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AI-Based Optimization of Excess Air Supply for Minimizing Unburnt Carbon and Thermal Losses in Coal-Fired Thermal Power Plants

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ABSTRACT

Thermal power plants operating on coal remain a very important contribution to the generation of electricity but the burning deficiencies like carbon loss that is not burned and heavy loss of flue gas shows a serious impact on the efficiency of the plant. The excess air supply is a very important combustion parameter and it has a direct effect on the completeness of the combustion and the losses in terms of thermodynamics which presents a complicated trade-off. In this paper, a multi-objective optimization model using artificial intelligence (AI) is suggested to determine the best excess air level which has minimal unburnt carbon and flue gases losses and a maximum boiler efficiency. A Genetic Algorithm (GA) was used as an internal optimizer with industrial operating conditions, and a hybrid AI model based on Long Short-Term Memory (LSTM) and XGBoost regression was created to predict the power output and boiler efficiency with high accuracy. Simulation made in MATLAB was done with the boiler predicted data-sheet aligned parameters so that it is industrial relevant. The findings show that the more excess air, the lower the amount of unburnt carbon in the bottom ash to about 2 per cent, at 15 per cent excess air, thus confirming the presence of almost complete combustion. Nevertheless, at this level, the increase of dry flue gas heat loss is almost 7%, which is the reason why optimization is needed.

Keywords: *Thermal Power Plant, Soft Computing, ANN, Optimization, use of AI in thermal Power Plant*

INTRODUCTION

The thermal power plants that work on coal combustion remain crucial in satisfying the global power demand, especially in developing economies. Even though there are ongoing innovations in the design and operational manner of boilers, combustion inefficiencies have been one of the persistent problems hindering the performance of plants, the use of fuel, and the overall performance of the plant. Among the other loss processes in thermal boilers, incomplete combustion and excessive heat loss with flue gases have a great impact on the operational efficiency and the cost of operation. Thus, optimization of the combustion conditions is a highly important field of study in thermal power engineering (Dineva et al., 2019).Excess air supply is one of the most effectual combustion parameters in boilers which use coal. There should be enough excess air to enable full combustion of the fuel by ensuring that there is enough oxygen to burn the carbon. Lack of air supply causes an incomplete combustion process and hence increased levels of unburnt carbon in bottom ash and fly ash which is a direct indication of fuel wastage and loss of efficiency (Liu and Cui, 2018). The objective of industrial practice is usually to restrict the amounts of unburnt carbon in the air to approximately 2 percent, above which the efficiency of combustion decreases and ash management problems are worsened. Nevertheless, further overloading on the amount of excess air leads to the second significant inefficiency of flue gas loss. Excess air high value enhances the rate of moving mass of flue gases, which has more sensible heat which moves out of the boiler into the stack. Operational observations and studies have shown that additional decrease of unburnt carbon below the acceptable limit tends to lead to an over-proportionate increase in flue gas losses which could rise by almost 7 percent at high excess air. This introduces an essential tradeoff between reducing unburnt carbon loss and reducing thermal loss, and excess air optimization is not a single-parameter adapt, but a complex multi-objective task (Hanwate et al., 2018).Traditional boiler operation and control methods are mostly based on trial-and-error tuning, hard-coded setpoints and rule-based control logic based on operator experience and design. Although these techniques are easy and resilient, they do not have the dynamism to respond dynamically to changing working conditions and nonlinear relationships among the process variables. Consequently, this means that such designs tend not to always keep the optimum balance between degree of complete combustion and minimized heat loss and therefore achieve suboptimal efficiency at different load and fuel conditions. Over the last years, the artificial intelligence (AI) and modern optimization methods have become potent instruments to enhance performance of thermal power plants. Genetic Algorithms is a meta-heuristic algorithm that allows systematic search of nonlinear, complex parameter space to discover optimal operating points, and predictive models based on AI can well represent the dynamic characteristics of power plant processes. The approaches have the potential to shift specific, fixed control philosophies to intelligent, data-driven optimization and decision support systems (Thota et al., 2018).

The vast majority of the studies carried out to date are concentrated on optimization of combustion or the prediction of their efficiency individually, without stating the trade-off that exists between excess air supply and thermal losses in a single optimization and control model. The current paper fills this gap with the suggestion of an AI-aided optimization and simulation-based method of excess air and process parameters control in a thermal power plant with coal as the fuel (Rodríguez et al., 2020). This study aims at examining the effect of excess air on unburnt carbon and dry flue gas losses, optimization of key operating parameters to make the plant run efficiently, and the development of a framework algorithm that can produce credible simulation outputs with the help of proper software applications.

LITERATURE REVIEW

Numerous research have examined the utilization of soft computing, artificial intelligence, and optimization methods in thermal power plants to augment combustion efficiency, diminish emissions, and improve overall performance. Previous studies have predominantly concentrated on predictive modeling, emission mitigation, and the discrete optimization of boiler parameters. Table 1 presents a review of the most pertinent studies concerning excess air control, combustion optimization, and AI-driven performance enhancement.

