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Boiler Performance Analysis Reviewed from Natural Gas Consumption and Steam Production at Fluctuating and Stable Operating Conditions at PT Petrokimia Gresik's Sulfuric Acid and Utility Units

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ABSTRACT

Boilers are a critical component in the chemical industry's utility system that functions to provide thermal energy through steam production. Fluctuating fuel supply and varying steam load conditions significantly affect boiler performance, yet systematic evaluation under such conditions remains limited in industrial settings. This study aims to analyze the performance of Boiler B6201 at the Sulfuric Acid and Utility Unit of PT Petrokimia Gresik over the period September–December 2025. Performance was evaluated under fluctuating and stable operating conditions based on natural gas consumption and steam production data. Parameters analyzed include Specific Fuel Consumption, Steam-to-Fuel Ratio, and 7-day Rolling Coefficient of Variation of gas consumption as an objective classifier of operating stability. Operational data were obtained from daily and hourly logsheets covering gas flow inlet, air flow, boiler feed water, and steam outlet temperature and pressure. October 2025 recorded the most stable conditions with a Coefficient of Variation of 12.89%, the best Specific Fuel Consumption of 2.4401 Kilo Standard Cubic Feet per ton (Kscfh/ton), and the highest Steam-to-Fuel Ratio of 0.4157 tons/Kscfh. November 2025 recorded the most volatile conditions with a Coefficient of Variation of 43.78% and the worst Specific Fuel Consumption of 3.3449 Kscfh/ton. A 36.5% decrease in steam production was not followed by a proportionate decrease in gas consumption, as most energy was absorbed to maintain boiler operating pressure and temperature. Fluctuating conditions were therefore 26.2% more fuel-wasteful than stable conditions. This disproportionate relationship is an inherent consequence of boiler thermal characteristics, and efficiency improvements require better coordination of steam load management at the utility system level.

1. Introduction

Utility systems are an integral part of supporting the sustainability of chemical industry operations, especially in the provision of continuous thermal energy for all production units. One of the main equipment in the system is the boiler, which is a pressurized vessel that converts the

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chemical energy of fuel through the combustion process into high-pressure steam as a medium for thermal energy transfer in industrial processes [1]. Combustion reactions in a furnace involve a simultaneous interaction between the fuel, combustion air, and ignition source, where operating parameters such as excess air ratio and fuel flow rate directly determine the combustion characteristics as well as the thermal efficiency achieved [2]. In industrial operational practices, natural gas has been widely used as the main fuel in boiler units because it has stable combustion characteristics, so the continuity of supply and reliability of natural gas-based combustion processes are important factors in maintaining the overall operational quality of the utility system [3].

Given the large role of boiler-based utility systems in supporting the sustainability of chemical industry operations, the reliability and operational efficiency of boilers are a primary concern across various industrial facilities, particularly in the fertilizer industry, where steam systems exhibit a high degree of complexity owing to interdependencies between equipment and limited supply redundancy [4]. Operating parameters such as steam pressure, temperature, and drum level are critical variables that must be monitored continuously, as failure to maintain these parameters can degrade efficiency and cause significant operational losses [5]. This condition is directly relevant to the operation of Boiler B6201 in the Sulfuric Acid and Utility Unit at PT Petrokimia Gresik, where the reliability of the boiler system is the main foundation in maintaining the continuity of thermal energy supply for the entire production process. Previous studies have shown that disruptions in boiler operating parameters can result in significant operational losses; energy consumption during the operational phase has been identified as the dominant contributor to the total energy load of industrial systems, and fuel utilization efficiency therefore requires systematic evaluation to improve overall system performance. Kristanto [6] demonstrated this through a boiler disturbance at a steam power plant, while Varganova *et al.,* [7] confirmed it through boiler load optimization modeling at an industrial steam plant.

Such evaluation efforts can be quantitatively carried out through combustion efficiency analysis based on combustion gas parameters, which allows the identification of the amount of heat loss as well as a thorough assessment of the performance of the combustion system [8]. Computational modeling approaches such as Artificial Neural Network (ANN) and Response Surface Methodology (RSM) have been developed and proven to be able to identify boiler optimal operating points based on historical long-term operating data[9]. However, this approach requires relatively stable operating conditions so that its ability to reflect the dynamics of boiler performance under conditions of actual load fluctuations in the field is still limited. Therefore, an approach is needed that is able to capture the dynamics of the relationship between natural gas consumption and steam production directly under the actual conditions of field operations. A summary of representative studies related to boiler performance analysis and system modeling approaches is presented in Table 1.

