METHODS TO IMPROVE FLY ASH QUALITY IN LAKVIJAYA POWER STATION

H.K.M. Malraj

(139512V)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

December 2017

METHODS TO IMPROVE FLY ASH QUALITY IN LAKVIJAYA POWER STATION

H.K.M. Malraj

(139512V)

Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Electrical Engineering

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

December 2017

Declaration

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date:

The above candidate has carried out research for the Masters under my supervision.

Signature of the supervisor: Date:

Abstract

Fly ash is a byproduct of coal fired power generation which may cause environmental and social problems. Lakvijaya power station which is the largest power station in Sri Lanka is facing problems with fly ash dumping. Dumping of fly ash inside the power plant premises has created environmental and social issues. These issues have caused to arise objections from the society against developing new coal fired power plants in Sri Lanka.

Fly ash can be sold to the cement manufactures for productive use without dumping at the power station premises. Though cement manufactures need the Loss of Ignition (LoI) value of fly ash to be less than 5% it is often higher in the Lakvijaya power station. It is observed that reducing the load gives better fly ash quality but, it has an impact on economical dispatchof power plants in the system. Therefore, the study focused on the methods to reduce fly ash LoI level by analyzing boiler operating parameters.

Nine boiler related parameters were identified that would have impact on fly ash LoI level. Data were extracted from unit 1 boiler of Lakvijaya power station for one month. Factor analysis and multiple linear regression methods were used to analyze data. Factor analysis is used to identify correlated variables and suitable adjustments were made prior to conduct of multiple regression analysis.

Regression model of the system was used to identify the impact of each parameter on the fly ash LoIlevel. The results show that total air flow and primary air pressure are not sufficient for the complete combustion at the higher coal rates so that, capacity enhancements for those systems are recommended. Further, boiler operators should be advised to maintain highest possible set points for primary air temperature and secondary air pressure which will contribute to reduce the LoI level in fly ash.

Key words: *fly ash quality, factor analysis, multiple linear regression*

Acknowledgements

I pay my sincere gratitude to Prof. H.Y.R. Perera who really encouraged and guided me to make this endeavor to be a successful one especially in developing this model and preparing the thesis.

Also, I extend my sincere thanks to all the engineers of Lakvijaya power station of Ceylon Electricity Board who supported and facilitated for providing necessary data and information.

My special thanks to Ms. ChaminiThilanka, assistant lecturer, Department of Economics and Statistics, University of Peradeniya for her great support on statistical analysis and the inspiration in every step to accomplish this study.

It is a great pleasure to appreciate all my lecturers at University of Moratuwa and all friends in the post graduate program, for backing me from beginning to the end of this course.

This study would never be taken shape without the commitment and support of those persons so that, I am truly thankful to them.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
ANN	Artificial Neural Network
APH	Air Pre Heater
BMCR	Boiler Maximum Continuous Rating
BPG	Breusch-Pagan-Godfrey
CEB	Ceylon Electricity Board
CMEC	China National Machinery & Equipment Import & Export Corporation
ESP	Electro Static Precipitator
KMO	Kaiser–Meyer–Olkin
LoI	Loss of Ignition
MLR	Multiple Linear Regression
PAP	Primary Air Pressure
PAT	Secondary Air Temperature
PCPP	Puttalam Coal Power Project
SAP	Secondary Air Pressure
SAT	Secondary Air Temperature
SPSS	Statistical Package for Social Sciences

LIST OF APPENDICES

1. INTRODUCTION

1.1. Lakvijaya power station

Lakvijaya coal power station is the first coal fired power station in Sri Lanka. The location of power station is in Norochcholei village of Kalpitiya peninsula in Puttalam district and it is 130 km from Colombo. Since the power station is located in a coastal area, it facilitates cooling water requirement to be taken from the sea as an open cycle system and coal supply to be taken from ships to the power plant premises.

Lakvijaya power station consists of three units each having 300 MW capacity. Unit 1 of Lakvijaya power station commissioned in 2010 under the Puttalam Coal Power Project (PCPP) phase-1 while the units 2 and 3 were commissioned in 2014 under the Puttalam coal power project phase-II. Main contractor for both the projects was China National Machinery & Equipment Import & Export Corporation (CMEC) while Poyry Energy ltd gave the consultancy service. Project costs were USD 455 million and USD 891 million for the phase I and II respectively. The project is funded by EXIM Bank of China.

Power station is connected with the national grid through 220kV transmission lines to New Chillaw grid substation and New Anuradhapura grid substation.

1.2. Importance of the power station

Being a small electricity grid the total installed capacity before the Lakvijaya power station was around 2500 MW and the peak demand was around 1800 MW. The power system was hydro dominant in the wet season while being high cost oil fired thermal power dependent in the dry season. Addition of the Lakvijaya power plant to the system caused the system to be changed to a coal dominant system from an oil dominant system and which created a healthier energy mix in the Sri Lankan power generation system. At present Lakvijaya power station supplies approximately 40% of the country's electricity demand at a unit cost of 9 Rs/kWh which is lower than average power generation cost.

1.3. Boiler unit of the power station

Boiler is the main energy conversion equipment in a coal fired power plant. Boiler is used to generate superheated steam by burning coal. The main inputs to the boiler are coal and air. The 300MW unit boiler of Lakvijaya power plant is a sub-critical, one-stage reheat and natural circulation drum type boiler, which adopts balance draft and tangential firing, fired sub bituminous coal. The maximum continuous steam generating capacity of the boiler is 1025 T/h while the rated output is 964 T/h which is at the 300 MW power output. The boiler is manufactured by Harbin Boiler Company. Thermal parameters of the boiler are shown in table 1.1.

Table 1.1: Thermal parameters of the boiler

Boiler Model: HG-1025/17.3-YM			
Thermal Parameter		Unit	300 MW
Superheated Steam	BMCR	T/h	1025
	Steam Pressure(BMCR)	MPa (g)	17.3
	Steam Temperature (BMCR)	˚C	541
Reheated Steam	Steam Pressure(BMCR)	MPa (g)	3.99/3.79
	Steam Temperature (BMCR)	˚C	337.8/541
Feed Water	Feed Water Temp. (BMCR)	˚C	282

Source : O&M Mannual of Harbin Boiler Manufauterer

The main fuel used in the boiler is sub bituminous coal while at the start up and shut down it is using Diesel to make the fire stable because the fire is not stable at the low load conditions. The combustion equipment is equipped with tilted nozzles and horizontal bias burners. Tilting the nozzles can alter the center position of the flame to adjust the steam temperature of the reheater. The horizontal bias burners could avoid slag building and high temperature corrosion, and could make sustained combustion, and could decrease the NO_x emission. The boiler layout is presented in figure 1.1.

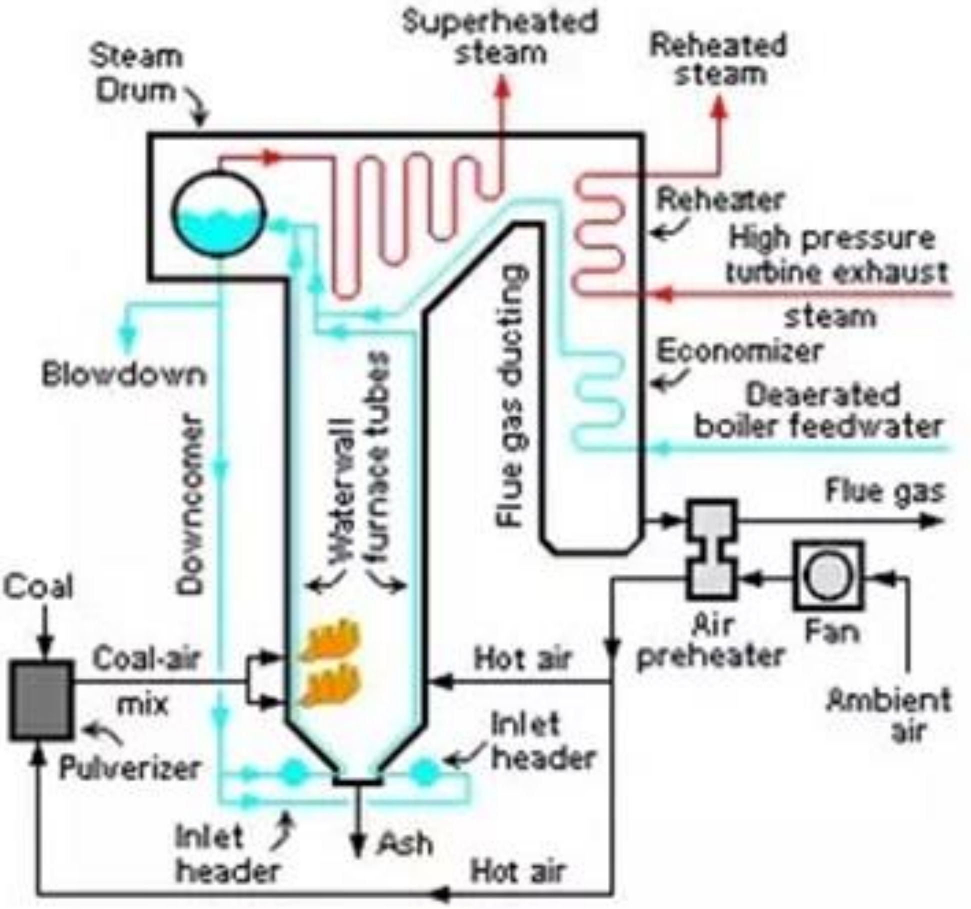

Figure 1.1: Boiler layout of a subcritical coal power plant

1.4. Ash Handling System

Flue gas with fly ash and bottom ash are the output of the boiler in addition to the energy output which is used for steam generation process. The quantity of ash produced after combustion is highly depending on the ash content of raw coal. Usually the total ash content of coal used in Lakvijaya power station is around 11%. The coal consumption rate is around 110 T/h at 300 MW. Therefore, the total ash production rate is around 12 T/h on which fly ash is 10T/h while bottom ash is 2T/h. Parameters of design coal is shown in appendix A.

