power Plants (CFPP) are the main pillar of support for Malaysia's power generation sector, providing over 40% of the country's energy needs (Bujang et al., 2016). With the ever-growing demand of energy in a fast-developing economy, efficient and optimum operations of CFPP are critical to lowering the cost of producing energy and ensuring the plant remains profitable and sustainable for the nation's well-being (Zhang et al., 2018).

Subcritical CFPPs generally have an efficiency of 33-37% during the commissioning performance test. However, the efficiency of CFPPs deteriorate over time causing monetary losses due to poor heat rate. Furthermore, Majority CFPPs are base load plants producing maximum power output which further emphasizes the importance of the units operating at the maximum possible efficiency. The potential performance improvement for baseload CFPP is significant due to higher Net Energy Output (NEO) which translates into greater fuel cost savings.

With the increasing global prices of coal, it is vital to ensure the plant remains efficient to reduce coal consumption. Since majority of CFPP units only have around 10 years remaining on PPA, it is logical to only focus on operational parameters and not major retrofitting or redesign of the CFPP since the plant is operational and the opportunity for long shutdowns is not present due to stringent clauses in the Power Purchase Agreement (PPA) which has allocated limited shutdowns only for routine maintenance works. Furthermore, retrofitting works require capital investment and ageing plants will not be able to recover the cost. The CFPP also has obtained revised safety approvals from local authorities which further complicates the matter to consider retrofitting.

Actual operational data from a 700 MW CFPP is utilized in this study. The plant has been in operations since 2004. Therefore, relevant data from the commissioning stage are readily available to conduct investigation and analysis of the plant's performance deviation between the present and commissioning stages.

*Footnote
MW_n: Net Unit Load (MW)
MW_g: Gross Unit Load (MW)

1.2 Problem Statement

The CFPP's performance has been a topic of interest by several previous studies. However, the methodologies of the past research work had focused mainly on performance modelling of the CFPP using relationships of CFPP thermodynamics without focusing comprehensively on the Turbine Cycle Heat Rate which is more accurate methodology of evaluating CFPP performance (Opris et al., 2020; Almedilla et al., 2018; Gupta & Kumar, 2015a). In addition, a significant number of past research work has not incorporated economic analysis in their studies even though economic analysis is critical for plant operations and maintenance personnel to obtain the daily amount of profit or loss. Furthermore, majority of the units investigated are under $500MW_n$ (Neshumayev et al., 2018; Wijaya & Widodo, 2018).

Many subcritical CFPPs are approximately ten to fifteen years old with roughly 10 years or less remaining on the PPA. With the ageing of the plant, the deviations of key performance related parameters are expected due to ageing factor and other factors such as lack of knowledge among new plant operators as the senior operators retire. Therefore, it is of utmost importance that the deviations of the key performance parameters are continuously monitored and a relationship between deviation in parameters and HR is established to assist and guide plant personnel to make better and more well-informed decisions with regards to plant performance.

With less than 10 years remaining on the PPA, it is certainly not advisable to consider any major upgradation works on the plant which require retrofitting due to poor returns on investments. In an ageing plant, upgrading works are complex since most of the original design manuals may not reflect the actual plant setup due to frequent repair works being carried out over the course of the years. Furthermore, certain equipment at the plant may also be obsolete and the replacement process for newer modern equipment is complex and requires subsequent changes for similar functions which incurs even more capital cost. The most significant issue for ageing plants is that since upgradation works require a long time, there is insufficient downtime or outage time permitted in the PPA and any unplanned extended outage will lead to even more financial losses in terms of capacity payments of the plant. Last but not the least, design changes require local safety regulatory approvals which are both time consuming and complex as the original drawings and manufacturers drawings will require a long time to be reproduced for the regulatory approval process thus is it totally undesirable to even consider upgradation works.

