

Assessment of feedwater hardness effects on thermal efficiency of an industrial fire-tube boiler

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Abstract

Boiler efficiency remains an important factor in industrial energy management, where feedwater quality can directly influence heat transfer performance and fuel consumption. This study evaluates the relationship between feedwater hardness and the thermal efficiency of an industrial fire-tube boiler operating under actual industrial conditions. Operational data were collected over a 30-day observation period, including feedwater hardness, steam production rate, natural gas consumption, and boiler thermal efficiency. The boiler performance was initially assessed using engineering-based calculations, including steam energy output, fuel energy input, gas-to-steam ratio, and direct efficiency evaluation. Statistical methods, including Pearson correlation, linear regression, and multiple regression, were then applied to strengthen the analysis. The results indicate that feedwater hardness exhibited a strong negative statistical association with boiler thermal efficiency. The linear regression analysis produced a coefficient of determination of approximately $R^2 = 0.96$, indicating that variations in feedwater hardness were strongly associated with changes in thermal efficiency under relatively stable operating conditions. Lower hardness levels were also associated with lower fuel consumption and improved gas-to-steam ratios. Multiple regression analysis further indicates that steam production and fuel consumption also contribute to boiler efficiency. These findings provide field-based evidence supporting the importance of feedwater treatment in maintaining efficient industrial boiler performance.

Keywords:

Boiler; feedwater hardness; water softener; industrial steam generation

1 Introduction

Boilers are widely used in industrial processes as primary sources of thermal energy for steam generation and heat transfer applications [1][2]. The operational efficiency of industrial boilers is strongly influenced by several parameters, including combustion conditions, fuel quality, operating load, and feedwater quality [3][4][5]. Among these factors, feedwater hardness is considered one of the most critical operational parameters because excessive dissolved minerals, particularly calcium and magnesium ions, can promote scale formation on boiler heat transfer surfaces. Scale deposits reduce heat transfer effectiveness, increase fuel consumption, and potentially accelerate equipment deterioration during long-term operation [6][7].

Previous studies have extensively discussed the thermodynamic effects of scaling and the importance of water treatment systems in maintaining boiler performance [8][9][10]. Several investigations have shown that poor feedwater quality may contribute to reduced heat transfer efficiency and increased operational costs due to higher fuel demand and maintenance requirements [11][12]. In addition,

water softening systems are commonly implemented in industrial facilities to reduce hardness levels before feedwater enters the boiler system [13][14]. However, many of these studies are primarily based on laboratory-scale experiments, theoretical thermodynamic analyses, or simplified engineering calculations performed under controlled operating conditions.

Despite the established understanding regarding the relationship between water quality and boiler performance [15][16][17][18], quantitative field-based evaluations under actual industrial operating conditions remain relatively limited. In particular, relatively few studies have combined operational boiler efficiency calculations with statistical analyses, such as correlation analysis and regression modeling, using real industrial datasets collected over continuous operating periods. As a result, the statistical strength and operational consistency of the relationship between feedwater hardness and boiler thermal efficiency under practical industrial conditions are still insufficiently discussed in the literature.

Furthermore, previous studies generally focused only on thermodynamic interpretation or scaling mechanisms without integrating operational indicators such as steam production rate, fuel consumption, and feedwater hardness into a unified statistical evaluation framework. Consequently, the available literature still provides limited field-based evidence regarding how variations in feedwater quality are statistically associated with boiler thermal efficiency during actual industrial operation. This limitation becomes important because industrial boiler systems are affected by fluctuating production loads, operational variability, and multiple interacting process parameters that are difficult to reproduce under laboratory conditions.