Electrostatic precipitator (ESP) units are used to collect fly ash which is coming with the flue gas. Ash collecting efficiency of ESP units is as high as 99.9% so that most of fly ash particles would be captured by ESP units.

1.5. Research Problem

1.5.1. Coal fly ash

Fly ash is a hazardous byproduct of coal fired power generation. Earlier fly ash released directly to the atmosphere through the flue gas chimney, but later ESP units were mandatory to add to the newly constructing coal power plants to reduce the air pollution. Although ESP units are capable of collecting fly ash at a higher efficiency, it is a challenging task to properly dump the collected fly ash. Composition of fly ash is presented in the table 1.2.

Table 1.2: Composition of coal fly ash

Component	Composition %
SiO_2	40-60
Al_2O_3	20-30
Fe_2O_3	4-10
CaO	5-30
LoI	0-3

Source: www.wikipedia.com

In addition to the components listed out in the table 1.2 there are traces of heavy metals such as Mercury, Lead, Cadmium and Arsenic in coal fly ash. Some researchers have found significant levels of radioactivity in coal fly ash. Level of these hazardous components greatly depends on the type of coal used in the boiler.

1.5.2. Wet unload method of fly ash

There are two methods to unload fly ash collected by ESP units as dry unload and wet unload. Water is used to reduce the dust formation while transporting and unloading in the wet unload method. In this method fly ash is directly dumped in the fly ash yard which is in the power station premises. Trucks are used to transport fly ash from ash silos to the yard. Although spraying water reduces the dust formation to some extent during the unloading and transporting processes, the prevailing hot and dry weather condition in Kalpitiya peninsula throughout the year causes water to rapidly evaporate leading to dust formation at the ash yard.

1.5.2.1. Environmental and social issues of wet unloading

Since Lakvijaya power station is situated in the North Western coast of Sri Lanka, it directly faces heavy wind. This strong wind carries ash particles from ash yard to the inland of the country causing environmental and social issues. Most of the land nearby the power station is used for mass scale vegetable cultivation. When fly ash particles deposit on these crops, it affects the quality of harvest and it would be dangerous to consume since fly ash is a hazardous waste. There are several villages nearby the power station so that the fly ash issue affects their day to day life. Inhaling of fly ash could have an adverse impact on the human respiratory system and the health effects of fly ash on both villagers and employees of the power station cannot be neglected.

Puttalam lagoon is by the side of the power station and it is an environmentally sensitive area. Depositing of fly ash adversely affect the flora and fauna of the lagoon environment. Adding of fly ash particles to the sea is inevitable by the wind and rain water. Thus, the effect on the ocean environment also needs to be concerned. If the disposal process of fly ash is not properly handled, the ground water also will be contaminated.

1.5.3. Dry unload method of fly ash

1.5.3.1. Dry unload method

Dry unload is the method that is used to sell fly ash to the outside parties for productive use of fly ash so that dumping at the power station premises is not needed. Fly ash is an additive used in cement industry and cement manufactures are the main buyers of fly ash from coal power plants. There are two cement manufactures to buy fly ash from Lakvijaya power station and one of them has a cement factory at Puttalam. There are other buyers such as roofing sheet manufactures and land filling contractors but their requirement is at a lower level compared to that of cement manufactures.

1.5.3.2. Financial benefits of dry unload

CEB sells fly ash at a rate of Rs 2500.00 per metric ton to cement manufactures and other buyers. It is expected to produce fly ash at a rate of 30 T/h when all three units of Lakvijaya power station are operating at the rated load (300 MW). Therefore, CEB can earn approximately Rs. 1.8 million per day by selling fly ash to the cement manufactures. If CEB can't fulfill the fly ash quality requirements it will lose this income and it has to expend on fly ash dumping which involves higher cost on labor, transportation, water and land as well as the socio-environmental cost.

If CEB does not produce fly ash with required quality level cement manufactures will have to rely on imported fly ash. Importing fly ash affects negatively the national economy and cement manufactures would face shortage of raw materials and higher production cost.


Figure 1.2: Flue gas-ESP in operation Vs out of operation

Figure 1.3: ESP units of the power plant

Figure 1.4: Dumped ash inside the power plant premises by wet unloading

Figure 1.5: Dry unloading of fly ash for cement production

1.5.4. Quality of fly ash

It is needed to maintain the quality of fly ash in an acceptable level to be used in the cement manufacturing process. Therefore, both cement manufactures and CEB continuously check the fly ash quality parameters by conducting laboratory tests before selling. The parameters for the quality of fly ash are Loss of Ignition (LoI), Level of cluster formation and fineness of powder.

1.5.4.1. Loss of Ignition

Loss of Ignition is the percentage of unburnt coal particles in fly ash. It can be calculated as follows,

$$LoI = \frac{Weight\ of\ unburnt\ coal\ in\ the\ fly\ ash\ sample}{Weight\ of\ the\ fly\ ash\ sample} \times 100$$

LoI value should be less than 5% to be accepted by cement manufactures for them to use in the cement manufacturing process. Coal particles exist in fly ash due to incomplete combustion. There are many reasons for incomplete combustion inside the furnace. Those reasons are identified through the literature survey related to coal power plants.

Reducing LoI is beneficial for plant performance aspect as well. Unburnt carbon in fly ash causes to increase the heat loss through flue gas and it will cause to reduce the plant efficiency. When unburnt carbon presents in fly ash, the coal usage is higher to generate a unit of electricity (1 MWh) causing an efficiency drop. Therefore, it is recommended to maintain a low value of LoI in fly ash by considering socio-environmental, financial and plant performance aspects.

1.5.4.2. Impact of fly ash quality on plant operation

It is observed that the fly ash quality reaches the acceptable level when the plant operates at a reduced load. Sometimes it is not possible to do the wet unload due to constraints such as water unavailability, heavy dust formation and breakdown of unloading equipment. In such instances operator has to operate the power station at a reduced capacity to reach the fly ash quality level so that, the produced fly ash can be sold to the cement manufactures. If the Lakvijaya power station which is the least cost thermal power station in Sri Lanka, operates on reduced load to meet the fly ash quality level the economical dispatch of power plants will be negatively affected.

Operator has to reduce the load to a certain extent for reaching the fly ash quality level and the exact load has to be found by experience or trial and error method. Therefore, it is important to model the system to find out the exact limits of operating the power station and other capacity limitations to reach the fly ash quality level. It is also expected to present guidelines to control various parameters in an optimum level to reach fly ash quality level. Recommendations for improving capacity and other shortages that cause to give bad quality fly ash are important to improve the efficiency and the environmental suitability of the boiler.

02. LITERATURE REVIEW

2.1. Background of the study

Although there are several research focusing on the relationship between fly ash LoI and boiler input parameters in several power plants, an analysis on Lakvijaya power station is not conducted. Therefore, operators have to rely on trial and error methods and their experiences to operate the power station in a way that gives the fly ash LoI value in an acceptable level. Since this leads to deviate the both fly ash LoI and boiler parameters from the optimum level, it has an impact on plant efficiency and finally on the unit generation cost. Therefore, it is important to model the boiler of Lakvijaya power station to find out the exact relationship between boiler inputs and fly ash LoI value to find out the optimum way of controlling boiler input parameters to achieve the desired level of fly ash LoI.

2.2. Factors affecting fly ash LoI

According to the literature there are several factors that affect fly ash LoI. Those factors can be categorized into two groups as factors associated with coal and factors associate with boiler.

2.2.1. Factors related to coal

Factors related to coal are type of coal, particle size of coal and moisture content of coal. Type of coal is specified at the point of purchasing of coal and the parameters of calorific value, ash content and volatile matter content should be in compliance with the specified level to achieve the desired LoI level.

Coal particle size is determined by the grinding level at the coal pulverizers. Those pulverizers should be tuned to give the optimum level of particle size in order to achieve the desired level of LoI of fly ash. If the coal particle size is smaller than the optimum level it may cause to increase the LoI value because the coal particles may easily escape from the furnace without burning. Larger coal particles will also cause to give higher LoI because it may not have a sufficient time to completely burn inside the furnace. Therefore, it is advisable to maintain optimum level of fineness in coal particles to achieve the desired LoI in fly ash.

Moisture can be added to the coal at different places from coal mines to coal belts which supply coal to the boiler. Moisture content should be lower than the specified value when coal is supplied to the power plant premises. Coal should be stored in dry coal sheds to minimize the moisture content of coal which is fed to the boiler. When the moisture content increases it will cause to increase the fuel rate to generate the required output of power and thus, it may lead to give higher LoI values because, given air flow is insufficient to burn the coal completely.

2.2.2. **Factors related to boiler**

Factors related to coal should be maintained within the specified levels to maintain a healthy LoI value in fly ash. These factors cannot be controlled by the boiler operator and it should be checked at the purchasing, coal feeding and boiler equipment maintenance stages. Therefore, in this analysis the boiler input parameters to control the fly ash LoI level are considered.

Although the manufacture is given recommendations on boiler parameters to maintain the optimum output of the boiler, it is observed that the output fly ash LoI value is often higher than the acceptable level, especially when the plant operates at the rated load. The designed parameters are often given in a range rather than a fixed value and these ranges are given for the maximum efficiency of boiler and considering the safety of the equipment. Therefore, it is needed to find out the boiler related parameters that have an effect on fly ash LoI and their range of variability that will give the optimum level of fly ash LoI. Eight parameters that may have possible impact on fly ash LoI can be identified [1]. Those parameters are listed as follows.

- Boiler load
- Coal consumption rate
- Angle of the tilting burner
- Primary air pressure
- Hot-primary air temperature

- Total air flow
- Hot-secondary air temperature
- Furnace pressure

Impact of these parameters on fly ash LoI level has to be analyzed through a suitable mathematical model to find out the impact of each parameter. Since there is no any standard formula to describe relationship between these parameters with fly ash LoI, it is needed to build an empirical formula based on the observed values of these variables. There are several methods used in literature [1], [2], [3], [4], [5] to obtain the relationship between these kinds of variables. Multiple regression, Factor analysis and Artificial Neural Networks (ANN) are commonly used to model these kinds of systems effectively.