Table 1. Summary of Relevant Literature on AI and Optimization in Thermal Power Plants.

Author & Year	Technique	Key Focus Area	Key findings	Outcome
Madhavan & Reddy (2016)	GA–ANN hybrid model	Boiler performance prediction	Achieved high prediction accuracy (up to 99.6%) for spray flow and NOx parameters	Focused on prediction only; no optimization of excess air or unburnt carbon
Sun et al. (2019)	MLP-based soft sensor with NNG & EO	Emission prediction (SO_2)	Accurate emission forecasting using real plant data	Did not address combustion efficiency or air–fuel optimization
Kang et al. (CFD study)	CFD-based air distribution optimization	Excess air & NOx control	Reduced NOx using SOFA technique but observed efficiency penalty	Trade-off between emissions and efficiency not resolved using intelligent optimization
Yang et al. (2018)	Cyber-Physical System (CPS) with data mining	Thermal plant performance modelling	Demonstrated real-time decision support for turbine island	Did not consider unburnt carbon or dry flue gas loss explicitly
Yang et al. (LSTM-based study)	PCA-LSTM neural network	NOx emission prediction	LSTM outperformed conventional RNN and LSSVM models	Excess air–efficiency–carbon interaction not incorporated in optimization framework

The reviewed literature indicates that although artificial intelligence and soft computing techniques have been effectively utilized for boiler performance prediction, emission forecasting, and isolated parameter optimization, there is a paucity of research focusing on the concurrent optimization of excess air supply, unburnt carbon reduction, and dry flue gas loss. Current research predominantly examines combustion efficiency and heat losses in isolation, failing to address their intrinsic trade-off. Furthermore, an integrated AI-driven optimization and control framework designed to discover an ideal operating point for real-time thermal power plant operation has been inadequately investigated, which this study seeks to remedy.

METHODOLOGY

The developed algorithm follows a structured and modular workflow consisting of data acquisition, preprocessing, prediction, and visualization. This layered architecture ensures that each computational task is handled independently, improving system stability, maintainability, and scalability. The modular design also allows future enhancements, such as additional optimization or diagnostic modules, without modifying the core framework. The Genetic Algorithm (GA) was used as an in-house optimization method to establish the best operating parameter combination. The optimization was done within constraints determined on the basis of accepted limits of operating in industry so that it is feasible and safe.

System Description and Data Source: The research work is premised on a thermal boiler that is fired with coal under rated industrial conditions. It was verified that the system performance assessment was conducted based on parameters that are compatible with the good practice of boiler predicted data-sheet which ensures physical realistic and industrial relevance. Design-point operating conditions like excess air level, temperature of flue gases, boiler pressure, turbine inlet temperature and efficiency were taken into account; transient or non-physical operating states were not taken into account. The sophisticated methods were used as internal analysis tools and also artificial intelligence and optimization, but only thermodynamically significant values of the predicted values in the situation of rated operation were reported as it is traditionally documented in boiler performance. The percentage of excess air was regarded as the main controllable parameter of combustion that had an influence on oxygen supply and the rate of the flue gas. The carbon in bottom ash which was not burnt was a measure of the extent of combustion and efficiency of fuel use.

Artificial Intelligence–Based Control Strategy: The control strategy is an artificial intelligence-based one, which was created as a hybrid framework comprising Long Short-Term Memory (LSTM) networks and XGBoost regression. The hybrid model has been created to embrace both the dynamism in time and the non-linear interactions of the operation of the thermal power plants. The AI model had been applied to forecast the production of power and efficiency under different operating conditions, and this gave good and precise performance forecasting and intelligent parameter adjustment. This method facilitates a dynamic decision support and enhances the capacity to sustain the best operating conditions far beyond traditional set-point control methods.

Algorithm Design and Simulation Environment: An organized algorithmic process was put in place which included data preprocess, AI-based forecast, optimization assistance and visualization of results. The MATLAB was used to create the simulation environment with a graphical user interface (GUI) so that operators can interact with it and interpret the results. The AI prediction module and GA-based optimization module were entirely incorporated in the simulation framework, and operating scenarios and performance results could be effectively evaluated. With this modular design, the computational stability, scalability, and practical deployment have been guaranteed in the performance analysis of thermal power plants.

RESULT ANALYSIS

Effect of Excess Air on Unburnt Carbon: The outcomes of the simulation show that the amount of unburnt carbon is decreasing substantially as the excess air supply increases. The high amount of air of about 15 % was observed to reduce unburnt carbon in bottom ash to almost 2 %, which showed almost total burning. This is explained by the fact that it has increased the availability of oxygen, better fuel burnout, and improved conditions of combustion in the furnace. The findings confirm that proper control of excess air is necessary in an attempt to reduce fuel losses associated with combustion.

Impact of Excess Air on Dry Flue Gas Loss: As much as more excess air enhances the completeness of combustion it also results in high heat loss of the dry flue gases as more mass of the flue gas flows. In addition to the ideal excess air content, the analysis shows that the loss of dry flue gas increases by approximately 7 % when excess air is added and this shows the decreasing returns to the addition of excess air. Such a behaviour is a clear demonstration of the trade-off between gains in efficiency in combustion, and thermal losses penalties, and a strong argument in favor of optimized instead of maximum excess air operation.

