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Boiler Efficiency Improvement Through Analysis of Losses

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Abstract: ***The increasing demand for electricity, caused by global industrialization and urbanization, necessitates highly efficient energy generation technologies. Coal remains a popular choice due to its abundance and cost-effectiveness. Utility boilers play a pivotal role in this situation, acting as closed systems that process coal and generate steam by transferring heat energy to water. To address the difficulties inherent in boiler systems, a multidisciplinary effort was made to identify and thoroughly study their operating aspects. This project aims to discover and quantify the effects of each component influencing boiler performance, with a particular emphasis on predicting their values for user-specified loads. The successful execution of derived techniques is critical in reducing heat losses across various thermal components in the boiler system. By improving solutions, aberrant behavior can be avoided. Two approaches, namely data mining-based clustering and neural network-based clustering, were utilized to extract essential insights from thermal data. Furthermore, multiple regression analysis was applied to predict heat absorption patterns. Insights gleaned from clustered patterns enable the definition of optimal set points, which play a crucial role in enhancing operational efficiency and promoting sustainability in power generation.***

Keywords: Boiler Efficiency, Coal Flow Rate, Burner Tilt, Neural Network, Heat Loss, Regression Analysis, Thermal Power Plant, Energy Optimization

1. Introduction

Boilers are critical components in industrial processes, providing the necessary steam for power generation, heating, and various other applications. Their efficiency directly impacts operational costs, energy consumption, and environmental emissions. As energy demands and environmental concerns rise globally, improving boiler efficiency has become a priority for industries aiming to reduce fuel consumption and minimize greenhouse gas emissions. Boiler efficiency is the ratio of useful heat production to total energy input. While modern boilers are meant to be very efficient, a variety of variables can cause energy losses, resulting in diminishing efficiency over time. Understanding and managing these losses is critical for improving boiler performance.

Natural circulation boilers have become a vital part of several industrial energy sectors over the last few decades, owing to their efficient and uncomplicated steam generation procedure. These boilers do not use mechanical pumps to circulate water, instead depending on the natural convection currents generated during the heating process. This not only streamlines the design, but also increases reliability and lowers maintenance costs. Despite their extensive use, there is still a large gap between the changing requirements of industrial processes and the design approaches available for natural circulation boilers. Industries are constantly looking for more efficient, cost-effective, and adaptable boiler systems to meet strict energy and environmental laws.

Thermal modeling of natural circulation boiler components under high-temperature and high-heat flux circumstances is a significant problem in their design and optimization. The complexity are especially evident in the analysis of evaporator tubes (riser tubes), where the presence of a multi-phase flow regime, the possibility of critical heat flux (CHF), and the accompanying dangers of flow instabilities and tube burnout provide considerable obstacles. Several other flow regimes may exist inside the riser tubes, including subcooled flow, bubbly flow, slug flow, annular and mist flow, and eventually single-phase vapor.

The occurrence of departure from nucleate boiling (DNB) following the bubbly flow region results in a sharp reduction in the heat transfer coefficient. This phenomenon is attributed to high heat flux at comparatively low-quality steam in the flow. In mist flow, the wall-to-fluid heat transfer process is made up of single-phase vapor convection and scattered bubble interactions with the tube walls. This sort of boiling is referred to as dispersed flow film boiling (DFFB).

2. Literature Review

In the consideration of water circulation, while there is a considerable body of work on natural circulation boilers, there is a notable scarcity of thermal design concepts that particularly address the riser-downcomer system of industrial steam generators. Kim et al. (2009) developed a design technique for a steam boiler's riser-downcomer circuit based on constructal theory. Their approach identified the ideal design point as the highest point of mass flux through the riser-downcomer circuit, as well as the optimal number of riser tubes, with total water volume acting as a design constraint.

Discussions concerning the appropriate choice of circulation ratio for natural circulation boilers are prevalent. Al-Anizi (2012) suggested a circulation ratio range between 5 to 60 for low-pressure boilers. Ganapathy (2013) employed numerical simulations on a packaged D-type boiler to investigate the required heat flux for a specific steam production rate at a predefined circulation ratio. Tucakovic et al. (2007) observed that for natural circulation steam boilers with rifled evaporating tubes, the mass flux rose as the boiler load decreased. Lo et al. (1990) investigated natural circulation boilers and discovered that, under steady-state conditions, the size of the downcomer tubes had no significant effect on the operation of the boiler circuit.