A number of previous studies related to the CFPP boiler's operations have reviewed the boiler's parameters, unfortunately there is only minimal effort which can be done by the plant personnel since all of the recommendations require the plant to be on outage or shutdown to carry out the rectification works (Gupta & Kumar, 2015b; Pachaiyappan & Prakash, 2015). For example, most of the improvements of the Rotary Air Heater (RAH), which is a critical equipment of the boiler may only be achieved by offline methods (Sundaravinayaka & Jayapaul, 2017). In addition, while there has been previous investigation about improvising intelligent boiler maintenance interface to address boiler tripping, such studies are not focusing on the CFPP performance (Nistah et al., 2014). In short, it is not feasible to consider such methods of improving CFPP performance as shutdown of the unit will lead to monetary losses of not producing load (Braun, 2021).

Majority of the past studies related to CFPP did not utilize real life CFPP data and thus the outcome and proposed recommendations may not be directly applicable to an existing operational CFPP. In contrast, this study utilizes actual real-life operational plant data and commissioning plant data to improve the accuracy of the simulation model's outcomes and results. The plant commissioning data is obtained from the commissioning phase of the CFPP when the plant has been tested to ensure the plant satisfies the design performance requirements. Therefore, the present operational data may be compared against the plant's commissioning data to conduct through analysis and identify performance gaps.

In addition, the present investigation focuses on the Turbine Cycle Heat Rate (TCHR) which has not been investigated thoroughly in previous studies. The TCHR is defined as the efficiency of the steam turbine in converting main steam from the boiler superheater outlet to usable rotational energy of the turbine's shaft which is interconnected to the generation. Furthermore, while there have been several previous studies which focuses on thermodynamic analysis, there is minimal or no relationship developed between thermodynamic analysis and economic analysis and this study fills the research gap by using a TCHR model incorporating thermodynamic relationships with economic analysis which is crucial to determine the present performance of the plant with regards to operational gains or losses.

Plant operations personnel frequently face difficulty in determining the TCHR as the energy and mass balance of CFPP are not available in past literature or plant manuals. Furthermore, the determination of CFPP's performance is usually conducted by utilizing a simple input-output method in which the total power generated is divided by total fuel energy input to determine the CFPP efficiency however this method only provides a numerical value of the overall CFPP efficiency without in depth analysis of the TCHR. Therefore, the CFPP performance determination based on the 700 MW_n CFPP unit will greatly benefit the power generation industry as the outcome of this research work will provide assistance and guidance to the operations teams in appreciating and understanding key concepts related to CFPP plant performance. Furthermore, the developed numerical model is able to determine the CFPP performance at various operating loads which can further support the plant operations personnel in understanding the performance of the plant at part loads especially during the new regime of cyclic load operations due to changes in the energy industry outlook. The main goal of this investigation is to minimize financial losses caused by negative HR deviation.

In addition, previous studies have mainly focused on the CFPP performance as whole without paying any attention on the key operational parameters or indicators of the plant therefore the effect of HR deviations due to deviations of these crucial parameters has been overlooked. The lack of such important information also creates opportunity of plant personnel to overlook which key equipment of the plant is causing the most significant losses so that the plant personnel can address such issues with higher priority and proper planning with prior notice.

It is important to note that majority of past investigation related to CFPP performance have not conducted any economical or financial analysis of the CFPP although this information is crucial for plant personnel to evaluate the profit or loss of the CFPP based on the present operational condition. Furthermore, the impact of the coal price, namely the Applicable Coal Price (ACP) has not been considered in previous investigations related to CFPP performance.

One of the objectives of this paper is to investigate HR deviations of a CFPP based on the Applicable Coal Price (ACP) and the impact of ACP prices to the daily losses or gains to the plants are thoroughly analysed for key performance indicators. In the present global economic situation where prices of coal, or in other words, the price of ACP, the primary fuel of CFPP, have been soaring rocket high, it is of utmost importance to consider the effect of coal prices and its effect on plant performance. The main benefit of conducting HR deviation analysis is to analyse key areas of CFPP performance where the gaps or negative deviations of plant HR can be addressed by the operations personnel as the analysis is able to highlight key areas of concern which are significantly affecting plant performance.

