COAL COMBUSTION PREDICTION ANALYSIS TOOL FOR ULTRA SUPERCRITICAL THERMAL POWER PLANT

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DEDICATION

Dedicated to my beloved family especially my wife Nurdiana Abdullah and my father and mother, my brothers and sisters....

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Thanks to ALLAH swt, the Most Gracious, Most Merciful and Most Bountiful who has given me the courage and patience to accomplish this research work. Without His help and mercy, this would not have come into reality.

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ABSTRACT

Coal remains a major source of energy in the power generation industry in Malaysia. However, coal usage results in serious ecological and environmental problems due to greenhouse gas (GHG) emissions. One of the main objectives of the coal combustion research is to develop techniques that may help power plant operators (PPO) to utilize coal cleanly and efficiently by adopting good coal blending practices. Currently, the emission mitigation and boiler cleanliness measures through the coal blending process are focusing more on laboratory-scale tests and not utilizing the actual plant data and behavior. This study aims to evaluate the effectiveness of the developed Coal Combustion Prediction Analysis Tool (CPAT) as a method to facilitate the PPO in predicting the impact of the individual or blended coal quality. It provides early predictions on the boiler combustion performance related to the coal quality and assists the PPO in preparing for the boiler process control optimization. The CPAT combustion model is related to the calculations of the boiler performance and emissions while the CPAT boiler cleanliness model is to compute the slagging and fouling indices. The former model was tested and validated using the actual plant data with the results showing that all the models have mean percentage errors of less than 1%, implying that the combustion model is accurate. The latter model was verified with the actual boiler process parameters and actual site observation for the slagging behaviour. The results show that it gives accurate indications of the slagging and fouling tendencies and helps the PPO to strategize the coal combustion plan. The effect of the coal blending ratios to the power plant performance and SO_x emission is evaluated and the result shows that the CPAT is able to recommend the optimum blending ratio for optimum plant performance and SO_x emission. Thus, the proposed CPAT is able to provide accurate predictions for the SOx emission to ensure SO_x emissions of below 500 mg/Nm^3 and reduce the overall auxiliary power consumption by 12 MWh, thereby improving the overall power plant efficiency and establishing the optimal operational regime. The optimization of coal blending helps to improve the power plant efficiency as well as reduce the GHG emissions for a boiler in a coal fired power plant (CFPP) in Malaysia.