Existing two-phase flow models for natural circulation systems have primarily been developed for small-scale applications such as computer circuit cooling and solar water heaters. Gartia et al. (2006) used a steady-state, one-dimensional homogeneous model to predict the mass flow rate along a natural circulating loop in a nondimensional manner. Sudheer et al. (2018) utilized a one-dimensional, homogeneous equilibrium technique to analyze the steady-state behavior of a two-phase natural circulation loop under atmospheric and sub-atmospheric pressures. The analysis revealed that inlet flow temperature, pressure, and heat flux exerted significant influences on the thermo-hydraulic properties of the loop.

Paepe et al. (2014) conducted a thorough investigation into the measurement setup and instruments utilized to calculate boiler efficiency. They assessed several measurement equipment, including absolute and differential types, emphasizing on accuracy and overall impact on the results. Furthermore, Chungen et al. enhanced the air-fuel Weighted Sum of Gray Gas Model (WSGGM) with a focus on improving accuracy, completeness, and implementation in Computational Fluid Dynamics (CFD) simulations.

Moreover, data-driven approaches have been utilized for optimization. Andrew Kusaik & Zhe Song (2008) explored clustering-based performance optimization of boiler-turbine systems. Shieh et al. created an adaptive data-driven thermal efficiency estimator for multi-fuel boilers using statistical identification of important variables, allowing the application of a model-based controller to improve boiler efficiency.

3. Experimental Setup and Methodology

1) *Revomax RXA 03 Boiler Setup*

The main goal of this research is to create a control system that uses image processing and soft computing approaches to enable fast and fuel-efficient combustion. The experimental setup includes a 25-litre diesel-fired boiler that serves as the foundation for creating and executing the suggested control system. The Revomax RXA03, an adaptive and automatic steam-producing boiler intended for safe and reliable operation, was employed in the research. It has a specially built furnace and combustion system that can burn heavy oils while also providing fuel flexibility between light and heavy oils.

The furnace component of the boiler contains a membrane coil, which is essentially a helical coil surrounded by spacer strips. This coil serves as the location where fuel is burned to produce heat. The coil is encased within a jacket assembly that consists of an inner jacket and an outer jacket. A refractory cover is installed on the top side of the helical coil to provide additional insulation.

2) *Fuel Supply and Burner Assembly*

Fuel is supplied to the boiler by a gear-type positive displacement pump. During normal operation, fuel pressure is maintained at 12 kg/cm² to supply fuel at a rate of 21 liters per hour. The burner assembly's primary components are the Burner Rod, Flame Cone, Diffuser Plate, and Electrodes. The flame cone and diffuser plate improve the mixing of combustion air and fuel, which is essential for efficient and steady combustion. The adjustable guide pipe allows for vertical movement to fine-tune the location of burner components.

3) *Feed Water Pump and Pitot Tube*

The feed water pump is a reciprocating single-acting pump that supplies water to the boiler, driven by a three-phase electric motor through a V-belt system. It features a water chamber, crankcase, crankshaft, and a surge suppressor. A Pitot tube assembly is used to monitor air velocity in the boiler system, ensuring efficient fuel usage. Bernoulli's equation connects stagnation pressure and static pressure to fluid density and flow velocity.

4) *Formal Model of Utility Boiler*

Mathematics expressions are used to create a formal model of the utility boiler system. This system visualizes the input and output characteristics of the whole set of thermal components. The computation relies on key parameters: Coal Flow (CF), Inlet/Outlet Pressure (P), Inlet/Outlet Temperature (T), Higher Heating Value (HHV), and Specific Heat (Cp).

Polynomial equations were generated to model interactions. The linear polynomial P1(Xi) = a0 + a1Xi, quadratic polynomial P2(Xi) = a0 + a1Xi + a2Xi^2, and cubic polynomial P3(Xi) = a0 + a1Xi + a2Xi^2 + a3Xi^3 were used. The prediction accuracy showed minimal variances when considering a linear relationship between load and expected values.