2.3. **Multiple Linear Regression**

Multiple linear regression (MLR) is a statistical technique that uses several explanatory variables to predict the outcome of a response variable. The goal of multiple linear regression (MLR) is to model the relationship between the explanatory and response variables.

The model for MLR, given n observations, is:

$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + ... + \beta_p x_{ip} + \varepsilon$ where i = 1,2, ..., n

Where y_i = dependent variable

x_{ip} = independent variable

ε = random error in prediction, that is the variance that cannot be accurately predicted by the model also known as residuals.

β_0 = constant

β_p = regression coefficient that measures a unit change in the dependent variable when x_{ip} changes

A simple linear regression is a function that allows an analyst to make predictions about one variable based on the information that is known about another variable. Linear regression can only be used when one has two continuous variables an independent variable and a dependent variable. The independent variable is the parameter that is used to calculate the dependent variable or outcome. In reality, there are multiple factors that predict the outcome of an event. To understand a relationship in which more than two variables are present, a multiple linear regression is used.

Multiple linear regression (MLR) is used to determine a mathematical relationship among a number of random variables. In other terms, MLR examines how multiple independent variables are related to one dependent variable. Once each of the independent factors have been determined to predict the dependent variable, the information on the multiple variables can be used to create an accurate prediction on the level of effect they have on the outcome variable. The model creates a relationship in the form of a straight line (linear) that best approximates all the individual data points.

The least squares estimates, β_0, β_1, $\beta_2 \ldots \beta_p$ are usually computed by statistical software. As many variables can be included in the regression model in which each independent variable is differentiated with a number - 1, 2, 3, 4...p. The multiple regression model allows an analyst to predict an outcome based on information provided on multiple explanatory variables. Still, the model is not always perfectly accurate as each data point can differ slightly from the outcome predicted by the model. The residual value, ε, which is the difference between the actual outcome and the predicted outcome, is included in the model to account for such slight variations.

The multiple regression model is based on the following assumptions:

- There is a linear relationship between the dependent variables and the independent variables
- The independent variables are not too highly correlated with each other
- y_i observations are selected independently and randomly from the population
- Residuals should be normally distributed with a mean of 0 and variance σ

The co-efficient of determination, R-squared or R^2, is a statistical metric that is used to measure how much of the variation in outcome can be explained by the variation in the independent variables. R^2 always increases as more predictors are added to the MLR model even though the predictors may not related to the outcome variable. Therefore, R^2 by itself cannot be used to identify which predictors should be included in a model and which should be excluded. R^2 can only be between 0 and 1, where 0 indicates that the outcome cannot be predicted by any of the independent variables and 1 indicates that the outcome can be predicted without error from the independent variables.

2.4. **Factor Analysis**

Factor analysis is a statistical method used to describe variability among observed, correlated variables in terms of a potentially lower number of unobserved variables called factors. For example, it is possible that variations in six observed variables mainly reflect the variations in two unobserved (underlying) variables. Factor analysis searches for such joint variations in response to unobserved latent variables. The observed variables are modeled as linear combinations of the potential factors, plus "error" terms. Factor analysis aims to find independent latent variables. Factor analysis can be used to gain information about the interdependencies between observed variables that can be used later to reduce the set of variables in a data set.

2.5. **Artificial Neural Network**

An artificial neural network (ANN) is a computational model based on the structure and functions of biological neural networks. Information that flows through the network affects the structure of the ANN because a neural network changes - or learns, in a sense - based on that input and output. ANNs are considered nonlinear statistical data modeling tools where the complex relationships between inputs and outputs are modeled or patterns are found.

An ANN has several advantages but one of the most recognized of these is the fact that it can actually learn from observing data sets. In this way, ANN is used as a random function approximation tool. These types of tools help estimate the most costeffective and ideal methods for arriving at solutions while defining computing functions or distributions. ANNs have three layers that are interconnected. The first layer consists of input neurons. Those neurons send data on to the second layer, which in turn sends the output neurons to the third layer.

03. METHODOLOGY

3.1. Factor model of the system

3.1.1. Data collection for factor analysis

Factor analysis is used to identify the factors that affect fly ash quality and their significances. This analysis is also important to check the multicolienearity of independent variables to conduct the regression analysis. The data set of fly ash quality parameter is collected for one month period of unit 1 of Lakvijaya power station. Data collection is done from 14th January, 2017 to 14th February, 2017. Fly ash quality is checked three times per day as at 12 midnight, 8.00 AM and 4.00 PM by taking fly ash samples from the ESP. The parameters that could affect fly ash quality are identified through literature review. The values of each parameter corresponding to the fly ash sample are recorded in the relevant time slot. Variation of those values for each parameter for 30 days is shown in the figure 3.1. A sample of collected data for fly ash quality and other variables is shown in the appendix B.

Figure 3.1: Variation of variables for 30 days

3.1.2. **Tests before conducting factor analysis**

IBM SPSS statistics software is used to conduct the factor analysis. There are two tests that should be done prior to conduct factor analysis to check the suitability of data set for factor analysis. Those tests are called Kaiser-Meyer-Olkin measure of sampling accuracy (KMO) and Bartlett's tests for sphericity. KMO value is the measure to check the suitability of the data for factor analysis. When the KMO value is greater than 0.6 it indicates that sampling is adequate to perform factor analysis. Bartlett's test checks whether multicollinearity exist between variables. Level of significance in Bartlett's test should be less than 0.1 to perform factor analysis. Results of these two tests for the collected data set are presented in the table 3.1.

Table 3.1: KMO and Bartlett's test results

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.772
Bartlett's Test of Sphericity	Approx. Chi-Square	1316.398
	df	45
	Sig.	.000

KMO value of above test is 0.772 which is greater than 0.6. According to the Bartlett's test of sphericity the value of significant is 0.000 which is less than 0.1. Therefore, both tests verified that collected data set is suitable to conduct factor analysis.

3.1.3. **Results of Factor analysis**

3.1.3.1. **Total variance explained**

After testing the suitability of collected data to conduct the factor analysis, the next step is to extract factors by using the principle component analysis method. In IBM SPSS program the extraction of factors is given in the table named "Total Variance Explained". The table titled total variance explained for the collected data is given in table 3.2.

Table 3.2: Total variance explained

Total Variance Explained									
	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.753	57.532	57.532	5.753	57.532	57.532	5.711	57.109	57.109
2	1.203	12.032	69.564	1.203	12.032	69.564	1.201	12.009	69.118
3	1.132	11.323	80.887	1.132	11.323	80.887	1.177	11.769	80.887
4	.956	9.555	90.442						
5	.424	4.239	94.681						
6	.325	3.247	97.928						
7	.171	1.708	99.636						
8	.027	.266	99.902						
9	.008	.079	99.981						
10	.002	.019	100.000						

Extraction Method: Principal Component Analysis.

Factors are arranged according to the most explained variance in the table. Three factors are selected out of tenin the analysis since 80% of the total variance is represented by them. Thus, three independent patterns can be identified by analyzing the data for factor analysis.

3.1.3.2. **Factor Loadings**

Rotated component matrix is used to identify factor loadings and defining the factors. This gives the correlation between each factor and initial variables. Correlated variables can be grouped according to their level of correlation. Rotated component matrix for factor loadings is given in the table 3.3.

3.1.4. **Analysis of results of factor analysis**

Original variables can be grouped into three latent variables (factors) according to the collinearity. Collinearity coefficient for each variable is given in the table 3.4. Seven variables are correlated to each other which mean that change in one variable affects the others. Hot secondary air temperature and angle of tilting burner behaved independently indicating that the change in those variables has no or a little impact on others.

Furnace pressure neither has a correlation with other variables nor with any factors defined. i.e. obtained Furnace pressure values are not having any pattern.

Table 3.3: Rotated component matrix

Rotated Component Matrix[a]

	Component		
	1	2	3
Power	.992	.051	-.031
Coal rate	.992	.060	.005
Air flow	.977	.111	-.044
Furnance Pressure	.206	.338	.234
PA Pressure	.664	-.395	.392
PA temp	.838	.127	.257
Burner angle	-.111	.093	.937
SA Pressure	.936	.248	.048
SA Temp	.011	.908	.001
Ash quality	.845	-.034	-.139

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

Table 3.4: Collinearity coefficient for each variable

	Variable	**Collinearity Coefficient**
Factor 1	Coal consumption rate	0.992
	Boiler load	0.992
	Total air flow	0.977
	Secondary air pressure	0.936
	Fly ash quality	0.845
	Hot-primary air temperature	0.838
	Primary air pressure	0.664
Factor 2	Hot-secondary air temperature	0.908
Factor 3	Angle of the tilting burner	0.937
	Furnace pressure	0.338

Boiler load (power), coal rate and air flow variables are highly correlated with each other. Since multicollinearity affects the accuracy of the regression analysis, following modifications can be done as a remedy for multicollinearity.

1. Drop "Boiler load" variable from the regression model.

2. "Air to coal ratio" is introduced as a new variable instead of "coal rate" and "Air flow" variables.

$$Air\ to\ coal\ ratio\ = \frac{Total\ air\ flow}{Total\ coal\ flow}$$

3.2. Regression Model of the system

After conducting factor analysis, total variables are reduced to eight which was ten initially. The multicollinearity effect which should not be in the data set to conduct the regression analysis is eliminated by removing two variables. LoI value of the fly ash is taken as the dependent variable for the analysis while following boiler parameters are taken as the independent variables

A – Furnace Pressure

B – Primary Air temperature

C – Burner Angle

D – Secondary Air Pressure

E – Secondary Air Temperature

F – Primary Air Pressure

G – Air to Coal Ratio

3.2.1. Tests before conducting linear regression

There should be a linear relationship between the dependent variable and each independent variable to conduct the linear regression. Since there is no any significant relationship between independent variables (multicollinearity is removed by factor analysis), linearity can be checked by plotting each independent variable with LoI value.

3.2.1.1. **LoI Vs. Air to Coal ratio plot**

Figure 3.2 shows the scattered plot of LoI Vs. Air to Coal Ratio. Plot is checked for different cases as linear, exponential, logarithmic, polynomial and power to find out the best fit curve. Table 3.5 shows the R^2 value and the equation for each case.