The magnitude of HR deviation changes with the coal prices, known as Applicable Coal Price (ACP) which is quoted in RM/GJ and changes on a quarterly basis. In Malaysia, the ACP is regulated by the Energy Commission (EC) and the power plant management are informed in advance of the upcoming new ACP (Energy Commission of Malaysia, 2022). The ACP is affected by changes in coal pricing due to market demand and supply factors. In other countries, the ACP is affected by changes in coal pricing due to market demand and supply factors. However, it should be noted that the plant management has no authority to influence the ACP other than buying coal when the coal price is low and to delay coal shipments when the coal pricing is higher although the storage yard and ship handling capabilities are the main constraints, hindering such a move. Thus, during the higher ACP periods, it is even more crucial for plant operators to focus more on managing the plant at the optimum efficiency by frequent monitoring of the HR deviation to minimize any potential losses caused by operational parameters deviations.

There are three ACP prices considered in the HR deviations analysis, which are RM12, 18 and 24 per GJ and these three ACP prices reflects the transition of ACP from RM12 from the past 5 years to the higher ACP of RM24 due to increasing global coal prices (Energy Commission of Malaysia, 2022). At present, the coal price, or ACP, is Ringgit Malaysia (RM) 24/GJ which is equivalent to RM 482 per ton for coal with gross calorific value of 4800 kcal/kg. Therefore, it is vital for plant personnel to understand the more significant impact to gains or losses based on ACP so that more attention may be given to key parameters that might adversely affect the plant HR causing monetary losses.

The problem statement is summarized as per the following:

- CFPP units are mostly 20 years old with less than 10 years remaining on Power Purchase Agreement (PPA) thus it is not feasible to consider major retrofitting due to poor ROI.

- As the plant ages, the efficiency and heat rate deteriorate over time due to ageing and operational deviations from design values
.
- Previous investigations have only evaluated CFPP performance using simple input-output relationship without considering the comprehensive method of determining the Turbine Cycle Heat Rate (TCHR).

- Lack of economic analysis which is critical for plant personnel to obtain the daily amount of profit or loss.

- Previous investigations have not investigated effect of key operational parameters towards Heat Rate (HR).
.
- Impact of the coal price, the Applicable Coal Price (ACP), has not been considered in previous investigations related to CFPP performance.

1.3 Research Objectives

The main goal of this research is to develop a numerical model of the Turbine Cycle Heat Rate (TCHR) of a CFPP which will serve as a basis for conducting study on the performance of CFPP. The three key objectives are summarised as follows:

1. To investigate the Turbine Cycle Heat Rate (TCHR) based on the numerical simulation model.

2. To investigate the effect of key performance parameters deviations on the HR deviation of the CFPP and to determine which parameters affect CFPP performance the most.

3. To conduct economic analysis of the CFPP with regards to TCHR analysis and HR deviations analysis which include the effect of Applicable Coal Price (ACP).

1.4 Scope and limitations of the study

This study focuses on the development of a mathematical model to evaluate the TCHR of the CFPP. The model is developed from the first principle by utilising energy and mass balance relationships of the Turbine Cycle and the numerical model is validated against the Heat Balance Diagram (HBD) with an error of less than 1% to ensure the outcome and results obtained are valid. The model also includes economic analysis of the CFPP unit which is beneficial for the plant personnel to evaluate whether the plant is making a profit or loss. Furthermore, real life plant data from a 700 MW_n CFPP is utilised to further increase confidence level of the results of the study.

The impact of HR Deviations on the CFPP performance with regards to the ACP are analysed to determine the monetary daily gains or losses for a number of key performance parameters. Several rules of thumbs, as well as crucial information from plant commissioning manuals, are used in the process of monitoring HR deviation. The design parameters from the HBD serve as the guiding principles of having a robust HR deviation monitoring regime for any CFPP. In addition, the correct curves for several operational parameters are also provided in the Performance Guarantee Test which may be included in the HR deviation analysis. This enables comparative analysis to be conducted between the present key operating parameters against design data or from the commissioning data and therefore it is possible to identify gaps in the performance of the CFPP. In short, it is possible to study the effect of various parameters towards HR of the CFPP and to ultimately determine which parameters have the most significant effect on the CFPP.

