

Industrial Boiler Performance Assessment Using Combined Heat Loss and Input–Output Efficiency Methods: A Pulverized Coal Power Plant Case Study

Mochamad Denny Surindra*

Department of Mechanical Engineering, Politeknik Negeri Semarang, Semarang, Indonesia

E-mail: *dennysurindra@polines.ac.id

Abstract—Reliable evaluation of boiler thermal performance is essential for improving fuel utilization and operational stability in coal-fired power plants. Although boiler efficiency is commonly assessed using either heat-loss diagnostics or input–output energy balance, few industrial studies integrate both approaches to interpret real operational behavior under steady conditions. This study presents an integrated thermodynamic and operational analysis of a large-scale pulverized coal boiler operating at a steam power plant in Jepara, Indonesia. Field operational data were obtained from the plant distributed control system during stable operation, and corresponding coal samples were laboratory-tested to determine the High Heating Value (HHV). Boiler efficiency was evaluated using both the indirect heat-loss method and the direct input–output method across seven representative datasets. The indirect analysis yields efficiencies of 88.48–89.95%, with dominant losses associated with dry flue gas sensible heat and hydrogen-related vapor formation. The direct evaluation produces efficiencies of 87.53–89.64%, confirming stable near-constant load operation with adaptive fuel control. The results indicate that efficiency variations are governed primarily by combustion stability and thermodynamic loss structure rather than fuel calorific value alone.

Keywords—Pulverized coal boiler; Boiler efficiency; Heat loss method; Input–output method; Industrial power plant performance

I. INTRODUCTION

Coal-fired steam boilers remain one of the most widely used thermal energy conversion systems in large-scale power generation due to their operational reliability, fuel availability, and capability to maintain continuous power production under variable load conditions. The thermal performance of these boilers strongly influences plant efficiency, fuel consumption, and operational cost, making accurate efficiency evaluation an essential aspect of industrial power plant management [1].

In boiler performance assessment, thermal efficiency is commonly evaluated using two principal approaches: the indirect (heat loss) method

and the direct (input–output) method. The indirect method determines efficiency by quantifying individual heat losses such as dry flue gas loss, moisture evaporation loss, hydrogen combustion loss, and unburned fuel loss, allowing detailed thermodynamic diagnosis of combustion and heat transfer behavior [2]. By contrast, the direct method evaluates efficiency from the ratio between useful steam energy output and the chemical heat input from fuel, thereby reflecting the actual operational energy conversion effectiveness under real plant conditions [3]. Detailed loss-based boiler analysis has been widely applied to identify dominant thermodynamic inefficiencies in pulverized coal combustion systems, particularly those associated with exhaust gas sensible heat and vapor formation during fuel combustion [4]. Meanwhile, operational studies using input–output energy balance methods highlight the importance of combustion control stability, excess air management, and heat exchanger performance in determining overall boiler efficiency [5].

Although coal calorific value is frequently considered a major parameter affecting boiler performance, industrial studies indicate that within typical operating ranges, efficiency variations are often influenced more strongly by operational load control, combustion stability, and system-level thermodynamic limitations than by fuel heating value alone [6]. This observation suggests that comprehensive boiler performance evaluation requires integration of both thermodynamic loss analysis and real operational energy balance assessment [7]. Recent research in power plant performance monitoring further emphasizes that combining indirect diagnostic analysis with direct operational efficiency measurement provides a more realistic representation of large-scale boiler behavior and supports improved reliability assessment and optimization strategies [8]. Such integrated approaches are increasingly recommended in modern thermal power engineering studies to better capture both combustion physics and plant-level performance dynamics [9,10].

Therefore, the objective of this study is to perform an integrated thermodynamic and operational evaluation of a pulverized coal boiler by applying both indirect heat loss analysis and direct input–output efficiency calculation to the same industrial operating datasets. The study aims to determine the dominant heat loss mechanisms, assess the actual operational efficiency under near-constant load conditions, and clarify whether efficiency variations are primarily governed by fuel calorific value or by combustion control and system-level thermodynamic constraints.