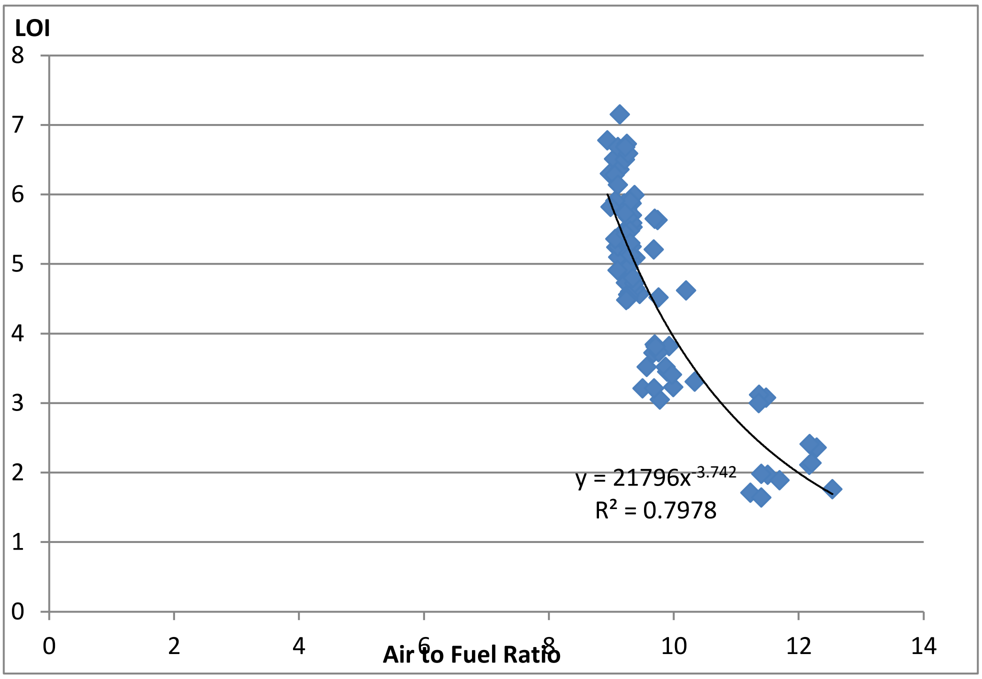

Figure 3.2: Scatter plot of LoI Vs. Air to Coal ratio

Table 3.5: R^2 values and Equation for each plot

Plot Type	R^2	Equation
Linear	0.7015	$y = -1.2892x + 17.239$
Exponential	0.7862	$y = 140.12e^{-0.355x}$
Logarithmic	0.718	$y = -13.65\ln(x) + 35.709$
Polynomial	0.7771	$y = 0.5411x^2 - 12.696x + 76.562$
Power	0.7978	$y = 21796x^{-3.742}$

Since the power plot has the highest R^2 value, the power of -3.742 is taken for Air to Coal Ratio of the linear regression model.

3.2.1.2. **LoI Vs. Furnace Pressure plot**

Figure 3.3 shows the scattered plot of LoI Vs. Furnace Pressure. Plot is checked for different cases as linear, exponential, logarithmic, polynomial and power to find out the best fit curve. Table 3.6 shows the R^2 value and the equation for each case.

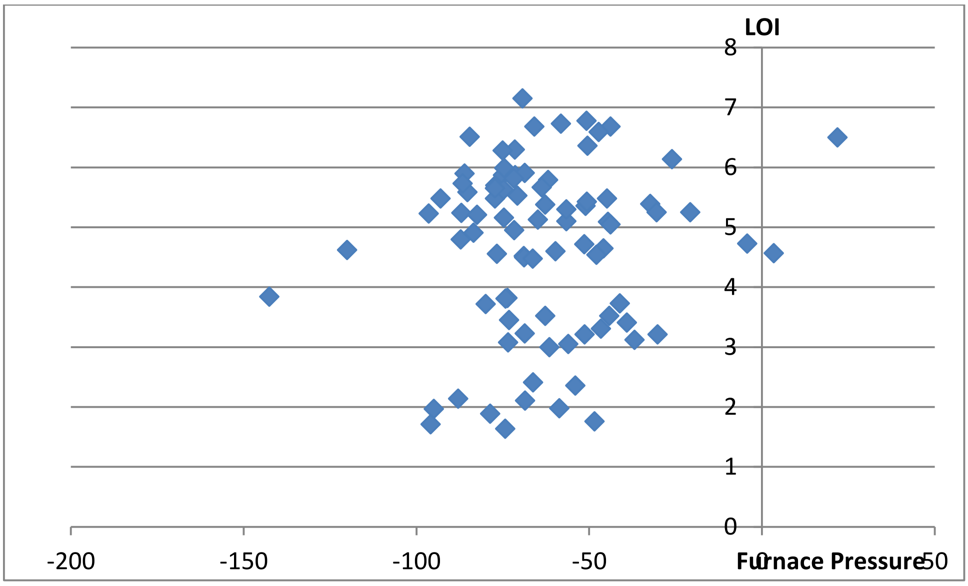

Figure 3.3: Scatter plot of LoI Vs. Furnace Pressure

Table 3.6: R^2 values and Equation for each plot

Type	**R^2**	**Equation**
Linear	0.0099	$y = 0.0058x + 5.046$
Exponential	0.0121	$y = 4.9058e^{0.0017x}$
Logarithmic	-	-
Polynomial	0.0102	$y = 2E\text{-}05x^2 + 0.0084x + 5.1058$
Power	-	-

Since all of these plots do not give a best fit curve, furnace pressure can be omitted from the analysis.

3.2.1.3. **LoI Vs Primary Air Pressure plot**

Figure 3.4 shows the scattered plot of LoI Vs Primary Air Pressure. Plot is checked different cases as linear, exponential, logarithmic, polynomial and power to find out the best fit curve. Table 3.7 shows the R^2 value and the equation for each case.

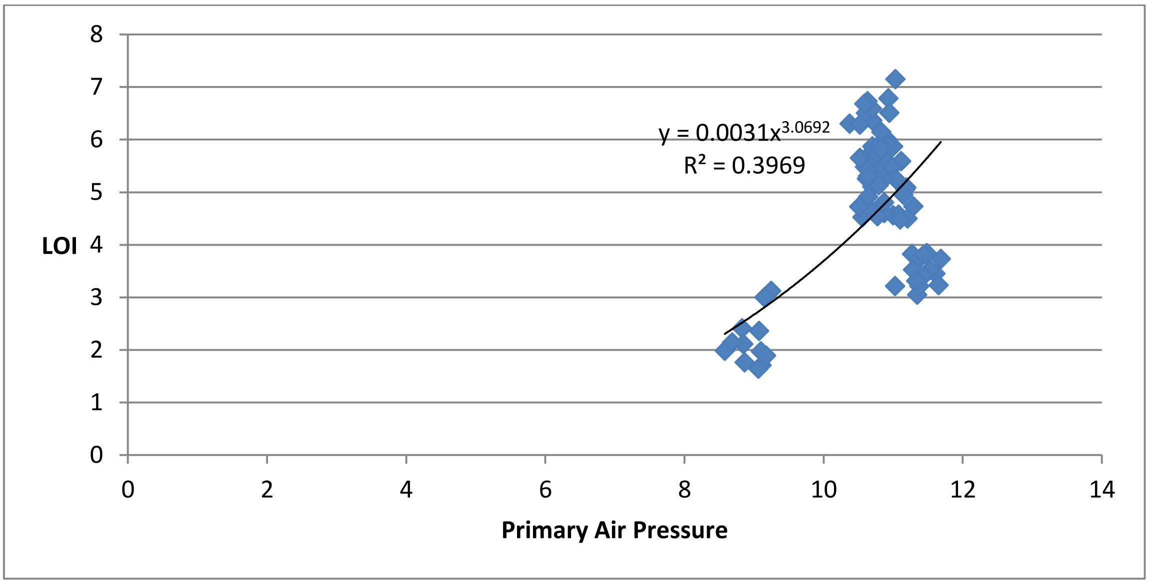

Figure 3.4: Scatter plot of LoI Vs. Primary air pressure

Table 3.7: R^2 values and Equation for each plot

Type	R2	Equation
Linear	0.253	y = 0.9369x - 5.2792
Exponential	0.3673	$y = 0.1951e^{0.2935x}$
Logarithmic	0.2791	y = 9.8989ln(x) - 18.69
Polynomial	0.2215	$y = -1.6011x^2 + 33.324x - 167.73$
Power	0.3969	$y = 0.0031x^{3.0692}$

Since the power plot has the highest R^2 value, the power of 3.0692 is taken for primary air pressure of the linear regression model.

3.2.1.4. **LoI Vs Primary Air Temperature plot**

Figure 3.5 shows the scattered plot of LoI Vs Primary Air Temperature. Plot is checked for different cases as linear, exponential, logarithmic, polynomial and power to find out the best fit curve. Table 3.8 shows the R^2 value and the equation for each case.