Table 1
Summary of representative studies on boiler performance analysis and fuel consumption efficiency under varying operating conditions

Simulation Model	Key Feature	Method	Main Finding	Result	Reference
Nonlinear Dynamic Boiler Model	Mass energy balance, drum water level	Dynamic modelling	Load changes trigger a nonlinear response at the drum level	New models reduce errors by up to 67%	[10]
Influence of Fuel Type on Boiler	Steam/fuel ratio, combustion efficiency	Direct & indirect method	The use of natural gas increases the evaporation ratio	Direct efficiency increased to 86.89%	[11]

Intelligent Monitoring Boiler	Operating variables (T flue gas, O_2, feedwater)	Online monitoring & baseline model	Gas consumption is not always comparable to steam production	Gas savings 9.01%	[12]
Fuel Switching HFO → Natural Gas	Emissions & thermal efficiency	Energy & economic analysis	Gas use lowers emissions and stack loss	Efficiency up 3.3%	[13]
Techno-Environmental Boiler Analysis	Energy parameters, excise, emissions	3E analysis & optimization	Efficiency is affected by load and excess water	Optimal efficiency at excess water 31.86%	[14]
Method of Controlling Combustion Products at Different Boiler Loads	Flue gas volume, flue gas temperature, load variation	Experimental analysis of boiler loads	Variations in cyclic loads cause a change in the temperature of the flue gas by 120–200°C; maximum load increases exhaust gas heat loss	Decreased efficiency at unstable loads due to increased stack loss	[15]

Most previous research on boiler performance has focused on mathematical modeling, combustion control system optimization, and thermal efficiency simulations assuming that increased fuel supply will be directly proportional to increased steam production. However, empirical analysis based on real operational data that tests these assumptions under conditions of actual load fluctuations is still very limited. This study aims to analyze the relationship between natural gas consumption and steam production of Boiler B6201 under fluctuating and stable operating conditions in the Sulfuric Acid and Utility Unit of PT Petrokimia Gresik. By utilizing actual operational data and the application of direct methods, this study provides an empirical study of the phenomenon of boiler thermal inefficiency in fluctuating operating conditions that have been poorly documented in industrial boiler performance studies.

2. Methodology

2.1 Research Flow Diagram

This research was conducted through an approach based on actual operational data of Boiler B6201 which was sourced from the daily and hourly logsheets of the Sulfuric Acid and Utility Unit of PT Petrokimia Gresik, then validated through literature review and problem identification to ensure that the data used met the feasibility of the analysis, as illustrated in the research flowchart presented in Figure 1. Data that did not meet the validity criteria were returned to the literature review stage for re-evaluation, while valid data were then subjected to a selection and classification process based on operating conditions using a 7-day Rolling CV as an objective basis to distinguish stable and fluctuating conditions. In each of these conditions, Specific Fuel Consumption (SFC) and Steam-to-Fuel Ratio (SFR) were calculated as the main parameters of efficiency assessment, the results of which were then analyzed comparatively to identify the pattern of relationship between natural gas consumption and steam production under the two operating conditions.

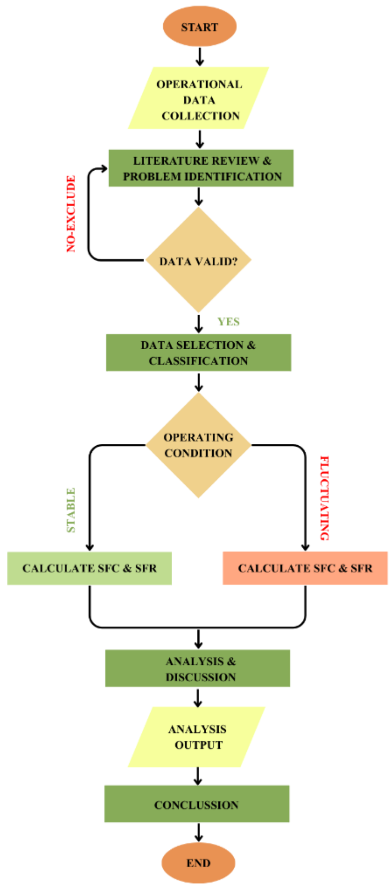

Fig. 1. Research flow diagram

2.2 Research Objects

The research object in this study is Boiler B6201, which operates within the utility system of the Sulfuric Acid and Utility Unit at PT Petrokimia Gresik. This boiler served as the primary source of operational data used to analyze the relationship between natural gas consumption and steam production during the observation period. The main technical parameters of the boiler that are the basis for the analysis of this study are presented in Table 2, which is sourced from the Technical Specification Manual of Boiler B6201 accessed at PT Petrokimia Gresik (2026).