Therefore, this study aims to conduct a field-based operational assessment of an industrial fire-tube boiler operating in the tobacco manufacturing industry by evaluating the statistical association between feedwater hardness, steam production, fuel consumption, and boiler thermal efficiency using a 30-day operational dataset. The novelty of this study does not lie in proposing a new thermodynamic theory regarding scaling or boiler performance, since such mechanisms are already well established in the literature. Instead, the contribution of this work lies in the integration of engineering-based boiler performance evaluation with statistical analyses, including Pearson correlation, regression modeling, ANOVA, and operational variability assessment, using real industrial operating data collected under practical production conditions.

The findings of this study are expected to provide practical field-based evidence regarding the relationship between feedwater quality and boiler efficiency while also contributing an operational evaluation framework that may support industrial boiler monitoring and energy efficiency assessment in real manufacturing environments.

2 Research methodology

This study was conducted using an observational and analytical approach to evaluate the relationship between feedwater hardness and the thermal efficiency of an industrial fire-tube boiler. The methodology includes a detailed description of the research location, system configuration, data collection procedure, data screening process, and the analytical and statistical methods used to assess system performance (Fig. 1).

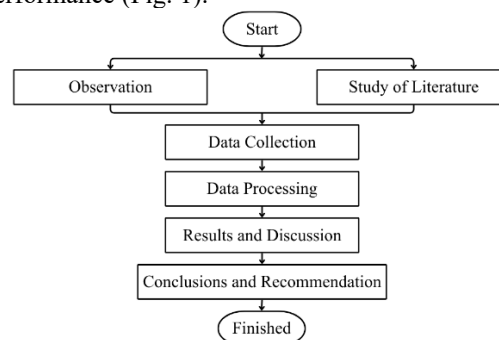


Fig. 1. Research flowchar

2.1 Research location

The study was carried out in an industrial tobacco facility that continuously operates a steam boiler system to support its production processes. The boiler is a natural gas-fired fire-tube boiler designed to generate saturated steam for industrial applications such as heating and drying. The system operates under relatively stable conditions with consistent production demand.

2.2 Boiler and water softener system

The steam generation system consists of a fire-tube boiler integrated with a water softener unit based on ion exchange technology. The softener removes hardness-causing ions (Ca^{2+} and Mg^{2+}) by exchanging them with Na^+ ions using a cation exchange resin. The main system components include a raw water tank, water softener unit, brine tank, feedwater pump, boiler unit, and steam distribution system.

The main components of the boiler and water softener system include a raw water tank, a water softener tank containing cation exchange resin, a brine tank for resin regeneration, a feedwater pump, a fire-tube boiler unit, and a steam distribution line. A schematic diagram of the overall system configuration, including the boiler and water softener units, is presented to illustrate the relationship between the water treatment process and the steam generation system (Fig. 2).