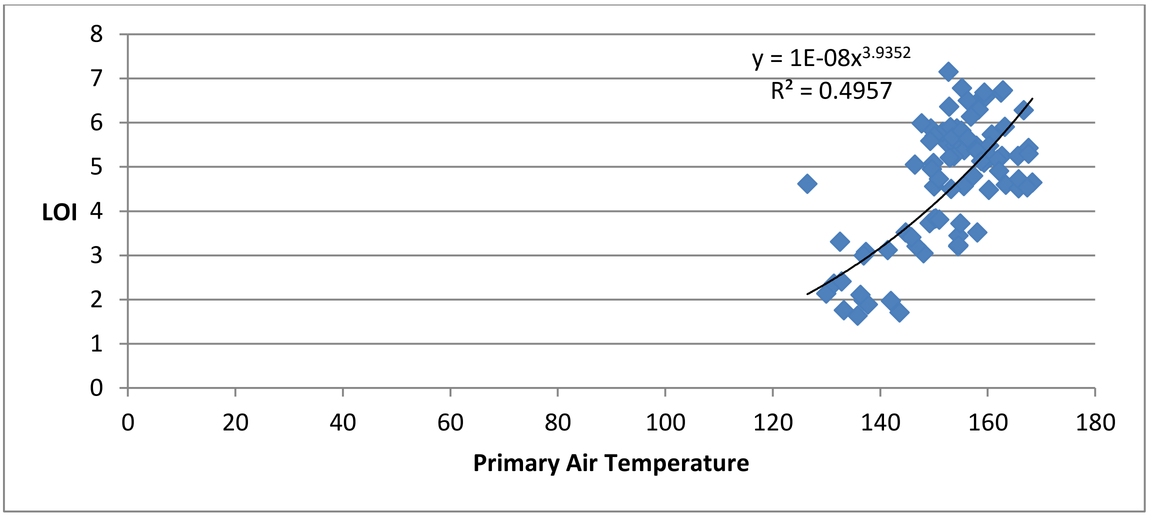

Figure 3.5: Scatter plot of LoI Vs. Primary air temperature

Table 3.8: R^2 values and Equation for each plot

Type	**R2**	**Equation**
Linear	0.4433	y = 0.0964x - 10.035
Exponential	0.4882	$y = 0.0797e^{0.0263x}$
Logarithmic	0.4499	y = 14.418ln(x) - 67.787
Polynomial	0.4675	$y = -0.0019x^2 + 0.6676x - 52.427$
Power	0.4957	$y = 1E\text{-}08x^{3.9352}$

Since the power plot has the highest R^2 value, the power of 3.9352 is taken for primary air temperature of the linear regression model.

3.2.1.5. **LoI Vs. Burner Angle plot**

Figure 3.6 shows the scattered plot of LoI Vs. Burner Angle. Plot is checked for different cases as linear, exponential, logarithmic, polynomial and power to find out the best fit curve. Table 3.9 shows the R^2 value and the equation for each case.

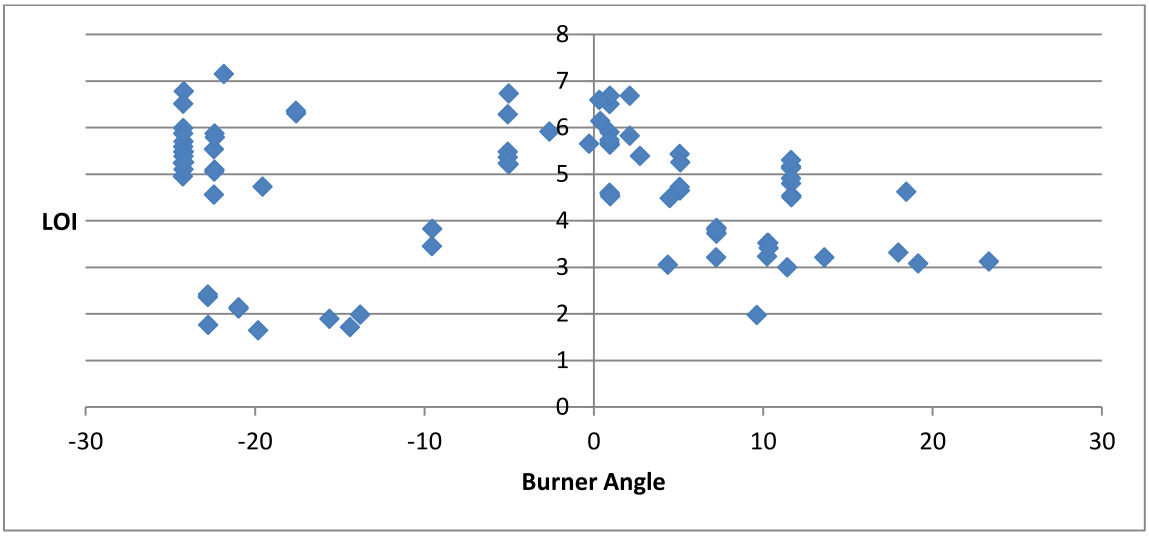

Figure 3.6: Scatter plot of LoI Vs. Burner angle

Table 3.9: R^2 values and Equation for each plot

Type	**R2**	**Equation**
Linear	0.0243	y = -0.0153x + 4.5984
Exponential	0.0052	$y = 4.3714e^{-0.002x}$
Logarithmic		
Polynomial	0.069	$y = -0.0018x^2 - 0.0362x + 4.9174$
Power		

Since all of these plots do not give a best fit curve, Burner Angle can be omitted from the analysis.

3.2.1.6. **LoI Vs. Secondary Air Pressure plot**

Figure 3.7 shows the scattered plot of LoI Vs.Secondary Air Pressure. Plot is checked for different cases as linear, exponential, logarithmic, polynomial and power to find out the best fit curve. Table 3.10 shows the R^2 value and the equation for each case.

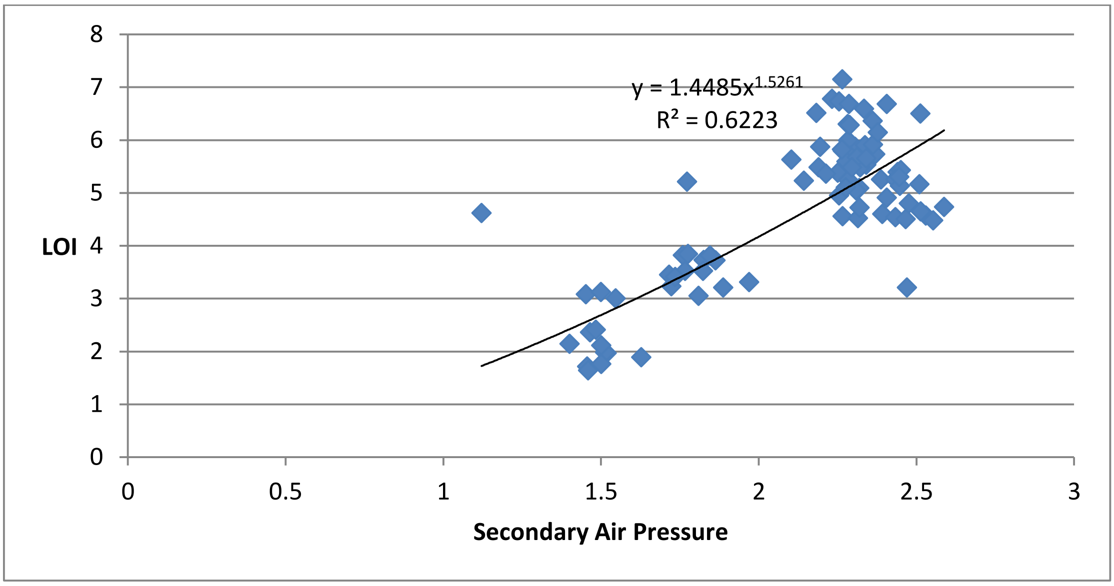

Figure 3.7: Scatter plot of LoI Vs. Secondary air pressure

Table 3.10: R^2 values and Equation for each plot

Type	R2	Equation
Linear	0.5819	$y = 2.9781x - 1.6068$
Exponential	0.6199	$y = 0.8174e^{0.7992x}$
Logarithmic	0.5828	$y = 5.68\ln(x) + 0.5304$
Polynomial	0.596	$y = -1.525x^2 + 8.9501x - 7.2206$
Power	0.6223	$y = 1.4485x^{1.5261}$

Since the power plot has the highest R^2 value, the power of 1.5261 is taken for Secondary air pressure of the linear regression model.

3.2.1.7. **LoI Vs. Secondary Air Temperature plot**

Figure 3.8 shows the scattered plot of LoI Vs. Secondary Air Temperature. Plot is checked for different cases as linear, exponential, logarithmic, polynomial and power to find out the best fit curve. Table 3.11 shows the R^2 value and the equation for each case.

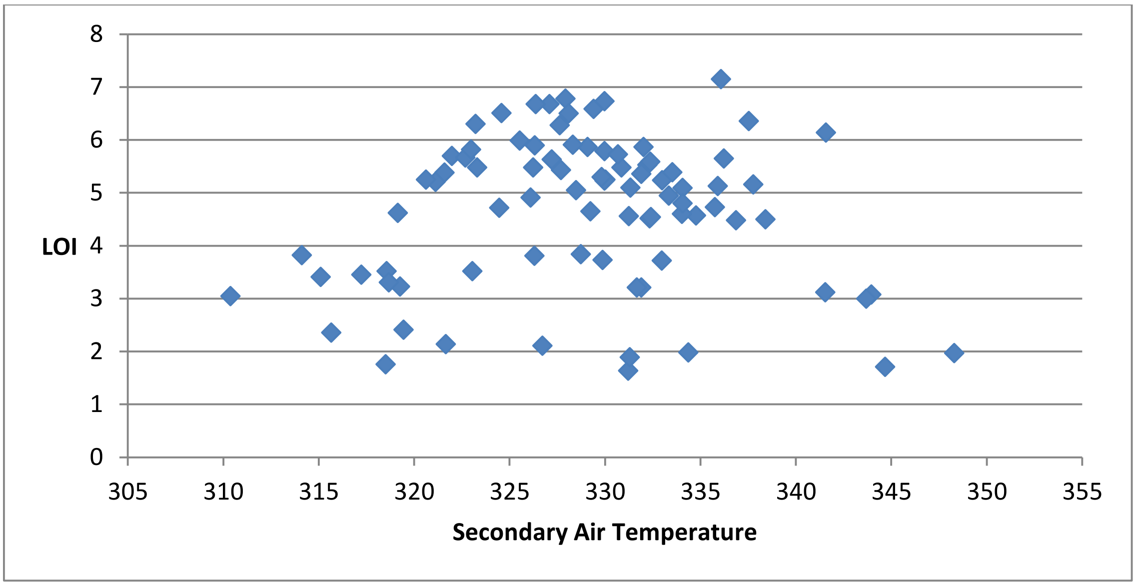

Figure 3.8: Scatter plot of LoI Vs. Secondary air temperature

Table 3.11: R^2 values and Equation for each plot

Type	**R2**	**Equation**
Linear	0.0012	y = 0.0066x + 2.494
Exponential	0.0001	$y = 3.6246e^{0.0006x}$
Logarithmic	0.0018	y = 2.6843ln(x) - 10.881
Polynomial	0.2445	$y = -0.0091x^2 + 5.9866x - 980.92$
Power	0.0004	$y = 0.6689x^{0.3255}$

Since all of these plots do not give a best fit curve, Burner Angle can be omitted from the analysis.