ABSTRAK

Arang batu adalah sumber tenaga utama dalam industri penjanaan kuasa di Malaysia. Walau bagaimanapun, penggunaan arang batu mengakibatkan masalah ekologi dan persekitaran yang serius disebabkan oleh pelepasan gas rumah hijau (GHG). Salah satu objektif utama kajian pembakaran arang batu adalah untuk mengembangkan teknik yang akan membantu pengusaha loji janakuasa (PPO) menggunakan arang batu dengan bersih dan cekap melalui amalan adunan arang batu yang baik. Pada masa ini, langkah mengurangkan pelepasan dan menjaga kebersihan dandang melalui proses adunan arang batu lebih terfokus kepada pengujian skala makmal dan tidak menggunakan data dan operasi loji janakuasa sebenar. Penyelidikan ini menilai keberkesanan Alat Analisis Ramalan Pembakaran Arang Batu (CPAT) sebagai satu kaedah untuk memudahkan PPO meramal kesan kualiti arang batu berbentuk individu atau adunan. Ia memberikan ramalan awal mengenai prestasi pembakaran dandang yang berkaitan dengan kualiti arang batu dan membantu PPO dalam menyediakan kawalan proses dandang yang optimum. Model pembakaran CPAT terdiri daripada pengiraan prestasi dan pelepasan GHG sementara model kebersihan dandang CPAT dibina untuk menentukan indeks pembentukan sanga dan penyisikan. Model CPAT yang pertama telah diuji dan disahkan menggunakan data loji sebenar dengan hasilnya menunjukkan bahawa semua model mempunyai nilai peratusan ralat purata di bawah 1%. Ini membuktikan bahawa model pembakaran adalah tepat. Model CPAT kedua pula telah disahkan dengan parameter proses dandang sebenar dan pemerhatian tapak sebenar bagi pembentukan sanga. Hasilnya menunjukkan bahawa model kebersihan dandang memberikan petunjuk yang tepat mengenai kecenderungan pembentukan sanga dan penyisikan. Maklumat ini akan membantu PPO menyusun strategi pembakaran arang batu. Pengaruh nisbah adunan arang batu terhadap prestasi loji janakuasa dan pelepasan SO_x dinilai dan hasilnya menunjukkan bahawa CPAT boleh digunakan untuk meramal nisbah adunan optimum bagi prestasi loji janakuasa dan pelepasan SO_x yang optimum. Dengan demikian, CPAT yang disarankan dapat meramalkan dengan tepat pelepasan SO_x untuk memastikan bahawa pelepasan SO_x adalah di bawah 500 mg/Nm^3 dan mengurangkan penggunaan kuasa sokongan keseluruhan sebanyak 12 MWh, serta meningkatkan kecekapan loji secara keseluruhan dan mewujudkan langkah operasi yang optimum. Adunan arang batu yang optimum membantu meningkatkan kecekapan loji janakuasa serta mengurangkan pelepasan GHG bagi dandang di dalam loji janakuasa arang batu (CFPP) di Malaysia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADB	-	Air dry basis
Al_2O_3	-	Alumina oxide
AR	-	As received
ASME	-	American Society of Mechanical Engineers
ASTM	-	American Society for Testing and Materials
APH	-	Air preheater
BA	-	Base Acid ratio
BMCR	-	Boiler maximum continuous rate
Ca	-	Calcium
CaO	-	Calcium oxide
$CaSO_4$	-	Calcium sulphate
CFD	-	Computational fluid dynamic
CFPP	-	Coal fired power plant
CGA	-	Conventional genetic algorithm
CHNS	-	Carbon, hydrogen, nitrogen, sulphur
Cl	-	Chlorine
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
COA	-	Certificate of analysis
COD	-	Commercial operation date
CPAT	-	Coal Combustion Prediction Analysis Tool
CSTA	-	Coal Supply and Transportation Agreement
CUJ	-	Coal unloading jetty
DAF	-	Dry ash free
DB	-	Dry basis
DCS	-	Distributed control system
DOE	-	Department of Environmental
EC	-	Energy Commission
FC	-	Fixed carbon
FD	-	Forced draught

FDF	-	Forced draught fan
Fe_2O_3	-	Iron oxide
FEGT	-	Furnace exit gas temperature
FF	-	Fabric filter
Ff	-	Fouling factor
FGD	-	Flue gas desulphurization
FRH	-	Final reheater
GA	-	Genetic algorithm
GCV	-	Gross calorific value
GDP	-	Gross domestic product
GGH	-	Gas-gas heater
GHGs	-	Greenhouse gases
HGI	-	Hardgrove grindability index
HRT	-	Hot reheat temperature
HHV	-	High heating value
HP	-	High pressure
HPT	-	High pressure turbine
HV	-	Heating value
ICR	-	Iron-Calcium ratio
IDF	-	Induced draught fan
IP	-	Intermediate pressure
IPT	-	Intermediate pressure turbine
IPFR	-	Isothermal plug flow reactor
K_2O	-	Potassium
kW	-	Kilowatt
LFO	-	Light fuel oil
LHV	-	Low heating value
LP	-	Low pressure
LTRH	-	Low temperature reheater
M	-	Moderate
MCR	-	Maximum continuous rate
MIT	-	Mill inlet temperature
MOT	-	Mill outlet temperature