The plant data utilised in this study is obtained from a 700 MW_n subcritical CFPP with a single reheat stage of the boiler. The plant's design main steam temperature is 540 ^oC and main steam pressure is 175 bar, the hot reheat steam temperature is 540 ^oC and hot reheat steam pressure is 35 bar. The condensate preheater is achieved by two duplex Low-Pressure Heaters (LPH) in the neck of the condenser and two LPH in series arrangement. The feedwater preheater is achieved by three High Pressure Heaters (HPH) in series arrangement. The cooling water system for the condenser is by means of seawater and the design cooling water temperature rise is 8 ^oC

1.5 Research Outcome

The CFPP performance study will be beneficial for the power generation industry as the outcomes of this study will assist and support plant personnel to understand and appreciate the concepts in evaluating the performance of the CFPP by utilising a numerical model.

Furthermore, the outcome and related recommendations will not impose any financial burden to implement as the outcomes will be purely operational in nature with no focus on major retrofitting which requires huge capital costs. The main purpose of this study is to ensure the CFPP remains profitable and sustainable in the ever-challenging power generation industry. The effects of changing ACP or coal prices towards the plant HR will also be thoroughly analysed.

1.6 Thesis outline

This thesis is structured into five main chapters in accordance with the thesis format of Universiti Putra Malaysia. The first chapter of the thesis, which is the introduction chapter has been further divided into subsections which focuses on key aspects of this research work. The subtopics provides the research backgroud and objectives of this study as well as the scopes and limitation of the study.

The second chapter, the literature review, focuses on presenting the findings and shortcomings of the previous research work done in the area of the CFPP performance. This chapter is also divided into a number of subdivisions to categorise the particular areas from which the literature was obtained. In the final subsection, the summary of the gaps highlighted from the previous work has been discussed including the Table which highlights the gaps the current study will address.

The third chapter, methodology, covers the key concepts in developing the numerical mathematical model including identification of key parameters, data collection and model validation which is crucial to ensure the outcomes of the study are accurate and reliable. The process of evaluation HR deviations are also discussed with two subsections namely for the FWH and condenser.

The fourth chapter, results and discussions, focuses on discussing the results obtained from the model. The TCHR is obtained at a number of cylic loads along side with comparison made against commissioning data in order to obtain the HR deviation. The economic analysis is also presented in one of the subsections.

The results of the HR deviation are also thoroughly discussed in the last subsection with the main focus on FWH and condenser.

The fifth chapter, the conclusion and recommendations for future works, contains the conclusion remarks of this study and a number of recommendations for future works have been presented.

REFERENCES

Almedilla, J.R., Pabilona, L.L. & Villanueva, E.P. (2018). Performance Evaluation and Off Design Analysis of the HP and LP Feed Water Heaters on a 3 × 135 MW Coal Fired Power Plant, Journal of Applied Mechanical Engineering, 7(3), 1-14. doi: 10.4172/2168-9873.1000308

Behbahaninia, A., Ramezani, S. & Lotfi Hejrandoost, M. (2017). A loss method for exergy auditing of steam boilers. Energy, vol. 140, 253-260.

Bisercic, A.Z. & Bugaric, U.S (2021). Reliability of Baseload Electricity Generation from Fossil and Renewable Energy Sources. Energy and Power Engineering, 13, 190-206. doi: 10.4236/epe.2021.135013.

Buckshumiyanm, A. & Sabarish, R. (2017), Performance Analysis of regenerative feedwater heaters in 210 MW thermal power plant, International Journal of Mechanical Engineering and Technology (IJMET), 8(8), 1490-1495.

Bujang, A.S., Bern, C.J., & Brumm, T.J. (2016). Summary of energy demand and renewable energy policies in Malaysia. Renewable and Sustainable Energy Reviews. 53, 1459-1467. Doi: 10.1016/j.rser.2015.09.047.

Chaojun, W., He, Boshu, H., Linbo, Y., Xiaohui, P., Shinan, C. (2014). Thermodynamic analysis of a low-pressure economizer based waste heat recovery system for a coal-fired power plant. Energy, vol. 65(C), 80-90.