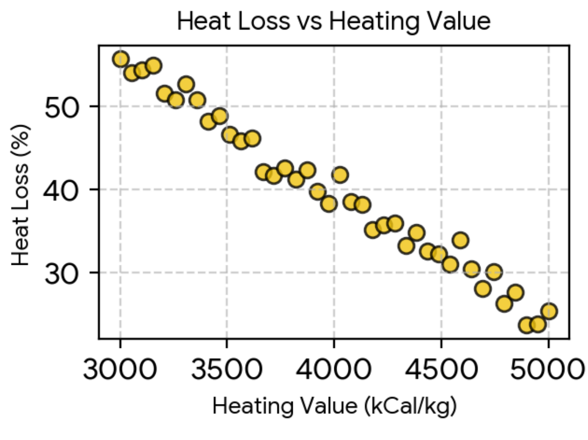

Figure 1: Heat Loss (%) With Respect To Heating Value

4. Results and Discussion

1) *Enthalpy and Energy Flow for Various Capacities*

The steam generation process follows a standard procedure with specific inlet and outlet values required for basic heating in the thermal components. The furnace heat absorptions were calculated using voluminous data from the power plant. The calculated values of heat absorption and enthalpy for various boiler capacities (250 MW, 300 MW, 400 MW, 500 MW, and 550 MW) are critical for understanding the system's performance. The equations contained in the basic terminology of thermal power plants generate steam, which results in a formal boiler model.

Table I: Computed Values FOR 250 MW Capacity Boiler

Component	T_in (°C)	T_out (°C)	P_in	P_out	H_in (kcal)	H_out (kcal)
Furnace	150	250	21	19	1300	1600
Economiser	100	175	19	18	1000	1400
Heat Opt.	80	102	15	17	750	1200

Table II: Computed Values FOR 300 MW Capacity Boiler

Component	T_in (°C)	T_out (°C)	P_in	P_out	H_in (kcal)	H_out (kcal)
Furnace	170	360	21	19	1500	1800
Economiser	112	165	19	18	1300	1500
Heat Opt.	85	111	16	16	1200	1100

Table III: Computed Values For 500 MW Capacity Boiler

Component	T_in (°C)	T_out (°C)	P_in	P_out	H_in (kcal)	H_out (kcal)
Furnace	180	380	23	21	1350	1650
Economiser	130	180	21	19	1150	1350
Heat Opt.	110	130	19	18	950	1150

The values illustrate how energy flow and enthalpy fluctuate across the boiler system. The Economiser (ECO) preheats the feed water by recovering heat from flue gasses, while the Water Wall (WW) absorbs heat from the combustion process to produce steam. The Superheaters (SH1, SH2, SH3) progressively raise the steam temperature, and the Attemperator (ATT) regulates it by mixing with water.

2) Thermal Factor Estimation Using Neural Network

To optimize major controllable parameters—Coal Flow Rate (CFR) and Burner Tilt (BT)—a neural network model was designed. The neural network takes input signals (boiler load, air flow rate, temperature, pressure), multiplies them by weights, applies activation functions (threshold, sigmoid, hyperbolic), and produces optimal set points. Through training, the network discerns intricate correlations between these variables.

Table IV provides the expected CFR values for various loads under three different coal grades. Fig. 2 visualizes these precise predictions, showing how increased load necessitates higher coal flow rates in a nearly linear manner.

Table IV: Coal Flow Rate (CFR) Set Points for Various Loads

Load (MW)	CFR for G1 (Kg/s)	CFR for G2 (Kg/s)	CFR for G3 (Kg/s)
260	64.1	53.5	42.2
310	73.8	61.8	48.3
410	94.2	79.8	61.4

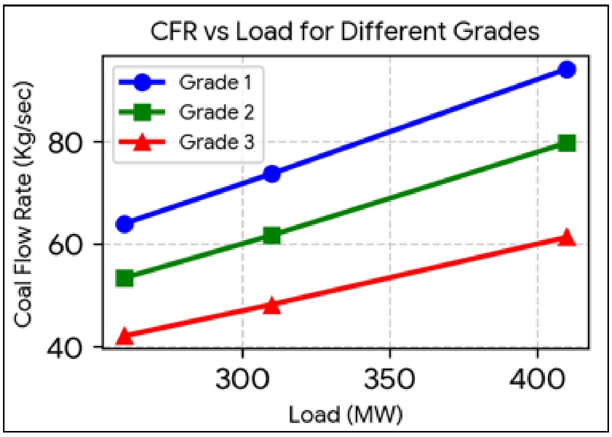

Figure 2: Performances for Different Grades of Coal - CFR

Burner tilt plays a pivotal role in optimizing combustion efficiency and emission control. By predicting burner tilt, operators can fine-tune the distribution of fuel and air within the combustion chamber, improving heat transmission and lowering pollutant emissions. Table V and Fig. 3 demonstrate the expected burner tilt values for different loads.