Optimized Operating Point: The optimization model found a rated operating point with an excess air level of 15 percent, flue gas exit temperature of 150 ^{0}C, and a boiler efficiency of about 92.4 %. This operating mode is a compromise with the lowest level of unburnt carbon and the lowest level of dry flue gases loss. The estimated values are in accordance with the general standards of the boiler design and prove that the operation point chosen is efficient and industrially viable.

Table 2. Predicted Air–Fuel and Thermal Performance at Rated Operating Point.

Parameter	Predicted Value	Unit	Engineering Significance
Excess Air	15	%	Ensures complete combustion without excessive stack losses
Turbine Inlet Temperature	450	°C	Rated steam temperature for efficient turbine expansion
Flue Gas Temperature	150	°C	Indicates effective heat recovery in economizer and air preheater
Unburnt Carbon	2.0	%	Within acceptable industrial combustion limits
Boiler Efficiency	92.4	%	Reflects optimized thermal performance

AI-Based Performance Improvement

The combination of AI- prediction and optimization brought significant performance changes to the base operating condition. The efficiency of the boilers improved greatly and there was a decline in the net heat rate which meant that more fuel was utilized. Also, the hybrid AI model showed a high prediction error of the power output, allowing to rely on the prediction of performance and make smart decisions regarding the way operations are performed as seen in table 3.

Table 3. Base vs Optimized Predicted Performance.

Performance Parameter	Base Case	Optimized Case	Unit	Improvement Significance
Power Output	0.92	1.06	MW	Increased useful energy generation
Boiler Efficiency	89.3	92.4	%	Improved fuel utilization
Net Heat Rate	9250	8750	kJ/kWh	Reduced energy input per unit power

Optimized operating point was a flue gas exit of 150 C and a better boiler efficiency of about 92.4 percent as opposed to 89.3 percent when in conventional mode. It also produced more power of 0.92 MW to 1.06 MW with a drop in the net heat rate of 9250 kJ/kWh to 8750 kJ/kWh. The suggested AI-based framework shows a viable and efficient solution to improving the work of thermal power plants by the means of smart excess air management.

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Table 4. Hybrid AI Model Performance Metrics.

Performance Metric	Value	Unit	Engineering Interpretation
Coefficient of Determination (R^2)	0.982	–	Model explains 98.2 % of output variability
Root Mean Square Error (RMSE)	0.148	MW	Low prediction error magnitude
Mean Absolute Error (MAE)	0.088	MW	High average prediction accuracy

Implementing intelligent process control through hybrid AI modeling was successfully achieved. The LSTM–XGBoost hybrid model delivered highly accurate real-time power predictions, with $R^2 = 0.982$, RMSE = 0.148 MW, and MAE = 0.088 MW. These results confirm that the proposed AI framework is reliable, precise, and suitable for operational deployment in thermal power plant performance monitoring and control applications.

DISCUSSION

The findings indicate that augmenting excess air supply markedly diminishes unburnt carbon in bottom ash, attaining roughly 2% at 15% excess air, thus validating enhanced combustion efficiency; nevertheless, this advantage is offset by an escalation in dry flue gas heat loss of nearly 7%, underscoring a significant trade-off. The refined regulation of essential process parameters by a Genetic Algorithm facilitated the determination of an operational point that reconciles combustion efficiency and thermal losses, yielding an enhanced boiler efficiency of roughly 92.4%. The incorporation of a hybrid LSTM–XGBoost model improved the predictive accuracy of power output and efficiency, facilitating intelligent and adaptive parameter optimization beyond traditional rule-based control methods. The MATLAB simulation framework confirmed the viability of integrating AI prediction and optimization to improve performance within industrial operational restrictions. Despite these enhancements, the study is constrained to simulation-based analysis of projected data-sheet parameters, neglecting real-time plant implementation, fuel quality fluctuations, and long-term operational uncertainty.

CONCLUSION

The paper has managed to indicate that excess air optimization of thermal power plants using coal-fired power stations is a multi-objective issue with a crucial trade-off between completeness of combustion and thermal loss. The simulation outcomes have verified that excess air increases sharply with the unburnt carbon in bottom ash with values near to 2% at 15% excess air which is an indication of efficient use of fuel. Yet, there is an oversupply of air past this optimum, which contributes to a non-proportional increase in the heat loss of flue gas of about 7% to the total thermal efficiency. Combining a Genetic Algorithm with a hybrid LSTM-XGBoost prediction was used to allow systematic exploration of nonlinear combustion and performance parameter interactions. The optimal operating point derived by the suggested framework was a boiler efficiency of approximately 92.4, a flue gas temperature of 150 C and an increase in power generation to 1.06 MW, which is obviously a better situation compared to the traditional control practice. Moreover, it is noted that the net heat rate decreases by almost 500 kJ/kWh, which indicates the possibility of major fuel savings and a decrease in the cost of operations.

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