Chen., H., Qi., Z., Dai., L., Li., B., Xu., G., Yang., Y. (2020). Performance evaluation of a new conceptual combustion air preheating system in a 1000 MW coal-fueled power plant, Energy, 116739

Devandiran, E., Shaisundaram, V.S., Ganesh, P.B., Vivek, S. (2016), Influence of feedwater heaters on the performance of coal fired power plants. International Journal of Latest Technology in Engineering, Management & Applied Science, 5(3), 115-119.

Elhelwa, M., Dahmaa, K.S.A. & Attiaa, A.E.H. (2019). Utilizing exergy analysis in studying the performance of steam power plant at two different operation mode. Applied Thermal Engineering 150, 285-293

Eke, M.N, Onyejekw, D.C, Iloeje, O.C., Ezekwe, C.I. & Akpan, P.U. (2018), Energy and Exergy Evaluation of A 220mw Thermal Power Plant, Nigerian Journal of Technology (NIJOTECH), Vol. 37, No. 1, pp. 115 – 123

Energy Commission of Malaysia (2020). Peninsular Malaysia Electric Supply Outlook 2020.Retrieved from https://www.ketsa.gov.my/msmy/pustakamedia/Penerbitan/Report%20on%20Peninsular%20Malaysia%20Generation%20Development%20Plan%202020%20(2021-2039).pdf

Energy Commission of Malaysia (2022). Trend of fuel prices. Retrieved from https://www.st.gov.my/contents/2022/Fuel%20Prices/8-%20ACP%20as%20of%20Mac%202022.pdf

Fuzi, N.F.A., Alnaimi, F.B.I., & Nasif, M.S. (2020), Intelligent Risk-Based Maintenance Approach for Steam Boilers: Real Case. Pertanika Journal of Science and Technology, 28 (S1), pp. 69 – 81

Gang, X., Luyao, Z., Shifei Z., Feifei, L., Cheng, X., Yongping, Y. (2015). Optimum superheat utilization of extraction steam in double reheat ultra-supercritical power plants. Applied Energy, 863-872. doi:101016/japenergy201501027

Gupta, M. & Kumar, R. (2015a), Optimization Of A Turbine Used In Coal Fired Thermal Power Plants Based On Inlet Steam Temperature Using Thermoeconomics, International Journal of Recent advances in Mechanical Engineering (IJMECH), 4(4), 59-66. doi: 10.14810/ijmech.2015.4405

Gupta, M. & Kumar, R. (2015b), Thermoeconomic Optimization Of A Boiler Used In A Coal Fired Thermal Power Plant Based On Hot Air Temperature, International Journal of Recent advances in Mechanical Engineering (IJMECH), 4(2), 39-44. doi: 10.14810/ijmech.2015.4205

Hagia, H.,Nemer, M., Moulleca, Y.L., Bouallou, C. (2017). Techno-Economic Optimization of First Generation Oxy-Fired Pulverized-Coal Power Plant. Energy Procedia 114, 490 – 500

Han, Y., Xu, G., Zheng, Q., Xu, C., Hu, Y., Yang, Y., Lei, J. (2017). New heat integration system with bypass flue based on the rational utilization of low-grade extraction steam in a coal-fired power plant. Applied Thermal Engineering, 113 (C), 460-471

Heng, C., Yunyun W., Zhen, Qiao, C. , Gang, X., Yongping, Y., Wenyi, L.(2019). Improved combustion air preheating design using multiple heat sources incorporating bypass flue in large-scale coal-fired power unit. Energy, vol. 169(C), 527-541

Han, X., Chen, N., Yan, J., Liu, J., Liu, M., Karellas, S. (2019). Thermodynamic analysis and life cycle assessment of supercritical pulverized coal-fired power plant integrated with No.0 feedwater preheater under partial loads, Journal of Cleaner Production 233, 1106-1122

Ibrahim H.G., Okasha, A.Y. &Ahmed G. Elkhalidy, A.G., (2010), Improve Performance and Efficiency of the Steam Power Plant, First Scientific Conference on Petroleum Resources and Manufacturing, Libya

Jianlan, L., Zhaoyin, Z., Jizhou, W., Shuhong, H., (2016). On-line fouling monitoring model of condenser in coal-fired power plants. Applied Thermal Engineering. 104. 10.1016/j.applthermaleng.2016.04.131.