MSP	-	Main steam pressure
MST	-	Main steam temperature
MW	-	Megawatt
Na_2O	-	Sodium oxide
Na_2SO_4	-	Natrium sulphate
NaCl	-	Sodium chloride
NA	-	Not applicable
NEM	-	New economic model
NO	-	Nitrogen monoxide
NO_x	-	Nitrogen oxide
PA	-	Primary air
PAF	-	Primary air fan
PFBC	-	Pressurized fluidized bed combustion
PI	-	Plant Information
PI ACE	-	Plant Information Advance Calculation Engine
PI AF	-	Plant Information Asset Framework
PM	-	Particulate matter
PPA	-	Power purchase agreement
PPO	-	Power plant operators
PTC	-	Performance test code
RBI	-	Reliability based inspection
RCA	-	Root Cause Analysis
RMSE	-	Root mean square error
SAGA	-	Simulated annealing genetic algorithm
SF	-	Slagging factor
SFT	-	Slag forming tendency
SiO_2	-	Silica dioxide
SOFA	-	Separated over fire air
SO_2	-	Sulphur dioxide
SO_x	-	Sulphur oxide
SP	-	Silica percentage
TM	-	Total moisture
UNFCCC	-	United Nation Framework Convention on Climate Change

USP	-	Unsworth sootblower performance
VM	-	Volatile matter
XRD	-	X-ray diffraction

LIST OF SYMBOLS

$^\circ$	-	Degree
%	-	Percentage
n	-	Total number of iterations
t	-	Time
x_1	-	Actual value
x_2	-	Simulated value
=	-	Equal
$<$	-	Less than
$>$	-	Greater than
$\sum$	-	Sum
$(x1 - x2)$	-	Variance of x
wt%	-	Weightage percentage
$DVPO_2$	-	Measured O_2 concentration in the flue gas
EF	-	Efficiency in %
EX	-	Drive efficiency for pulveriers
HHVF	-	Heating value of the fuel
HStLvCr	-	Enthalpy of vapor
HWRe	-	Enthalpy of water
HHVFcv	-	Heating value of the fuel on a constant volume basis
MpAsF	-	Ash in fuel, mass percent
MpCRs	-	Unburned carbon in residue
M_pC_b	-	Carbon burned
MpCF	-	Fuel carbon mass percent
MpUbC	-	Unburned carbon per pound of fuel
MF_rWDA	-	Moisture in air
MqDA	-	Dry air per btu
MpCb	-	Carbon burned, mass percent
MpO2F	-	Fuel oxygen, mass percent
MFrThACr	-	Theoretical air
MoDPc	-	Moles of dry products from combustion

MoThACr	-	Moles of theoretical air
MpSF	-	Fuel sulphur, mass percent
MpN2F	-	Fuel nitrogen, mass percent
MqDA	-	Total dry air for combustion
MqWA	-	Moisture in air
MqFgF	-	Wet gas from the fuel
MqWAd	-	Additional moisture in flue gas
MqFg	-	Total wet gas flow
MqWFg	-	Total moisture in gas
MqWF	-	Moisture from fuel
MqWH2f	-	Moisture from combustion of hydrogen
MqDFg	-	Dry gas per btu of fuel based on the excess air
MpH2F	-	Fuel hydrogen, mass percent
MrF	-	Fuel flow rate
Pa	-	Barometric pressure
PpWvA	-	Partial pressure of water vapor in air
PsWvTdb	-	Saturation pressure of water vapor at dry-bulb
QpL	-	Sum total of heat losses in % of fuel heating value
QpB	-	Sum total of heat credits in % of fuel heating value
Qpulvf	-	Measured power consumption of the pulverizers
RHM	-	Relative humidity
T_{250}	-	T_{250} temperature
Tf3	-	Fuel inlet temperature
XpA	-	Excess air

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background and Motivation

Coal remains a major source of energy in the power generation industry in Malaysia. Based on data from Malaysia's Energy Commission (EC), the total installed generation capacity in 2017 was 22,919 MW from which 53% was from the coal-fired power plants (CFPPs), 40% from gas-fired power plants, and the remaining 8% from renewable energy and hydropower [1]. According to the Energy Commission's 5-year projection from 2018 to 2022, CFPPs will remain as the main provider of electric power in Malaysia. The average growth rate for coal-fired power generation is around 1.8% per year. Based on this scenario, it is projected that the coal combustion emission in the atmosphere will increase proportionally to the growth rate of the CFPPs. Although coal will remain relevant in the power generation industry of this country, the industry players need to ensure that necessary measures to control the emissions are implemented in accordance with the government's push towards cleaner energy production. The solutions may vary from increasing the thermal power plant's efficiency, installation of new technology for emission reduction, and introduction of renewable energy.