3.2.2. **Analysis of linearity test**

Three variables namely Furnace Pressure, Burner Angle and Secondary Air Temperature are not qualified from the linearity test. Therefore, those three variables are dropped from the regression analysis and the variables that include in the analysis is listed below.

Dependent Variable: Loss of Ignition (LoI)

Independent Variables

A – Air to Coal Ratio

B – Primary Air Pressure

C – Primary Air Temperature

D – Secondary Air Pressure

From the above analyze for linearity, none of the variable shows a linear relationship between the dependent variable (LoI). Therefore, each variable should be converted into their respective power to get a linear relationship with the dependent variable as follows.

$Air\ to\ Coal\ Ratio^{*}(ACR^{*}) = Air\ to\ Coal\ Ratio^{-3.742}$

$Primary\ Air\ Pressure\ ^{*}(PAP^{*}) = Primary\ Air\ Pressure\ ^{3.0692}$

$Primary\ Air\ temperature\ ^{*}(PAT^{*}) = Primary\ Air\ temperature^{3.9352}$

$Secondary\ Air\ Pressure\ ^{*}(SAP^{*}) = Secondary\ Air\ Pressure^{1.5261}$

A sample of modified data table is shown in the table 3.12.

The regression model can be presented as follows.

$$LoI = \beta_0 + \beta_1 ACR^{*} + \beta_2 PAP^{*} + \beta_3 PAT^{*} + \beta_4 SAP^{*} + \in$$

Table 3.12: Sample of modified data

Air to coal ratio	PA Pressure	PA temp	SA Pressure	Ash quality
0.000238908	1473.830964	563066893.4	3.88410957	4.54
0.000236719	1417.059371	566513629.8	3.91338318	5.3
0.000257695	1419.514304	496575814.1	3.81852159	4.91
0.000240513	1664.22374	397534215.8	3.964794	4.5
0.000243478	1615.940499	474499675	4.18023068	4.48
0.000219295	1583.988086	411054136.9	3.97461274	3.21
0.000188303	1853.332793	411970989.1	2.2798004	3.45
0.00018599	1692.641104	365982786.4	2.36755566	3.82
0.000196755	1727.451934	347901828.9	2.47102419	3.05
0.00020481	1736.34666	415671254.5	2.58447204	3.72
0.00020401	1741.98026	335614361.8	2.63545434	3.21
0.000198391	1890.827805	358084864.1	2.50445518	3.73
0.000203359	1792.759059	369338492.7	2.40256366	3.84
0.000202224	1772.234368	375270210.9	2.5485678	3.81
0.000213611	1698.640779	449913052.5	2.50026784	3.52
0.000181522	1874.97871	411611052.1	2.29400818	3.23
0.000190044	1817.309319	317922000.5	2.38194926	3.52
0.000182898	1771.283606	327433678.8	2.31843506	3.41
0.000159836	1720.45152	224766111.3	2.81221414	3.31

3.2.3. Test the violation of assumptions

The flowing tests should be conducted to check the violation of the regression model.

- Normality test - Normality of residuals is checked with a normal P-P plot.
- Test the heteroscedasticity - BPG test is used to test the heteroscedasticity
- Test the auto-correlation - The Durbin-Watson (d) value of the model is used to check the auto-correlation
- Test the multicollinearity- Tolerance should be more than 0.1 (or VIF<10). for all variables to have a negligible multicollinearity in the model.
- F test - check whether independent variables are jointly significant.

04. RESULTS AND DISCUSSION

4.1. Results of Regression Analysis

Transformed data can be used to do the regression analysis effectively. Model summary of the regression analysis is shown in the table 4.1. It gives the multiple linear regression model summery and overall fit statistics. It can be found that the adjusted R^2 value of the model is 0.811 with original R^2 of 0.820. This means that the model explains 82% of the variance of the dependent variable.

Table 4.1: Model summary of the regression analysis

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.906[a]	.820	.811	.61436	1.558

a. Predictors: (Constant), SA Pressure*, PA Pressure*, PA temp*, Air to coal ratio*

b. Dependent Variable: Fly Ash LoI

It can be tested whether the regression model violate the assumptions by conducting following tests

4.1.1. Test the normality

Normality of residuals is checked with a normal P-P plot. The plot shows that the points generally follow the normal (diagonal) line with no strong deviations indicating that the residuals are normally distributed. (figure 4.1).

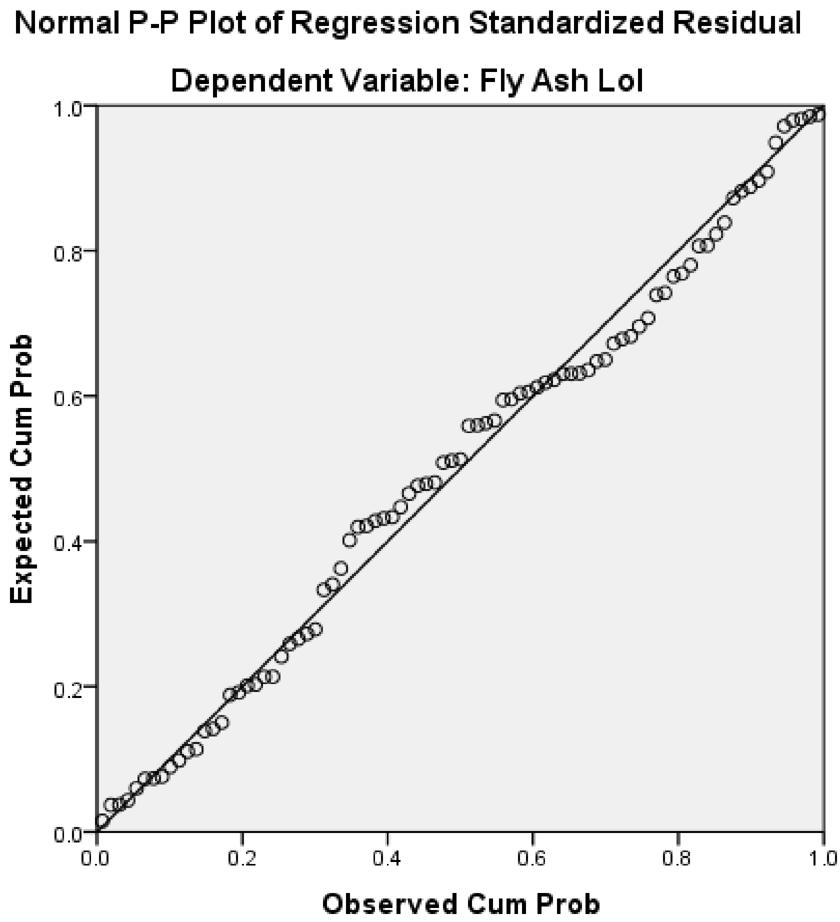

Figure 4.1: P-P plot of the residuals

4.1.2. Test the heteroscedasticity

BPG test was used to test the heteroscedasticity. According to BPG test for checking the heteroscedasticity which is one of the violations of assumptions of the regression model H_0 is accepted at 5% significant level indicating that heteroscedasticity does not exist in the model. (Appendix C).

H_0: Homoscedasticity
H_1: Heteroscedasticity

P $>\alpha$
$0.8324 > 0.05$ ⟶ Accept H_0

4.1.3. Test the auto-correlation

The hypothesis can be set up as follows to test the auto-correlation.

H_0: No auto-correlation

H_1: Auto-correlation

The Durbin-Watson (d) value is 1.558 which lies inH_1 rejection area (between 1.503 and 2.397). Therefore, there is no first order linear auto-correlation in the multiple linear regression data.

4.1.4. Test the multicollinearity

The information in the table 4.2 allows to check the multicollinearity in the multiple linear regression model. Tolerance should be more than 0.1 (or VIF<10) for all variables to have a negligible multicollinearity in the model. The result shows that all the variables are having a VIF value less than 10 so that, a multicollinearity issue does not exist in the data set.

Table 4.2: Coefficients and collinearity statistics of the variables

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	1.232	.413		2.983	.004		
	Air to coal ratio*	33793.320	3348.387	1.279	10.092	.000	.140	7.146
	PA Pressure*	-.002	.000	-.339	-4.848	.000	.460	2.175
	PA temp*	-2.144E-9	.000	-.142	-1.778	.079	.351	2.846
	SA Pressure*	-.132	.186	-.073	-.710	.480	.210	4.752

a. Dependent Variable: Fly Ash LoI

Results of above tests verify that no issues related to violation of assumptions of the regression model. Therefore, the regression analysis can be carried out.

Estimated regression model can be expressed by using original variables as follows

$$LoI = 1.232 + 33793.32ACR^{-3.742} - 0.002PAP^{3.0692} - 2.144 \times 10^{-9}PAT^{3.9352} - 0.132SAP^{1.5261}$$

Above results show that all independent variables are within 5% significant level indicating that all independent variables affect the fly ash LoI. The magnitude of the impact of each independent variable on dependent variable is shown by their coefficients.

4.1.5. F test

The next step of the regression analysis is the F-test which shows whether independent variables are jointly significant. The result of the test is shown in the table 4.3. The hypothesis related to F-test is set up as follows.

H_0: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$

H_1: $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq 0$

$F_{cal} > F_{cv}$

91.315 > 2.71 ⟶ Reject H_0

According to the result of the F-test H_0 is rejected at 5% significant level indicating that all coefficients of the independent variables are jointly significant so that, independent variables have a joint impact on the dependent variable.