Despite the extensive application of both indirect heat loss analysis and direct input–output efficiency evaluation in boiler performance studies, most previous investigations treat these two methods separately, focusing either on thermodynamic loss diagnosis or on operational efficiency monitoring. Consequently, limited research has systematically combined both approaches within the same real industrial operating dataset to examine how thermodynamic loss structure relates to actual operational performance under stable load conditions. Furthermore, many existing studies implicitly assume that variations in coal calorific value produce proportional changes in boiler efficiency. However, relatively few works critically evaluate whether such relationships remain valid in real industrial pulverized coal boilers where combustion control systems continuously adjust fuel flow, air distribution, and heat transfer conditions to maintain operational stability. As a result, the relative dominance of fuel quality versus operational control constraints in determining boiler efficiency remains insufficiently clarified in practical plant-scale analyses. These limitations indicate the need for an integrated thermodynamic–operational evaluation framework capable of simultaneously identifying dominant heat loss mechanisms, assessing real energy conversion performance, and determining whether efficiency variations arise primarily from fuel properties or from system-level operational constraints.

In this context, the present study proposes a unified evaluation of boiler performance that simultaneously applies indirect heat loss analysis and direct operational efficiency calculation to the same industrial pulverized coal boiler datasets. Unlike conventional studies that emphasize either combustion thermodynamics or operational monitoring alone, this work explicitly links heat loss distribution, operational energy balance, and fuel calorific variation within a single analytical framework. The study demonstrates that efficiency variations in real industrial operation are governed more strongly by combustion stability and thermodynamic loss structure than by calorific value differences alone, thereby providing a more realistic interpretation of boiler performance behavior under

near-constant load conditions. This integrated diagnostic approach offers a practical methodology for industrial performance assessment and operational optimization of large coal-fired steam boilers.

II. METHODS

A. Study Location and Boiler System

The study was conducted at a coal-fired steam power plant (PLTU) located in Jepara Regency, Indonesia. The investigated unit operates a large-scale pulverized coal boiler designed for continuous baseload electricity generation. The boiler is equipped with a distributed control system (DCS) that continuously records operational parameters including fuel flow rate, steam generation, flue gas temperature, and combustion air conditions. The plant operates under near-constant load conditions, where steam production is maintained by automatic adjustment of coal feed rate and combustion air distribution. This operational characteristic allows evaluation of boiler thermodynamic performance under realistic industrial conditions.

B. Field Data Acquisition Procedure

Operational data were collected directly from the plant monitoring system and verified through routine operational logs during stable unit operation. Only datasets recorded under steady operating conditions were selected in order to eliminate transient disturbances such as startup, shutdown, or load ramping.

The field data acquisition process was conducted sequentially as follows:

1. Identification of steady operating periods
Plant operation records were first screened to identify time intervals in which boiler load, steam pressure, and main steam temperature remained stable within normal operational tolerance limits.
2. Extraction of fuel input parameters
For each selected interval, the coal mass flow rate supplied to the pulverized coal feeders was obtained from the DCS database. Simultaneously, coal samples corresponding to the same operating period were taken from the fuel handling system and laboratory-tested to determine the High Heating Value (HHV).
3. Collection of steam output parameters
Main steam flow rate, pressure, and temperature were obtained from calibrated plant instrumentation. These parameters were used to calculate the useful heat output of the boiler based on standard steam property tables.
4. Recording of combustion and flue gas conditions
Flue gas temperature, combustion air temperature, and other furnace operating parameters required for indirect heat loss

analysis were obtained from the boiler monitoring system.

5. Validation of dataset consistency

Each dataset was checked to ensure synchronization between fuel measurements, steam parameters, and flue gas readings. Any incomplete or inconsistent records were excluded from the analysis.

C. Boiler Efficiency Evaluation

Boiler performance was evaluated using both indirect and direct methods.

Indirect Method (Heat Loss Method)

The indirect efficiency was determined by calculating the sum of individual heat losses including:

- dry flue gas loss
- hydrogen combustion loss
- moisture evaporation loss
- ash loss
- blowdown loss
- unburned carbon loss
- miscellaneous losses

The boiler efficiency was then obtained by subtracting total heat loss from 100%.

Direct Method (Input–Output Method)

The direct efficiency was calculated from the ratio between useful steam heat output and total fuel heat input:

- Fuel heat input = coal mass flow \times HHV
- Steam heat output calculated from measured steam mass flow and enthalpy rise

This method represents the actual operational energy conversion performance of the boiler.

D. Dataset Selection for Comparative Analysis

Seven representative operating datasets satisfying steady-state criteria were selected for final analysis. Each dataset corresponds to a distinct coal heating value condition while maintaining comparable boiler load.