Coal combustion brings on serious ecological and environmental problems as the main constituents of the emitted flue gases are carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxide (NO_x), carbon monoxide (CO), and particulate matter (PM); which are known to be the main pollutants contributing to the global warming [2]. Optimum coal combustion is essential in CFPPs because it results in higher efficiency and reduces the harmful emissions in the flue gases. One of the main objectives in coal combustion research is to develop techniques to help the power plant operators (PPO) to utilize coal cleanly and efficiently. The emission of CO_2, SO_x, NO_x, CO, and PM from coal combustion is an important factor affecting the operation of power plants. The quantum of these emissions is mainly determined by the coal properties, coal preparation such as coal fineness and blending ratio, and also boiler design.

One of the important aspects to consider in designing a CFPP is the coal quality. The boiler design will need to accommodate a certain range of coal quality parameters. The current trend of deteriorating coal quality has many adverse effects on the performance of a CFPP. The main consequence is a decrease in the combustion performance that will contribute to the increased slagging and fouling issues in the boiler. This will then affect the boiler cleanliness, rendering the boiler less efficient and ultimately contributes to higher emissions.

Another contributing factor to the emissions from coal combustion is the boiler cleanliness and coal properties. PPO are able to optimize the boiler combustion and boiler cleanliness by managing the slagging and fouling inside the boiler to maximize the heat absorption. This is achievable through clean boiler tube surfaces. Slagging and fouling indices for every coal type can be used by the PPO as early indicators for the overall coal combustion behavior. These indicators can be used by the PPO to predict the impact of individual or blended coal quality on the power plant performance. It will give an early indication of the boiler combustion performance related to the coal quality and surely will assist the PPO in preparing for any additional boiler process controls such as the sootblower strategy, mill operation set point, boiler excess air control, and burner control through tilting or auxiliary air dampers adjustment.

The power generation industry is the main source of coal combustion emissions compared to other industries. Therefore, the development of a prediction tool is crucial to the boiler cleanliness and towards quantifying the emissions and establishing a real and measurable mitigation plan. Reducing the emissions from the CFPPs is achievable by improving the combustion efficiency [2]. The improved efficiency strategy can be achieved through either optimizing the power plant operating conditions such as the boiler cleanliness or minimizing the losses within the system. Applying these two approaches can lead to improved power plant efficiency by maximizing the energy absorbed from each grain of the coal consumed, which results in lower power plant emissions.

By considering these facts, the present study is designed to find the correlations for the prediction of the boiler cleanliness, thus improving the overall combustion efficiency and emissions. This study is also aimed at determining the optimal operation regime including the optimization of coal blending that will help to improve the power plant efficiency as well as reducing the coal combustion emissions.

1.2 Problem Statement

In recent years, the quality of coal used in one of the CFPPs located in southern Malaysia has been observed to have greatly deteriorated in terms of its gross calorific value (GCV), total moisture content (TM), and ash content. The CFPP database shows that the GCV level has decreased while the TM and ash content have increased. These degradations have a significant impact on the overall efficiency of the boiler. Plant capacity has been significantly affected by the high moisture content, where a higher primary air volume is needed to ensure that the moisture level is controlled to its specified value. This will further increase the auxiliary power consumption of the plant and reduce the plant efficiency. Furthermore, the utilization of individual coal types with the deteriorated quality can potentially lead to the power plant process upsets such as the main steam temperature (MST) and main steam pressure (MSP) fluctuations.