Li, K. & Vani, G. (2014). DCS Technology-Based Design of Electrical Control System for Thermal Power Plant. The Open Electrical & Electronic Engineering Journal, pp 700-704

Li, Y., Zhou, L., Xu, G., Fang, Y., Zhao, S., Yang, Y. (2014), Thermodynamic analysis and optimization of a double reheat system in an ultra-supercritical power plant, Energy, 74, 202-214

Liu, Y., Li, Q., Duan, X., Zhang, Y., Yang, Z., Che, D. (2018). Thermodynamic analysis of a modified system for a 1000 MW single reheat ultra-supercritical thermal power plant, Energy, 145, 25-37

Majoumerda., M.M.,, Raasc,.H., Janad.,K., Ded, S., Assadib, M. (2017), Coal quality effects on the performance of an IGCC power plant with CO2 capture in India, Energy Procedia, 6478 – 6489

Malaysia Standards (2017). MS ISO 17025:2017. General requirements for the competence of testing and calibration (Second revision). Retrieved from https://mysol.jsm.gov.my/previewfile/eyJpdiI6IjZHTnFScGI4aEF5MENLVDRrZE1vSWc9PSIsInZhbHVlIjoiTm1WdjB2WEZ1MzFLSEsrRkZVTWNLUT09IiwibWFjIjoiYzU1NTcxZGNhZWEyYWJmM2ZjYTc0NWVmZTM5ZTQ0MzI1NGE2YjdjNjViY2YwY2M4OTRjMzc3NDIwYWUwM2JiOCJ9

Mathews, E.H.,van Laar, J.H., Hamer, W., Kleingeld, M., (2020) A simulation-based prediction model for coal-fired power plant condenser maintenance, Applied Thermal Engineering, Volume 174

Mohammed, M.K., Al Doori, W. H. ., Jassim, A.H., Ibrahim, T. K. & Al-Sammarraie, A. T. (2020). 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(2), pp. 211–222.

Neshumayev, D., Rummel, L., Konist, A., Ots, A. & Parve, T. (2018), Power plant fuel consumption rate during load cycling, Applied Energy, 224(C), 124–135. doi: 10.1016/j.apenergy.2018.04.063

Nistah, N. N. M., Motalebi, F. , Samyudia, Y. & Alnaimi, F. B. I. (2014), Intelligent Monitoring Interfaces for Coal Fired Power Plant Boiler Trips: A Review, Pertanika Journal of Science and Technology, 22 (2), pp. 593 - 601

Opriş, I., Cenuşă, V.E., Norişor, M., Darie, G., Alexe, F.N. & Costinaş, S. (2020). Parametric optimization of the thermodynamic cycle design for supercritical steam power plants. Energy Conversion and Management, 208. doi: https://doi.org/10.1016/j.enconman.2020.112587

Oyedepo, S.O., Kilanko, O., Waheed, M.A., Fayomi, O.S.I., Ohunakin, O.S., Babalola, P.O, Ongbali, S.O., Nwaokocha, C.N, Mabinuori, B., O.O.

Shopeju, O.O., (2020), Dataset on thermodynamics performance analysis and optimization of a reheat – regenerative steam turbine power plant with feed water heaters, Data in Brief, 32

Oyedepo S.O, Fakeye, B.A, Mabinuori.,B., Babalola., P.O, Leramo, R.O, Kilanko, O., Dirisu, J.O, Udo, M.,, Efemwenkiekie, U.K, Oyebanji, J.A, (2020), Thermodynamics analysis and performance optimization of a reheat –Regenerative steam turbine power plant with feed water heaters, Fuel, 280

Pachaiyappan, J. & Prakash, D. (2015), Improving the Boiler Efficiency By Optimizing The Combustion Air, Applied Mechanics and Materials, 787, 238-242. doi: https://doi.org/10.4028/www.scientific.net/AMM.787.238

Pengcheng, X., Yanping, Z., Yuanjing, W., Jizhou, W. (2019). Analysis of an improved economizer system for active control of the coal-fired boiler flue gas temperature, Energy, vol. 170(C), 185-198