The selected datasets were then used for:

- thermodynamic heat loss distribution analysis
- operational efficiency calculation
- comparison between indirect and direct evaluation methods

E. Coal Sampling and Laboratory Analysis

Coal samples corresponding to each selected operating dataset were collected from the plant fuel handling system during normal boiler operation. Sampling was performed at the conveyor transfer point supplying coal to the bunker to ensure that the collected material represented the actual fuel delivered to the pulverized coal feeders. To obtain representative samples, multiple incremental samples were taken over the same time interval used for operational data recording. These incremental

samples were combined and homogenized to form a composite sample for each operating condition. The composite samples were then sealed in airtight containers to prevent moisture exchange prior to laboratory testing. Laboratory analysis was conducted to determine the High Heating Value (HHV) of each coal sample using a bomb calorimeter in accordance with standard coal testing procedures commonly adopted in industrial fuel analysis. Prior to calorific value measurement, the samples were crushed, dried under controlled conditions, and prepared following standard laboratory sample preparation practices to ensure measurement consistency. The resulting HHV values obtained from laboratory testing were used as the fuel energy input parameter in both the indirect heat loss calculation and the direct input–output efficiency evaluation.

III. RESULTS AND DISCUSSION

This section presents the thermodynamic performance analysis of the pulverized coal boiler based on both indirect (heat loss) and direct (input–output) efficiency evaluation methods. The dual-method approach is employed to distinguish between combustion-related thermodynamic losses and actual operational performance under real plant conditions. The analysis is structured in three stages. First, the boiler efficiency and detailed heat loss distribution obtained from the indirect method are examined to identify the dominant thermodynamic loss mechanisms inside the furnace and heat recovery sections. Second, the direct efficiency calculated from the energy balance between fuel heat input and useful steam output is evaluated to assess the actual operational performance of the boiler under near-constant load conditions. Finally, the results from both approaches are compared to provide a comprehensive interpretation of the boiler thermal behavior and operational stability. Through this structured evaluation, the study aims to determine whether variations in coal calorific value alone can explain efficiency changes, or whether combustion control conditions and system-level thermodynamic constraints play a more dominant role in governing industrial boiler performance.

A. Boiler Performance Based on Heat Loss (Indirect) Method

To establish the thermodynamic performance baseline of the boiler, the efficiency was first evaluated using the heat loss (indirect) method, which allows detailed identification of individual combustion-related losses and their contribution to the overall thermal balance. The calculated efficiency values together with the corresponding heat loss components for each operating condition are summarized in Table 1. Table 1. Boiler efficiency and detailed heat loss

components calculated using the indirect (heat loss) method for each operating dataset. The table presents the distribution of individual thermodynamic loss mechanisms, including dry flue gas loss, hydrogen combustion loss, moisture-related loss, ash loss, blowdown loss, and unburned carbon loss, which collectively determine the overall boiler thermal efficiency.

Table 1. Boiler Efficiency Calculation Using Heat Loss Method

HHV (kJ/kg)	Rugi Rugi Panas							Total (%)	ηB (%)
	LUC (%)	LG' (%)	Lmf (%)	LH (%)	LmA (%)	LB (%)	Lun (%)		
2483 7,35	0, 07	4, 44	2, 16	4, 32	0, 16	0, 16	0, 14	10, 35	89, 62
2472 2,64	0, 11	4, 38	2, 14	4, 34	0, 13	0, 18	0, 15	10, 46	89, 95
2512 1,63	0, 12	4, 48	2, 12	3, 74	0, 18	0, 17	0, 14	11, 53	88, 73
2463 5,34	0, 09	4, 25	1, 96	4, 17	0, 14	0, 18	0, 15	11, 74	89, 89
2459 3,20	0, 18	4, 15	1, 87	4, 48	0, 14	0, 17	0, 14	11, 32	88, 48
2483 4,47	0, 25	4, 22	1, 98	4, 75	0, 14	0, 18	0, 15	11, 53	89, 93
2513 6,27	0, 2	4, 18	1, 77	4, 64	0, 14	0, 16	0, 15	11, 23	89, 85

The calculated efficiency varies between approximately 88.48% and 89.95%, indicating that the boiler operates within a relatively narrow efficiency range typical for large pulverized coal utility boilers. Importantly, the data do not show a strictly monotonic relationship between coal High Heating Value (HHV) and efficiency. Several operating points with higher HHV do not correspond to higher efficiencies, demonstrating that boiler thermal performance is not governed solely by fuel calorific value within the observed operating range. This observation suggests that variations in combustion conditions and internal heat loss distribution have a more direct influence on efficiency than HHV alone. While the indirect efficiency values provide an overall indication of boiler thermal performance, a deeper understanding of the governing thermodynamic behavior requires examination of how individual heat loss components contribute to the total energy balance. Therefore, the distribution of these losses is analyzed in detail in the following subsection.