Table 4.3: F test

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	137.863	4	34.466	91.315	.000[b]
	Residual	30.195	80	.377		
	Total	168.059	84			

a. Dependent Variable: Fly Ash LoI

b. Predictors: (Constant), SA Pressure*, PA Pressure*, PA temp*, Air to coal ratio*

4.2. **Analysis of the results**

4.2.1. **Air to coal ratio**

As air to coal ratio is significant within 5% significant level it has an impact on fly ash LoI. From the linearity analysis it is found that air to coal ratio does not have a linear relationship with fly ash LoI. Therefore, it was needed to transform and the modified variable of air to coal ratio value (Air to Coal Ratio*) is used for the analysis.

$$Air\ to\ Coal\ Ratio^{*} = Air\ to\ Coal\ Ratio^{-3.742}$$

From the multiple linear regression analysis, it is found that Air to Coal Ratio* is having a positive impact on fly ash LoI with a coefficient of 33793.32. Therefore, Air to Coal Ratio will have a negative impact on fly ash LoI. In other words, increase in air to coal ratio will cause to reduce the fly ash LoI value. Air to coal ratio can be increased either increasing the air flow or decreasing the coal flow to the boiler.

When excess air is supplied to the combustion process it helps for the complete combustion and reduces the unburned carbon percentage (LoI) in the flue gas. Since excess air causes to reduction of boiler efficiency, it is needed to supply required amount of excess air that will give the desired level of fly ash LoI. Table 4.4 shows the variation of fly ash LoI for different air to coal ratio values keeping other variables at their maximum limits. From the table 4.4 it is found that air to coal ratio should be greater than 8.9 to give fly ash with less than 5% LoI value. The maximum air flow that can be obtained from the unit 1 boiler of Lakvijaya power station is 1000 T/h. Therefore the coal flow should be less than 112 T/h to give an acceptable level of LoI in fly ash eventhough the coal mills are designed to supply coal at a rate of 120 T/h. If the calorific value of coal is sufficiently higher it is possible to reach 300 MW with a coal rate of 112 T/h but the load has to be reduced if the coal quality is not good enough to obtain fly ash with less than 5% LoI value. Air flow has to be increased to 1128 T/h to obtain good quality fly ash if the unit is operating with a coal flow of 120 T/h.

Table 4.4: Variation of fly ash LoI for different air to coal ratio values

Air flow (T/h)	Coal flow (T/h)	Air/Coal Ratio	PAP (kPa)	PAT (^0C)	SAP (kPa)	LoI %
1000	120	8.33	11.5	150	2.4	7.72
1000	118	8.47	11.5	150	2.4	6.98
1000	116	8.62	11.5	150	2.4	6.28
1000	114	8.77	11.5	150	2.4	5.61
1000	112	8.93	11.5	150	2.4	4.97

4.2.2. **Furnace Pressure**

Furnace pressure neither shows a linear relationship nor a nonlinear relationship with fly ash LoI. Therefore the variable did not consider for the multiple linear regression analysis.

According to the literature, decreasing of furnace vacuum pressure would support for the complete combustion as it let the coal-air mixture to remain sufficient time inside the furnace. Analysis of actual data of Lakvijaya power station for a one month period and the furnace pressure set point did not change much within the period, the obtained data did not show any relationship between furnace pressure and fly ash LoI. Due to turbulence nature inside the furnace it is hard to measure the vacuum pressure of furnace accurately. There are four pressure transmitters installed at four different locations and median value of those four transmitters is obtained as the furnace pressure. This highly changing furnace pressure reading would also cause to give this discrepancy between the analysis and the literature.

4.2.3. **Primary air pressure**

Primary air is used to convey pulverized coal from the coal mills to the furnace. According to the multiple linear regression analysis, primary air pressure is significant at 5% significant level. From the linearity check it is found that the primary air pressure does not have a linear relationship with fly ash LoI. Therefore, it is needed to transform and the modified variable of primary air pressure value (primary air pressure *) is used for the analysis.

$$Primary\ Air\ Pressure^{*} = Primary\ Air\ Pressure^{3.0692}$$

From the multiple linear regression analysis, it is found that primary air pressure* is having a negative impact on fly ash LoI with a coefficient of -0.002. Therefore, primary air pressure also will have a negative impact on fly ash LoI. In other words, increase in primary air pressure will cause to reduce the fly ash LoI value. Primary air pressure can be increased by increasing the pitch position of the primary air fan blades. Maximum primary air pressure can be obtained when the primary air fan blade pitch is at fully opened position. Primary air pressure can't be increased beyond this value and the capacity of primary air fan is the limiting factor. Increasing of the primary air pressure will cause to direct the air-coal mixture into the firing area of the furnace effectively. If the primary air pressure is reduced, pulverized coal particles will tend to escape with the flue gas without burning, causing unburnt coal particles to be present in the fly ash.

Table 4.5 shows the variation of fly ash LoI value when changing primary air pressure keeping other variables at their maximum values. According to the table 4.5 primary air pressure has to be increased up to 14 kPa to obtain good quality fly ash. Maximum primary air pressure that can be obtained with prevailing conditions in unit 1 boiler of Lakvijaya power station is 11.5 kPa. Therefore it is needed to increase the capacity of primary air fans to obtain good quality fly ash if the coal rate is at its maximum level.

Table 4.5: variation of fly ash LoI value for different primary air pressure values

Air flow (T/h)	Coal flow (T/h)	Air/Coal Ratio	PAP (kPa)	PAT (^{0}C)	SAP (kPa)	LoI %
1000	120	8.33	11.5	150	2.4	7.72
1000	120	8.33	12	150	2.4	7.22
1000	120	8.33	12.5	150	2.4	6.67
1000	120	8.33	13	150	2.4	6.08
1000	120	8.33	13.5	150	2.4	5.43
1000	120	8.33	14	150	2.4	4.73

4.2.4. **Primary air temperature**

There are two primary air supplies to the coal mills as hot primary air and cold primary air. Cold primary air supply is directly taken from the outlet of the primary air fan while the hot primary air supply is taken after a heat exchanging process with the flue gas. Controlled mixing of hot and cold primary air is used to supply the primary air to the coal mills with the required temperature.

Primary air is used to convey pulverized coal from the coal mills to the furnace. According to the multiple linear regression analysis, primary air temperature is significant at 5% significant level. From the linearity check it is found that the primary air temperature does not have a linear relationship with fly ash LoI. Therefore, it was needed to transform and the modified variable of primary air temperature value (primary air temperature *) is used for the analysis.

$$Primary\ Air\ temperature^{*} = Primary\ Air\ temperature^{3.9352}$$

From the multiple linear regression analysis it is found that primary air temperature * is having a negative impact on fly ash LoI with a coefficient of 2.144×10^{-9}. Therefore, primary air temperature also will have a negative impact on fly ash LoI. In other words, increase in primary air temperature will cause to reduce the fly ash LoI value. Primary air temperature can be increased by mixing more hot primary air with the cold primary air. It is not advisable to increase the primary air temperature at the inlet of the coal mill beyond 200 °C due to fire risk inside the coal mill. Primary air temperature at the outlet of the coal mill should be less than 75 °C to avoid pre combustion of pulverized coal before entering to the furnace. Since 75 °C limit of the coal mill outlet reaches before the 200 °C limit at the coal mill inlet, coal mill outlet primary air temperature is the limiting factor to control the primary air temperature.

Increasing of primary air temperature will help to reach the ignition temperature quickly and make a favorable environment for the complete combustion inside the furnace. Therefore increasing of primary air temperature reduces the presence of unburnt coal particle in the fly ash thereby reducing the fly ash LoI value.

Table 4.6 shows the variation of fly ash LoI value when the primary air temperature is changing by keeping the other parameters at their maximum values. According to the table 4.6 primary air temperature has to be increased beyond 195 ºC to obtain good quality fly ash. Most of the time mill outlet temperature reaches to 75 °C limit when the primary air temperature is around 150 °C unless the moisture content of the coal is higher. Therefore it is not possible to obtain good quality fly ash only by increasing the primary air temperature. But keeping the primary air temperature at its highest level is favorable to obtain good quality fly ash.

Table 4.6: Variation of fly ash LoI for different primary air temperature values

Air flow (T/h)	Coal flow (T/h)	Air/Coal Ratio	PAP (kPa)	PAT (˚C)	SAP (kPa)	LoI %
1000	120	8.33	11.5	150	2.4	7.72
1000	120	8.33	11.5	160	2.4	7.28
1000	120	8.33	11.5	170	2.4	6.76
1000	120	8.33	11.5	180	2.4	6.13
1000	120	8.33	11.5	190	2.4	5.39
1000	120	8.33	11.5	195	2.4	4.98

4.2.5. **Burner angle**

Furnace of the Lakvijaya power station is equipped with a tilting burner that allows changing the angle of directing coal-air mixture and secondary air supply. This arrangement facilitates to control the superheated steam temperature. Increasing of tilting angle leads to increase of superheated temperature and vice versa.

Burner angle neither shows a linear relationship nor a nonlinear relationship with fly ash LoI. Therefore this variable is not considered in the multiple linear regression analysis.

According to the literature, decreasing of burner angle would support for the complete combustion as it let the coal-air mixture to remain a sufficient duration inside the furnace. Since this variable is primarily used to control the superheated steam temperature, the effect on fly ash LoI is not predominant from the data set obtained. Therefore this variable is also dropped from the multiple linear regression analysis.

4.2.6. **Secondary Air Pressure**

Secondary air is used to supply oxygen (air) that is needed for the combustion. According to the multiple linear regression analysis, secondary air pressure is significant within 5% significant level. From the linearity check it is found that the secondary air pressure does not have a linear relationship with fly ash LoI. Therefore, it was needed to transform and the modified variable of secondary air pressure value (secondary air pressure *) is used for the analysis.

$$Secondary\ Air\ Pressure^{*} = Secondary\ Air\ Pressure^{1.5261}$$

From the multiple linear regression analysis it is found that secondary air pressure* is having a negative impact on fly ash LoI with a coefficient of -0.132. Therefore, secondary air pressure also will have a negative impact on fly ash LoI. In other words, increase in secondary air pressure will cause to reduce the fly ash LoI value. Secondary air pressure can be increased by increasing the pitch position of the forced draft fan blades. Maximum secondary air pressure can be obtained when the forced draft fan blade pitch is at fully opened position. Secondary air pressure can’t be increased beyond this value and the capacity of forced draft fan is the limiting factor. Increasing of the secondary air pressure will cause to direct the air supply into the firing area of the furnace effectively causing complete combustion of coal.