Environmentally, the high ash and sulphur contents will affect the fabric filter (FF) and flue gas desulphurization (FGD) performance, thus making it difficult for the plant to operate within the specified environmental limits. Changes in the ash parameters such as sodium oxide (Na_2O), potassium oxide (K_2O), iron oxide (Fe_2O_3), calcium oxide (CaO), alumina oxide (Al_2O_3), silica oxide (SiO_3) etc. will also affect the boiler cleanliness, resulting in the boiler operation upset, thereby affecting the emissions. These parameters contribute to the slagging and fouling in the boiler furnace, which in turn directly affects the boiler cleanliness and boiler efficiency. One of the options to tackle this coal quality issue is through the coal blending process.

This option will help to improve the combustion efficiency and heat transfer as well as reduce emissions [3]. Considering these facts, the utilization of individual coal types may not be optimal for the plant operation, as each of the coal parameters has its own impact on the plant process and plant equipment performance.

The capability to handle diverse types of coal quality will greatly improve the situation. This issue needs to be tackled by considering and implementing appropriate solutions such as the plant improvement initiatives for the combustion system. Due to the changing market dynamics and regulations in the power sector, more key players are now sourcing coal from different mines and suppliers with the goal of minimizing the production costs. Such varied sourcing obviously leads to the varying coal qualities and coal types. Since attributes such as GCV, TM, ash content, volatile matter (VM), sulphur content, hardgrove grindability index (HGI), and other ash parameters such as Fe_2O_3, CaO, SiO_2, Al_2O_3, Na_2O, K_2O, etc. have great impact on the combustion process and boiler cleanliness, it is important to monitor and utilize this information adequately in an effort to improve the combustion efficiency.

Even with this scenario, coal will remain relevant to the power industry for many years to come. However, getting good quality coal economically has become a major challenge. One of the options that may help PPO to achieve the objective of getting the correct coal quality for the boiler operation is by coal blending. The optimum blending ratio improves the coal combustion behavior and leads to improvements in the plant efficiency as well as reduction of emissions in the flue gases. Subsequently, PPO faces an uphill challenge to ensure that the desired power output is achieved and, at the same time, to maintain a strict emission standard at all times.

An appropriate coal combustion analysis process remains a challenge for the PPO due to the lack of an effective prediction analysis tool. Several methodologies have been implemented in the power plants to assist the PPO, including the Reliability-Based Inspection (RBI) and Root Cause Analysis (RCA). However, these tools' primary focus is on the after event analysis or post incident investigation. Currently, there are no specific analytical tools for the PPO to predict the power plant process behavior before commencing the actual operation especially for the coal combustion in ultra-supercritical boilers.

Due to the unavailability of a prediction analysis tool for the combustion analysis at the power plants, PPO have not been able to determine the correct coal quality prior to actual consumption at the boiler. As such, this thesis proposes a coal combustion prediction analysis tool to be used by PPO for predicting the boiler cleanliness and emissions by determining the optimum coal quality for the boiler operation. This tool is a practical technique to predict and quantify the measurable mitigation action to improve the plant efficiency, thereby reducing the undesirable emissions. Its focus is on the coal blending optimization to predict the coal requirement that will result in the best boiler cleanliness in terms of slagging and fouling indices. This will in turn result in the increased power plant efficiency and reduced emissions. Indirectly, this will lead to a reduction in the overall fuel consumption and lower the production of greenhouse gases (GHG).

1.3 Research Objectives

Three research objectives have been identified based on the research background and identified research gaps:

i. To establish and validate a combustion model consisting of the boiler performance, milling performance, and SO_x emission through the Coal Combustion Prediction Analysis Tool (CPAT) for optimum plant operation.
ii. To develop and verify the boiler cleanliness model through slagging and fouling indices as well as the boiler operation parameters for single and blended coals.
iii. To investigate and evaluate the effect of the coal quality with different blending ratios on the plant performance parameters and SO_x emissions using the CPAT.