B. Distribution of Individual Heat Loss Components

A detailed breakdown of the individual heat loss components in Table 1. reveals that the dominant contributors to total boiler heat loss are: dry flue gas sensible heat loss, hydrogen-related combustion loss and moisture evaporation loss. The dry flue gas loss remains consistently around 4.15-4.48%, while hydrogen combustion loss varies

between approximately 3.74-4.75%. Moisture-related losses remain within a smaller but still significant range of roughly 1.77-2.16%. In contrast, other losses including ash-related loss, blowdown loss, unburned carbon loss, and miscellaneous losses remain very small and nearly constant. The extremely low unburned carbon loss indicates high combustion completeness inside the pulverized coal furnace. This loss structure confirms that the primary thermodynamic limitation of the boiler originates from unavoidable flue gas and vapor-related energy losses rather than incomplete combustion. Having identified the dominant thermodynamic loss mechanisms, the next step is to quantify their relative importance within the overall loss structure. This allows the contribution of each loss component to be ranked in order to determine which mechanisms most strongly constrain boiler efficiency.

C. Ranking of Heat Loss Contributions

To further evaluate the relative importance of each loss mechanism, the contribution of individual heat losses was ranked relative to the total heat loss. The analysis shows that hydrogen combustion loss and dry flue gas loss jointly account for nearly 80% of the total boiler heat loss, while moisture loss contributes roughly 18%. All remaining losses each contribute less than 2%. To better visualize the relative magnitude of each thermodynamic loss mechanism, the individual heat loss components were aggregated and ranked according to their contribution to the total boiler heat loss. The resulting distribution is illustrated in Figure 1.

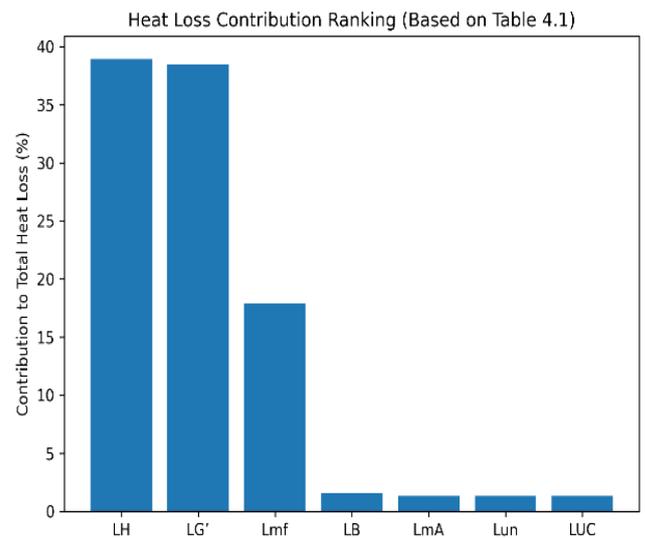


Figure 1: Loss Contribution Ranking

Figure 1. Relative contribution of individual thermodynamic heat loss components to the total boiler heat loss based on the indirect method calculation. The ranking highlights the dominant role of dry flue gas sensible heat loss and hydrogen-

related latent heat loss, which together account for the majority of total thermal losses in the pulverized coal boiler. Although the indirect method provides detailed insight into combustion-related thermodynamic losses, it does not fully represent the actual operational performance of the boiler under real plant conditions. To complement this thermodynamic analysis, the boiler efficiency is next evaluated using the input–output (direct) method, which captures the overall energy conversion effectiveness based on measured fuel input and steam output.

D. Boiler Performance Based on Input–Output (Direct) Method

After examining the combustion-related thermodynamic losses using the indirect method, the boiler performance was further evaluated using the input–output (direct) method in order to quantify the actual operational thermal efficiency under real plant conditions. This approach determines efficiency from the balance between fuel heat input and useful steam energy output. The calculated operational parameters and efficiency values for each dataset are summarized in Table 2. The table lists the measured coal mass flow rate, total fuel heat input, useful steam heat output, and the resulting direct thermal efficiency, providing an evaluation of the actual energy conversion performance of the boiler under real plant operating conditions.

Table 2. Operational boiler efficiency calculated using the input–output (direct) method for each operating dataset.