Table 4.7 shows the variation of fly ash LoI by changing secondary air pressure while keeping the other variables at their maximum values. According to the table 4.7 secondary air pressure has to be increased to 8.5 kPa to obtain good quality fly ash. Since the rated value for secondary air pressure is 2.5 kPa, it is not a feasible option to increase the pressure up to 8.5 kPa. But keeping the secondary air pressure as high as possible is favorable to maintain the fly ash LoI value in a low range.

Table 4.7: Variation of LoI for different secondary air pressure values

Air flow (T/h)	Coal flow (T/h)	Air/Coal Ratio	PAP (kPa)	PAT (˚C)	SAP (kPa)	LoI %
1000	120	8.33	11.5	150	2.4	7.72
1000	120	8.33	11.5	150	3	7.52
1000	120	8.33	11.5	150	3.5	7.33
1000	120	8.33	11.5	150	4	7.13
1000	120	8.33	11.5	150	4.5	6.91
1000	120	8.33	11.5	150	5	6.68
1000	120	8.33	11.5	150	5.5	6.44
1000	120	8.33	11.5	150	6	6.19
1000	120	8.33	11.5	150	6.5	5.93
1000	120	8.33	11.5	150	7	5.65
1000	120	8.33	11.5	150	7.5	5.37
1000	120	8.33	11.5	150	8	5.07
1000	120	8.33	11.5	150	8.5	4.76

4.2.7. **Secondary Air Temperature**

Secondary air which is supplied from the forced draft fan goes through the Air Pre Heater (APH) to recover the heat of flue gas. Heated secondary air supplied to the furnace for the combustion after heat recovery.

Secondary air temperature neither shows a linear relationship nor a nonlinear relationship with fly ash LoI. Therefore this variable is not considered in the multiple linear regression analysis.

According to the literature, increasing of secondary air temperature will help to reach the ignition temperature quickly and make a favorable environment for the complete combustion inside the furnace. Therefore an increase of secondary air temperature reduces the presence of unburnt coal particle in the fly ash thereby reducing the fly ash LoI value. There is no direct method to control the secondary air temperature and increasing of secondary air temperature will always increase the boiler efficiency as it comes through a heat recovery process. Frequent soot blowing of the APH will increase the heat transferring rate so that the secondary air temperature increases.

05. CONCLUSIONS AND RECOMMENDATIONS

Multiple linear regression results show that four variables are having a considerable impact on fly ash LoI. Out of these variables air to coal ratio is having the highest impact on fly ash LoI, following primary air pressure, primary air temperature and secondary air pressure respectively.

Based on the analysis, it is recommended to maintain the air to coal ratio greater than 8.3 to obtain good quality fly ash. Since the maximum air supply capacity of unit 1 boiler of Lakvijaya power station is around 1000 T/h, maintaining above ratio in recommended limit is not possible when the total coal flow is greater than 112 T/h. Therefore, it is recommended to increase the total air flow up to 1130 T/h to obtain good quality fly ash at the rated coal flow of 120 T/h.

It is identified that the primary air pressure is not sufficient to maintain a healthy LoI value in fly ash at the higher coal rates. Therefore, increasing the primary air pressure up to 14 kPa by increasing the capacity of primary air fans can be recommended.

Primary air temperature is allowed to increase up to 200 °C subjected to maintaining the coal mill outlet temperature less than 75 °C. The analysis shows that increasing of primary air temperature helps to reduce the fly ash LoI level. Therefore, the operator can be advised to maintain the highest possible primary air temperature.

Secondary air pressure shows a week relationship with fly ash LoI although the LoI level slightly reduced when the secondary air pressure is increased. Increasing the capacity of forced draft fans is needed to increase the secondary air pressure. Since the impact on fly ash LoI from secondary air pressure is comparatively low, it is not economical to increase the capacity of forced draft fans to reduce the fly ash LoI level. Therefore, the operator should be advised to maintain a higher secondary air pressure set point without introducing a capacity addition to the system.

References

[1] Li Jun, Dong Jiancong, and Li Chun. “The Analysis of the Unburned Carbon in Fly Ash for Tangentially Pulverized Coal-Fired Boiler Based on Factor Analysis Method”, *Asia-PacificPower and Energy Engineering Conference (APPEEC)*,2011.

[2] Gabriel Vladut, Liana SimonaSbirna, Sebastian Sbirna, Clement IonescuandClementinaSabina Moldovan. “CFD simulation of controlling nitrogen oxides emissions reduction and loss-on-ignition for a corner-fired pulverized-coal furnace”, *2012 16th International Conference on System Theory, Control and Computing (ICSTCC)*, 2012.

[3] Ya-qing Zhu, Feng-ping Pan and Shi-he Chen. “Research on methods of forecasting unburned carbon content in the fly ash from coal-fired power plant”,*2013 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 2013

[4] Weijing Shi, Jingcheng Wang, Yuanhao Shi and Zhengfeng Liu. “Clustering LS-SVM Models for the Prediction of Unburned Carbon Content in Fly Ash”,*The 27th Chinese Control and Decision Conference (CCDC)*, 2015

[5] Weijing Shi, Jingcheng Wang, Yuanhao Shi and Guanglei Zhao. “Online Prediction of Unburned Carbon Content in Fly Ash with Clustering LS-SVM Models”,*2015 34th Chinese Control Conference (CCC)*, 2015

[6] Operation manual of Lakvijaya power station.

[7] Operation manual of ash handling system of Lakvijaya power station

[8] Operation and maintenance manual of HG-1025/17.3-YM boiler model, Harbin boiler co. ltd

[09] http://www.statisticalsolution.com

[10] http://www.iea-coal.org.uk/documents/82354/7536/Reducing-carbon-in-ash

[11] http://en.wikipedia.org

[Appendix-A: Coal quality parameters]

Parameter	SYMBOL	UNIT	DESIGN COAL	CHECK COAL 1	CHECK COAL 2
High calorific value as received basis	Qv.ar	MJ/kg	26.4	25.3	24.7
Industrial analysis					
Total moisture content as received basis	Mt	%	12	16	19
Moisture content as air dried basis	Mad	%		6	
Ash content as received basis	Aar	%	11	15	10.1
Volatile matter content as received basis	Var	%	27	25	24.9
Elementary analysis					
Carbon content as received basis	Car	%	65	60	60.5
Hydrogen content as received basis	Har	%	3.8	3.6	3.4
Oxygen content as received basis	Oar	%	6.2	3	5.1
Nitrogen content as received basis	Nar	%	1.5	1.7	1.4
Sulphur content as received basis	Star	%	0.5	0.7	0.5
Grindability factor	HGI		50	42	50
Ash deformation temperature	DT	℃			
Ash softening temperature	ST	℃	1250	1170	1250

Source: Operation manual,Lakvijaya Power Station

[Appendix-B: Sample of data set obtained]

Date/Time	Power (MW)	Coal rate (T/h)	Air flow(T/h)	Furnace Pressure (Pa)	PA Pressure (kPa)	PA temp(°C)	Burner angle(°)	SA Pressure (kPa)	SA Temp(°C)	LoI(%)
1/26/17 00:00	301.388	110.65	1030.124	-56.627	10.636	167.62425	11.652	2.445	329.815	5.3
1/25/17 16:00	298.751	111.291	1012.849	-83.437	10.642	162.1045	11.638	2.406	326.107	4.91
1/25/17 08:00	298.943	109.217	1012.472	-68.872	11.208	153.195	11.661	2.466	338.413	3.86
1/25/17 00:00	299.053	110.013	1016.517	-66.296	11.101	160.242	4.474	2.553	336.869	4.48
1/24/17 16:00	274.416	101.266	962.222	-30.201	11.029	154.5025	13.62	2.47	331.893	3.21
1/24/17 8:00	223.412	84.021	831.54	-73.193	11.608	154.59	-9.561	1.716	317.233	3.45
1/24/17 00:00	224.264	83.604	830.15	-73.636	11.27	150.0093333	-9.538	1.759	314.118	3.82
1/23/17 16:00	227.395	86.021	841.402	-56.091	11.345	148.0903333	4.369	1.809	310.366	3.05
1/23/17 08:00	227.972	86.136	833.542	-79.983	11.364	154.9416667	7.234	1.863	332.979	3.72
1/23/17 00:00	227.395	85.907	832.195	-51.287	11.376	146.7433333	7.23	1.887	331.668	3.21
1/22/17 16:00	227.203	85.65	835.922	-41.106	11.684	149.18	7.244	1.825	329.869	3.73

[Appendix-C: Heteroscedasticity Test]

Heteroscedasticity Test: Breusch-Pagan-Godfrey

F-statistic	0.365610	Prob. F(4,80)	0.8324
Obs*R-squared	1.525946	Prob. Chi-Square(4)	0.8220
Scaled explained SS	1.195053	Prob. Chi-Square(4)	0.8789

Test Equation:
Dependent Variable: RESID^2
Method: Least Squares
Date: 12/04/17 Time: 12:51
Sample: 1 85
Included observations: 85

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.588245	0.324437	1.813125	0.0736
AIR_TO_COAL_RATIO_	1787.756	2629.833	0.679798	0.4986
PA_PRESSURE_	-0.000326	0.000275	-1.185710	0.2392
PA_TEMP_	-2.11E-10	9.47E-10	-0.223013	0.8241
SA_PRESSURE_	-0.018665	0.146030	-0.127814	0.8986

R-squared	0.017952	Mean dependent var	0.355236
Adjusted R-squared	-0.031150	S.D. dependent var	0.475176
S.E. of regression	0.482520	Akaike info criterion	1.437434
Sum squared resid	18.62606	Schwarz criterion	1.581120
Log likelihood	-56.09096	Hannan-Quinn criter.	1.495229

H_0: Homoscedasticity
H_1: Heteroscedasticity

$P > \alpha$

$0.8324 > 0.05 \longrightarrow$ Accept H_0

According to BPG test for checking the heteroscedasticity which is one of the violations of assumptions in OLS H0 is accepted at 5% significant level indicating that heteroscedasticity does not exist in the model.