Table 2
Main specifications of boiler

Parameter	**Value**
Boiler code	B6201
Manufacturer	Hitachi Zosen Hiroshima
Boiler type	Hitachi Zosen HC-type corner tube boiler, water tube packaged outdoor type
Maximum continuous rating	52 t/h
Normal continuous rating	42 t/h
Minimum continuous rating	11 t/h
Steam pressure	36.5 $kg/cm^2 - g$
Steam temperature	405 $°C$
Boiler Efficiency	89% at NCR

2.2.1 Boiler operational data

The operational data of the B6201 boiler used in this study was obtained from the logsheet of the Sulfuric Acid and Utility Unit for the period September-December 2025 and summarized in the form of daily data and hourly data. The data analyzed consists of operational records that have undergone a selection process based on unit operating conditions, covering only periods during which the boiler was actively operating. In September, October, and November, several days were excluded from the analysis because the unit was not operating due to a natural gas supply disruption. A summary of the average operational data of boiler B6201 for each month during the observation period is presented in full in Table 3, which is obtained from the daily and hourly logsheets of the Sulfuric Acid and Utility Unit of PT Petrokimia Gresik.

Table 3
Average monthly operational data of boiler B6201 period September–December 2025

Parameter	09-2025	10-2025	11-2025	12-2025
Daily Data				
Active Days (days)	28	24	8	31
Average Gas Consumption (Kscfh/day)	1.601,8	1.930,1	926,8	1.512,2
Average Steam Production (tons/day)	631,6	812,4	300,6	515,9
Hourly Data				
Average Inlet Flow (Kscfh/hour)	69,77	81,32	50,50	63,16
Average Air Flow (Nm^3/hour)	48,21	51,19	34,46	47,50
Average BFW (tons/hour)	29,77	34,34	13,74	21,42
Average Outlet Temperature (°C)	415,52	428,21	425,42	407,28
Average Outlet Pressure (kg/cm^2)	32,38	32,95	33,52	33,27

2.3 Calculation Method
2.3.1 Specific Fuel Consumption (SFC)

The SFC of the boiler is expressed in Eq. (1):

$$SFC = \frac{m_{gas}}{m_{steam}} \tag{1}$$

Where m_{gas} represents the mass of natural gas consumed (Kscfh) and m_{steam} the mass of steam produced (ton), so a smaller SFC value indicates better conversion efficiency[16], [17].

2.3.2 Steam-to-Fuel Ratio (SFR)

SFR is defined as the inverse of SFC and formulated in Eq. (2):

$$SFR = \frac{m_{steam}}{m_{gas}} \tag{2}$$

Higher SFR values reflect more optimal fuel conversion productivity [16].

2.3.3 Rolling Coefficient of Variation (CV) 7 days for operating condition classification

Operating conditions are objectively classified using a 7-day Rolling CV as stated in Eq. (3):

$$CV_{rolling} = \frac{\sigma_{gas,7\ day}}{\underline{x}_{gas,7\ day}} \times 100\% \quad (3)$$

Where σ_{gas} is the standard deviation and $\underline{x}_{gas}$ is the average of gas consumption in a rolling 7-day window, which represents the relative variability of gas supply as the distinguishing basis of stable and fluctuating conditions[18], [19].

2.3.4 Hourly Specific Fuel Consumption (SFC)

For hourly temporal resolution, SFC is calculated using Eq. (4):

$$SFC_{hour} = \frac{Inlet\ Flow\ B6201\ (Kscfh)}{B6201\ Outlet\ Flow\ (ton/hour)} \quad (4)$$

This parameter describes the dynamics of gas usage efficiency in a 24-hour period of operation[16], [20].

2.3.5 Hourly Steam-to-Fuel Ratio (SFR)

Fuel conversion productivity per unit time is expressed via Eq. (5):

$$SFR_{hour} = \frac{B6201\ Outlet\ Flow\ (ton/hour)}{Inlet\ Flow\ B6201\ (Kscfh)} \quad (5)$$

Higher values indicate a more efficient conversion of gas to steam at that hour[16].