HHV (kJ/kg)	\dot{m} Batubara (kg/s)	Q_{in} (KW)	Q_{out} (KW)	η_B (%)
24837,35	78,64	1784638,29	1569854,35	87,53
24722,64	77,85	1793455,26	1574385,43	87,57
25121,63	76,74	1799897,46	1588796,53	88,22
24635,34	74,86	1806534,64	1590040,58	88,35
24593,20	75,64	1818567,24	1609487,64	87,85
24834,47	74,53	1818697,85	1608576,57	89,64
25136,27	73,64	1803879,56	1608345,53	88,75

The calculated efficiency ranges between approximately 87.53% and 89.64%, again indicating stable industrial boiler operation within a narrow performance band. A key thermodynamic observation is that the total heat input remains within a relatively small range, indicating that the boiler operates under near-constant load conditions. Under such conditions, the combustion control system

continuously adjusts the coal mass flow rate in response to variations in fuel calorific value. This adaptive control behavior is confirmed by the general decrease in coal mass flow with increasing HHV. Importantly, the highest efficiency does not occur at the highest HHV value, further demonstrating that direct boiler efficiency is primarily governed by operational combustion dynamics and heat transfer effectiveness rather than calorific value alone. Once the operational efficiency has been determined using the direct method, it becomes necessary to compare these results with those obtained from the indirect approach in order to assess the consistency between combustion-based thermodynamic estimation and actual plant performance.

E. Comparison Between Indirect and Direct Efficiency Methods

A systematic difference is observed between efficiencies calculated using the indirect and direct methods, with the indirect method consistently yielding slightly higher values. This discrepancy is expected because the direct method inherently captures real operational thermal penalties, including auxiliary steam consumption and other plant-level heat uses that are not explicitly included in the theoretical heat loss estimation. Therefore, the indirect method represents combustion thermodynamic efficiency, while the direct method reflects actual operational boiler performance. Figure 2. Representative efficiency levels illustrating the systematic difference between indirect thermodynamic efficiency and direct operational efficiency.

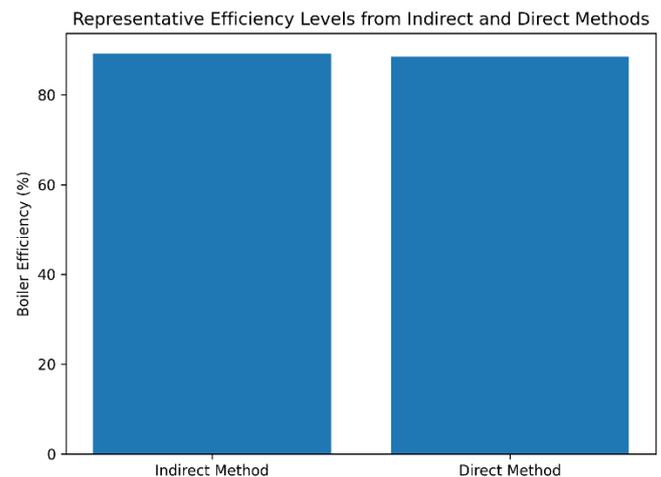


Fig. 2. Efficiency Method Comparison

IV. CONCLUSION

The main conclusions of this study can be summarized as follows:

1. The indirect (heat loss) method shows that the pulverized coal boiler operates within a

narrow thermal efficiency range, indicating stable combustion conditions and consistent thermodynamic performance during the observation period.

2. Analysis of individual heat loss components confirms that dry flue gas loss and hydrogen-related vapor loss are the dominant thermodynamic losses, jointly accounting for the largest portion of total energy dissipation, while unburned carbon, ash discharge, and blowdown losses remain comparatively negligible.
3. The direct (input–output) efficiency evaluation indicates that the boiler operates under near-constant load conditions, where coal mass flow is continuously adjusted to maintain stable steam generation despite variations in coal heating value.
4. No strict monotonic relationship is observed between coal High Heating Value (HHV) and operational boiler efficiency, demonstrating that industrial boiler performance is governed more strongly by combustion control stability and system-level thermodynamic constraints than by fuel calorific value alone.
5. The indirect method consistently produces slightly higher efficiency values than the direct method, reflecting the theoretical thermodynamic nature of the loss-based calculation compared with the operational energy balance captured by the direct approach.
6. Overall, the combined use of indirect and direct efficiency evaluation methods provides a comprehensive framework for assessing both combustion thermodynamics and real operational performance of industrial coal-fired boilers.

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