Table V: Burner Tilt Values for Different Loads

Load (MW)	BT for Grade C	BT for Grade D	BT for Grade E
260	2.60	2.10	42.2
310	73.8	61.8	48.3
410	28.2	25.8	-0.5

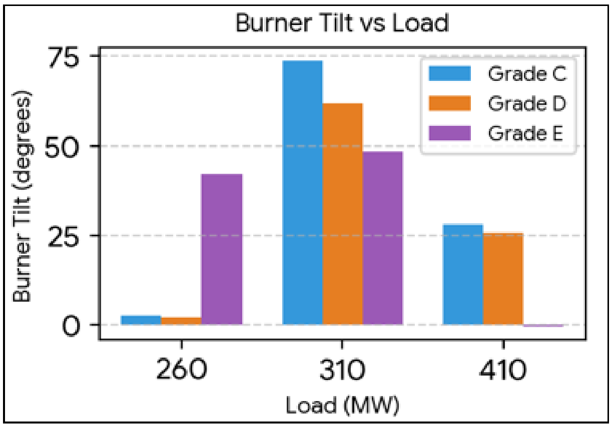

Figure 3: Performances for Different Grades of Coal - Burner Tilt

3) Heat Absorption Estimation Using Regression Analysis

Multiple regression analysis ($Y = \beta 0 + \beta 1X1 + \beta 2X2 + ... + \epsilon$) was employed to model the interaction between operational parameters (coal flow and burner tilt) and heat absorption across all boiler elements. The error rate ($\epsilon = A(k) - T(k)$) was calculated by measuring the difference between the actual target variables $A(k)$ and anticipated computed values $T(k)$.

The results of the regression analysis for 250MW and 300MW loads are presented in Table VI and Table VII, respectively. Fig. 4 compares these error rates graphically. The model is designed to forecast a boiler's Net Heat Input (NHI) and unit thermal efficiency based on total energy input and net electricity generation.

Table VI: Error Rate of Heat Absorption – 250MW

Boiler Element	Computed T(k)	Target A(k)	Error (Err)
NHI	1.8616	2.2435	-0.3819
WW	5.4245	6.5903	-1.1659
ECO	1.8799	2.324	-0.4440
SH1	1.7112	2.2309	-0.5197
SH23	3.7859	4.1939	-0.4080

Table VII: Error Rate of Heat Absorption – 300MW

Boiler Element	Computed T(k)	Target A(k)	Error (Err)
NHI	2.1728	2.3742	-0.2014
WW	6.2083	6.8384	-0.6301
ECO	2.2488	2.5204	-0.2715
SH1	2.0985	2.3038	-0.2053
SH23	4.2288	4.4248	-0.1960

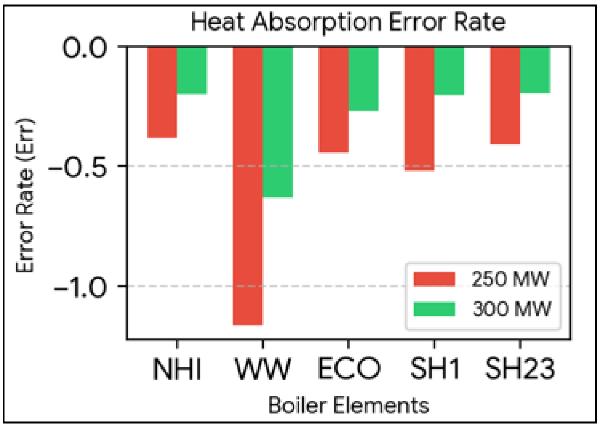

Figure 4: Comparison of Error Rates for Heat Absorption at 250MW vs 300MW.

The attained error rates are negligible and have minimal impact on normal operations. The investigated relationship reveals that the predicted error rate between actual and target values is negligible, indicating that it won't significantly deviate from the expected performance. This suggests that the system operates within acceptable tolerances despite minor discrepancies. This estimation strategy aims to enhance domain understanding from various perspectives, enabling plant operators to gain confidence in the operational execution of the system, reducing the need for constant guidance from domain experts.

5. Conclusion

The investigation into improving boiler efficiency through loss analysis highlights the critical need of identifying and regulating various sources of energy loss in boiler systems. Using data-driven approaches, neural networks, and regression modeling, crucial factors influencing boiler performance, such as burner tilt and coal flow, were analyzed and optimized. The predictive models successfully estimated the required operational parameter values for specific loads and coal qualities.

The small error rates observed between computed and actual target values confirm the reliability of the proposed models. By accurately anticipating unknown parameters, operators can dynamically adjust settings, significantly improving efficiency, lowering fuel consumption, and reducing the environmental impact of thermal power plants. Future study paths could include refining analytical models, investigating advanced control systems using real-time image processing, and incorporating renewable energy sources to improve overall sustainability and grid stability.

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