Ravinder, K., Jilte, R., Ahmadi, M.H., Kaushal, R., (2019), A simulation model for thermal performance prediction of a coal-fired power plant, International Journal of Low-Carbon Technologies, Vol 14, 122–134

Ravindra, P., Raju, V.R. & Kumar, N.R., (2016), Simulation and parametric Optimisation of thermal power plant cycles, Perspectives in Science, Vol.8, pp 304-306

Ravinder, K., Sharma, A.K. & Tewari, P.C., (2014), Thermal Performance and Economic Analysis of 210 MWe Coal-Fired Power Plant, Journal of Thermodynamics

Reza, G.A. & Toghraie, D. (2016). Energy and exergy analysis of Montazeri steam power plant in Iran, Renew. Sustain. Energy Rev. 56, 454–463

Sabzpooshani, M., Azadehfar, E., and Sardarian, S., (2019), Exergy Evaluation and Optimization of a New Steam Power Plant Configuration in order to Use the Boiler Blowdown Water, Journal of Energy Management and Technology (JEMT), Vol.3, Issue 1, pp 30-39

Saptoro,A., Huo, K.C. (2013). Influences of Indonesian coals on the performance of a coal-fired power plant with an integrated post combustion CO2 removal system: A comparative simulation study. Energy Conversion and Management, 235–243

Sebastian Braun (2021). Improving Flexibility of Fossil Fired Power Plants. Reference Module in Earth Systems and Environmental Sciences, Elsevier, doi https://doi.org/10.1016/B978-0-12-819723-3.00085-8.

Srinivas, G.T., Kumar, D.R., Mohan, P.V.V.M & Rao, B.N (2017), Efficiency of a Coal Fired Boiler in a Typical Thermal Power Plant, American Journal of

Mechanical and Industrial Engineering, 2(1), 32-36. doi: 10.11648/j.ajmie.20170201.15

Suresh, M.V.J.J, Reddy, K.S. & Kolar, A.K., (2011), Thermodynamic analysis of a coal-fired power plant repowered with pressurized pulverized coal combustion, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Vol. 226, pp. 5-16

Sundaravinayaka, U. & Jayapaul T. (2017), Optimization of Boiler Operation In Thermal Power Station, International Journal of Latest Engineering Research and Applications (IJLERA) , 2(3), 64-68.

Tian, Z., Xu, L., Yuan, J., Zhang, X. &Wang, J., (2017), Online performance monitoring platform based on the whole process models of subcritical coal-fired power plants, Applied Thermal Engineering, 124, 1368–1381. Doi: https://doi.org/10.1016/j.applthermaleng.2017.06.112

Umrao, O.P., Kumar, A. & Saini, V.K. (2017), Performance of Coal Based Thermal Power Plant at Full Load and Part Loads. Global Journal of Technology and Optimisation, 8(1)

Wang, Y., Cao, L., Hu, P., Li, B., Li, Y. (2019), Model establishment and performance evaluation of a modified regenerative system for a 660 MW supercritical unit running at the IPT setting mode. Energy, 179, 890-915. Doi: https://doi.org/10.1016/j.energy.2019.05.026

Wijaya, A.A. & Widodo, B.U.K (2018), The Effect of Feedwater Heaters Operation Schemes to a 200 MW Steam Power Plant Heat Rate Using Cycle-Tempo Software, IPTEK Journal of Engineering, 4(3), 33-37. Doi: 10.12962/joe.v4i3.4995

Zhang, Y., Wang, J., Yang, S., Gao, W. (2018). An all-condition simulation model of the steam turbine system for a 600 MW generation unit. Journal of Energy Institute, 91(2), 279–88. doi: https://doi.org/10.1016/j.joei.2016.11.007

Zhao, Z., Su, S.,Si, N., Hu, S., Wang, Y., Xu, J., Jiang, L., Chen, G., Xiang, J. (2017). Exergy analysis of the turbine system in a 1000 MW double reheat ultra-supercritical power plant. Energy, 119 (C), 540-548

Zhang, L., Kong, C.,Yang, T., Zhang, Y., Gao, W. (2020). Performance analysis of turbine extraction superheat utilization schemes of built power plant, Energy Reports, Vol 6, 2200-22