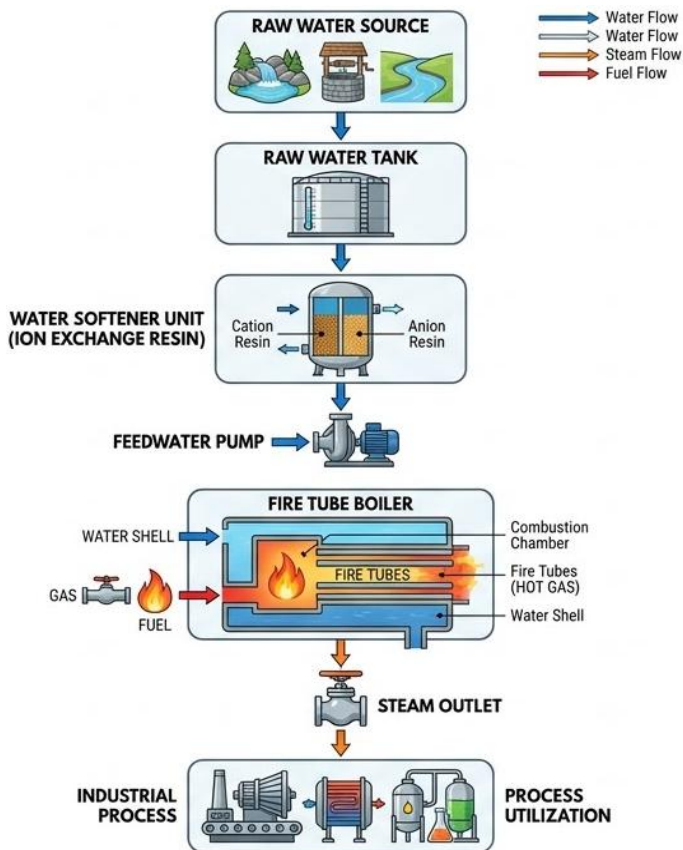


Fig. 2. Boiler and water softener system diagram

2.3 Data collection procedure

Operational data were collected over a period of 30 consecutive days ($n = 30$) under normal plant operation. Due to limitations in the availability of complete raw datasets, a reconstructed operational dataset was developed based on the reported measurement ranges and observed trends during the 30-day monitoring period (Table 1). The dataset preserves the physical consistency of boiler operation and is used for statistical analysis to explore potential relationships among variables.

To ensure comparability, the dataset represents relatively stable operating conditions, where no major shutdowns, startups, or abnormal operating events were recorded. Steam production remained within a narrow range (approximately 4800–5200 kg/h), while boiler pressure (7–8 bar) and feedwater temperature (80–90°C) were maintained within consistent limits. These conditions

indicate that the boiler operated under near steady-state conditions during the observation period.

Table 1. Daily operational data of feedwater hardness, steam production, fuel consumption, and boiler thermal efficiency over a 30-day observation period

Day	Hardness (mg/L)	Steam (kg/h)	Gas (Nm ³ /h)	Efficiency (%)
1	10	4800	402	86.0
2	9	4850	400	86.3
3	9	4900	398	86.7
4	8	4950	396	87.0
5	8	5000	395	87.3
6	7	5050	392	87.8
7	7	5100	390	88.1
8	6	5150	388	88.5
9	6	5200	385	88.9
10	5	5200	380	89.2
11	10	4800	401	86.2
12	9	4850	399	86.5
13	9	4900	397	86.9
14	8	4950	395	87.2
15	8	5000	394	87.5
16	7	5050	391	88.0
17	7	5100	389	88.3
18	6	5150	387	88.7
19	6	5200	384	89.0
20	5	5200	378	89.4
21	10	4800	402	86.1
22	9	4850	400	86.4
23	9	4900	398	86.8
24	8	4950	396	87.1
25	8	5000	395	87.4
26	7	5050	392	87.9
27	7	5100	390	88.2
28	6	5150	388	88.6
29	6	5200	385	89.0
30	5	5200	375	89.8

All operational parameters were measured using standard industrial instrumentation. Feedwater flow rate and natural gas consumption were measured using calibrated digital flow meters, while steam production was obtained from the steam flow meter installed on the main steam line. Feedwater hardness was analyzed using an EDTA-based hardness test kit, feedwater temperature was measured using a digital thermocouple, and boiler pressure was monitored using a calibrated pressure gauge installed on the boiler drum. The measurement procedures followed recognized standards, where water hardness analysis was conducted according to APHA Standard Methods for the Examination of Water and Wastewater, while boiler performance evaluation and efficiency calculations followed the ASME Performance Test Code (ASME PTC 4) for fired steam generators. The collected data were then used for several analytical calculations, including feedwater hardness load analysis, resin capacity evaluation, steam energy calculation, fuel energy input calculation, gas consumption–steam production ratio analysis, and boiler thermal efficiency evaluation using the direct efficiency method, to assess the relationship between feedwater treatment performance and boiler energy efficiency.