1.4 Research Scope

The research scope shall be based on the data acquired from a 1000 MW ultra-supercritical CFPP located in southern Malaysia where the main parameters of interest are the boiler cleanliness related to the slagging and fouling indices, SO_x emissions, and boiler performance parameters. A coal combustion prediction analysis model shall be developed using Microsoft Excel software with the assumption that the ultra-supercritical boiler and other processes are in normal operating conditions. The data acquired shall be based on the average ten-minute intervals from the plant performance calculation system and the Certificate of Analysis (COA) of the coal received at the power plant. The limited coal blending ratios due to the unavailability of a coal blending facility in the power plant will be a potential challenge for the research.

1.5 Research Significance and Contributions

One of the elements in the Malaysian New Economic Model (NEM) is to lead the global green revolution. In December 2009, Malaysia's Prime Minister announced in Copenhagen that Malaysia intends to reduce its GHG emission intensity of the GDP by 45% in 2030 relative to the emission intensity of the GDP in 2005. Malaysia is actively involved in the climate change process as the country needs to meet the obligations as a signatory party to the United Nations Framework Convention on Climate Change (UNFCCC). Malaysia gave a commitment to this initiative by signing the UNFCCC on 9th June 1993 and later, the Kyoto Protocol on 12th March 1999, and Paris Agreement on 16th November 2016.

The focus of this research is to develop a combustion prediction analysis tool (CPAT) consisting of the coal combustion and boiler cleanliness calculation models to improve the overall plant performance, combustion efficiency, and emissions. This research has been implemented at the Tanjung Bin Energy Power Plant, a 1000 MW Ultra-Supercritical Coal-Fired Power Plant located in the Iskandar Malaysia region, Johor. The Iskandar Malaysia region is the first in the nation to adopt the Global Protocol for the Community-Scale Greenhouse Gas Emission Inventories to account for its GHG emissions. The power plant consists of various complex process equipment such as the boiler, steam turbine, generator, and emission control systems such as the fabric filter (FF) and flue gas desulphurization (FGD) system. The generated electricity by the Tanjung Bin Energy Power Plant is supplied to the national grid and then distributed to the Malaysian peninsula via a 500-kV line.

Thus, the proposed research thesis aims to solve the real-world problems in the ultra-supercritical CFPPs by means of introducing and implementing smart innovations that will result in more efficient and enhanced power plant operations. One of the intended results is the reduction of flue gas emissions by the prediction of boiler cleanliness that will also indirectly improve the plant efficiency. This can be achieved by providing better input to the PPO regarding the combustion characteristics and emissions. This is positively in line with Malaysia's new economic model (NEM) planned for 2011-2020.

1.6 Thesis Outline

This thesis is organised into five chapters. Chapter 1 discusses the introduction of the thesis related to the research background and motivation, problem statements, research objectives, scope, research significance, and contributions. In Chapter 2, the literature review is comprehensively explored by looking at the emissions from coal combustion, coal quality, impact of slagging and fouling on boiler cleanliness, and coal blending practices and implementation in power plants. Based on the review, the identified coal parameters that have a significant impact on the boiler cleanliness and affect the emissions will be discussed in detail in this research.

Navigating further in this thesis, Chapter 3 describes the research methodology that first elaborates the description of a power plant and the coal quality verification process. The plant performance calculation system setup for the purpose of acquiring the plant process data is adequately explained. Next, the Coal Combustion Prediction Analysis Tool (CPAT) setup comprising the combustion and boiler cleanliness models will be explained. Chapter 4 presents the results and discussions of the undertaken research. In this section, the accuracy of the data will be proven and validated with a set of reference to the proposed coal combustion prediction analysis and actual plant operation data. The chapter then explains the prediction of the slagging and fouling tendencies and their impact on the plant operating parameters. The effect of the coal quality with different blending ratios on the plant performance and SO_x emissions will then be investigated against the actual plant operation data. The results produced by this analysis will validate the CPAT in terms of its reliability and accuracy, thereby making it applicable as a useful tool for the PPO to predict the boiler cleanliness and emissions as well as for improving the boiler efficiency.

Finally, Chapter 5 concludes the research with its findings that reiterate and support the research objectives. This is followed by the suggestions for improvement in future works that include the implementation of an on-line coal combustion optimizer in the power plants that may improve their efficiency.

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