3. Result and Discussion

The results of the analysis of SFC, SFR, and CV gas for the period September-December 2025 show that the stability of natural gas supply is significantly correlated with the fuel efficiency of Boiler B6201**.** October 2025 recorded the best performance with the lowest gas CV (12.89%), SFC 2.4401 Kscfh/ton, and SFR 0.4157 tons/Kscfh, while November 2025 recorded the worst performance with the highest gas CV of 43.78% and SFC of 3.3449 Kscfh/ton**.** September and December are between the two with SFC of 2.4994 and 3.1003 Kscfh/ton, respectively. Interestingly, September achieved a better SFC than December despite its higher gas CV, suggesting that steam load magnitude also influences efficiency months with higher steam loads tend to yield lower SFC values. This difference reflects the thermal influence of the boiler system, where efficiency increases in high and stable load conditions but decreases in partial load due to an increase in the percentage of excess air[12]. On the other hand, the use of natural gas under stable operating conditions has been shown to result in more optimal evaporation ratios and efficiency, whereas gas consumption is not always comparable to steam production because there is a fixed energy consumption component that does not depend on the magnitude of the load served, Carrasco *et al.,* [10] demonstrated this through a nonlinear dynamic boiler model showing that load changes trigger disproportionate drum-level responses, while Putri *et al.,* [11] confirmed it empirically by finding that a 36.5% reduction in steam output was not accompanied by a proportional decrease in fuel consumption across varying fuel compositions. The monthly fuel efficiency comparison is visually presented in Figure 2**,** where the SFC and SFR values plotted are derived using Eq. (1) and Eq. (2), respectively, with operating stability classified based on the 7-day Rolling CV as defined in Eq. (3).

The mechanism behind this pattern can be further explained through the relationship between steam load and SFC as shown in Figure 3, as well as the relationship between gas inlet flow and Air-to-Fuel Ratio in Figure 4. The 36.5% decrease in steam production was not followed by a proportionate decrease in gas consumption because most of the energy was absorbed to maintain boiler pressure and operating temperature rather than for steam production, so the fluctuating period proved to be 26.2% more wasteful than stable conditions. This waste margin is quantified through Eq. (4), where the hourly SFC directly captures how gas consumption fails to scale proportionally with steam output during fluctuating periods. This characteristic reflects the nonlinear nature of the boiler system's response to load changes, which involve complex interactions between the gas flow rate, drum pressure, and steam production rate [13]. Operation at partial loads tends to increase the percentage of excess air, which in turn enlarges the stack loss and depresses the overall thermal efficiency of the boiler, as demonstrated by Koochakinia *et al.,* [14] through techno-environmental analysis of a utility boiler in the South Pars Gas Complex where thermal efficiency was found to decrease as excess air percentage increased throughout the year. This behavior is further supported by Kryvda *et al.,* [15] who revealed that cyclic load variations in non-condensing boilers cause flue gas temperature fluctuations in the range of 120–200°C, where maximum load corresponds to maximum temperature and heat losses. Thus, the disproportion between gas consumption and steam production under fluctuating conditions is an inherent consequence of the thermal characteristics of the boiler, not merely the result of operational disruptions.

The disparity in fuel to steam conversion in each observation month further confirms that the thermal inertia of the boiler plays a dominant role in determining the overall efficiency of the system [10]. In low-load conditions, most of the fuel energy is directed to maintaining drum pressure and superheat temperatures rather than producing steam productively. This is reflected in the hourly SFR values computed via Eq. (5), which consistently drop during low-load periods as less steam is produced per unit of gas consumed. This phenomenon is consistent with the established finding that boiler efficiency is strongly dependent on load magnitude, where partial-load operation systematically increases stack loss and reduces thermal conversion rates [14]. Therefore, optimizing steam load distribution at the utility system level as a whole is a critical factor in reducing fuel waste without sacrificing the reliability of steam supply for the production process.

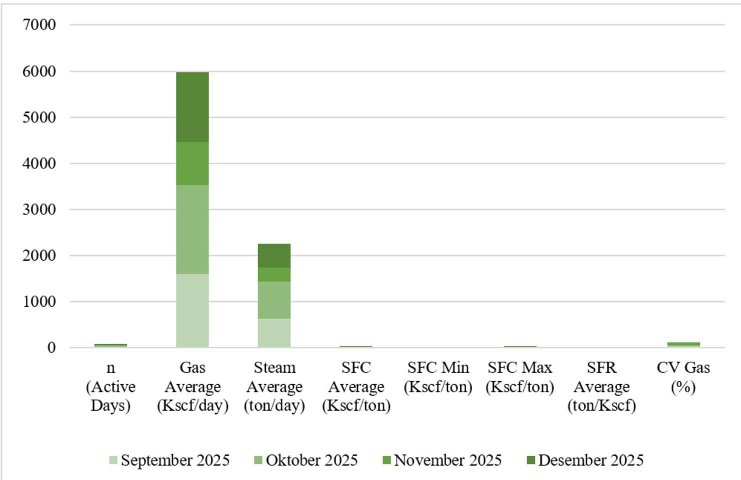

Fig. 2. Comparison of monthly fuel efficiency of boiler B6201 for the period of September–December 2025

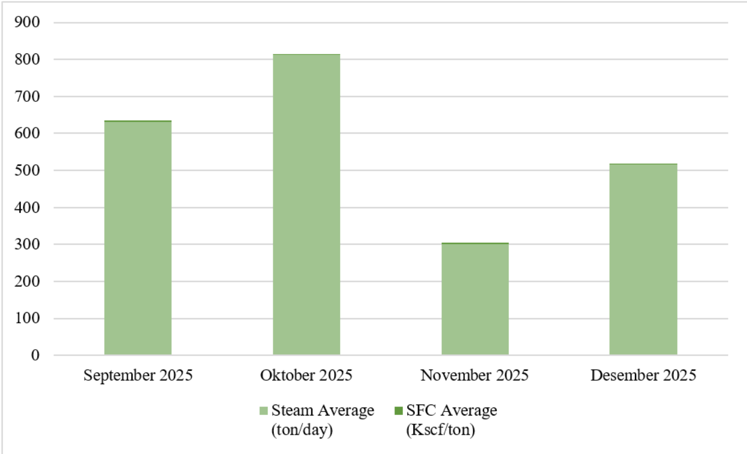

Fig. 3. Comparison of steam and SFC monthly load of boiler B6201 period September–December 2025

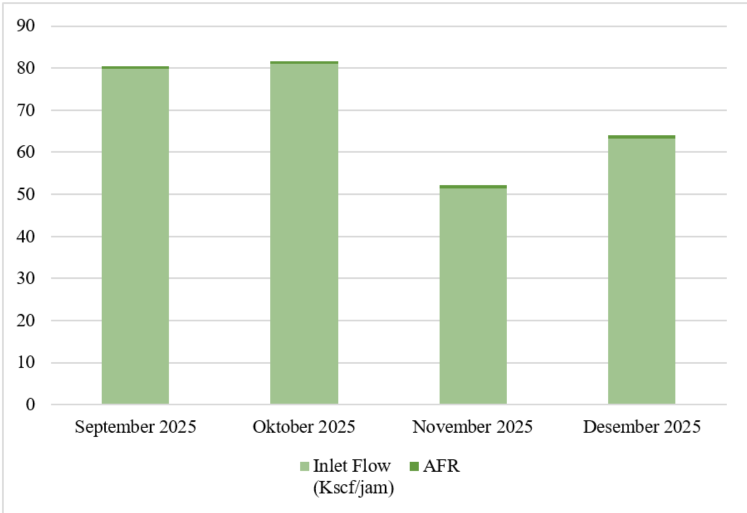

Fig. 4. Comparison of gas inlet flow and monthly air-to-fuel ratio of boiler B6201 for the period of September–December 2025

4. Conclusion

An analysis of the performance of Boiler B6201 for the period of September–December 2025 shows that fuel efficiency is determined not only by the stability of the gas supply, but also by the amount of steam load served as reflected in the four-month observation period. The reduction in steam production of up to 36.5% is not accompanied by a commensurate reduction in gas consumption because most of the energy is absorbed to maintain boiler operating pressure and temperature, making fluctuating conditions 26.2% more wasteful than stable conditions. This inequality is a reflection of the non-linear nature of the boiler's thermal response to load changes, therefore, efficiency improvement efforts should be directed toward a more evenly distributed and coordinated management of steam loads at the utility system level, so that gas consumption can be reduced without compromising the reliability of steam supply to the production process.

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