2.4 Data screening and preprocessing

To improve data reliability and ensure valid cross-data comparison, a data screening procedure was applied before analysis. Data points associated with non-steady-state conditions, such as startup, shutdown, or sudden load fluctuations, were excluded. In addition, outlier detection was performed based on inconsistencies in key operational parameters, including abnormal deviations in fuel consumption and imbalance between steam production and feedwater flow rate. Only data representing stable and consistent operating conditions were retained for further analysis. Despite these efforts, it is acknowledged that the dataset remains observational in nature, and complete control over all influencing variables is not feasible in real industrial environments.

2.5 Analytical and statistical methods

2.5.1 Engineering performance calculations

The performance of the boiler system was evaluated using standard engineering calculations, including:

- Feedwater hardness load
- Steam energy output
- Fuel energy input
- Gas-to-steam ratio
- Boiler thermal efficiency
- Water softener removal efficiency

The boiler efficiency was calculated using the direct efficiency method based on the ratio of useful heat output in steam to the total fuel energy input, following standard industrial practice.

2.5.2 Statistical analysis

To strengthen the analytical rigor and address the relationship between feedwater hardness and boiler efficiency, statistical analysis was performed using the collected dataset. First, a Pearson correlation analysis was conducted to evaluate the degree of association between feedwater hardness and boiler efficiency. Second, a simple linear regression model was applied to quantify the relationship between feedwater hardness (independent variable) and boiler efficiency (dependent variable). The regression model is expressed as Eq. (1), where η is boiler efficiency (%), H is feedwater hardness (mg/L), and β_0 and β_1 are regression coefficients. The coefficient of determination (R^2) was calculated to assess the strength of the relationship.

$$\eta = \beta_0 + \beta_1 H + \epsilon \quad (1)$$

Furthermore, to account for the influence of other operational variables, a multiple regression analysis was performed by including steam production rate and natural gas consumption as additional independent variables.

2.5.3 Uncertainty and variability analysis

To assess the reliability and consistency of the collected operational data, an uncertainty and variability analysis was performed using statistical approaches. The variability of key operational parameters was evaluated through the calculation of standard deviation values to determine the degree of data dispersion during the observation period. This analysis provides an indication of the stability of the boiler operating conditions and the consistency of the measured parameters.

Furthermore, graphical data presentations were supplemented with error bars representing the variability of the measurements in order to enhance data interpretation and improve the clarity of the observed trends. The inclusion of these statistical indicators supports a more comprehensive evaluation of the relationship between feedwater hardness and boiler thermal performance.

2.6 Study limitations

This study was conducted using observational data obtained from actual industrial operating conditions; therefore, complete control over all variables influencing boiler performance could not be fully achieved. Operational parameters such as production load fluctuations, combustion conditions, and other external factors may contribute to variations in the measured performance data. Consequently, the analysis in this study is primarily intended to identify statistical relationships and operational trends rather than to establish definitive causal relationships between variables.

Furthermore, the findings presented in this study should be interpreted within the context of real industrial operation, which inherently includes dynamic and variable conditions. Despite the implementation of data screening and stability criteria, a certain degree of operational uncertainty remains unavoidable. Nevertheless, the use of field-based operational data provides practical insights into the relationship between feedwater quality and boiler thermal performance under actual industrial conditions.

3 Results and discussion

3.1 Operational characteristics of the boiler system

The operational data collected during the 30-day observation period indicate that the boiler system operated under relatively stable industrial conditions (Fig. 3). Feedwater hardness after treatment by the water softener system ranged from 5 to 10 mg/L, while steam production remained within the range of 4800–5200 kg/h. Natural gas consumption varied between 375 and 402 Nm³/h, and the calculated boiler thermal efficiency ranged from 86.0% to 89.8%.

The relatively narrow fluctuation in steam production, feedwater temperature, and boiler pressure indicates that the system operated under near steady-state conditions during the monitoring period. This operational consistency is important because it improves the comparability of the collected datasets and reduces the influence of extreme transient conditions on the analysis results. The relatively stable operating conditions also support the validity of evaluating the statistical relationship between feedwater hardness and boiler thermal performance.

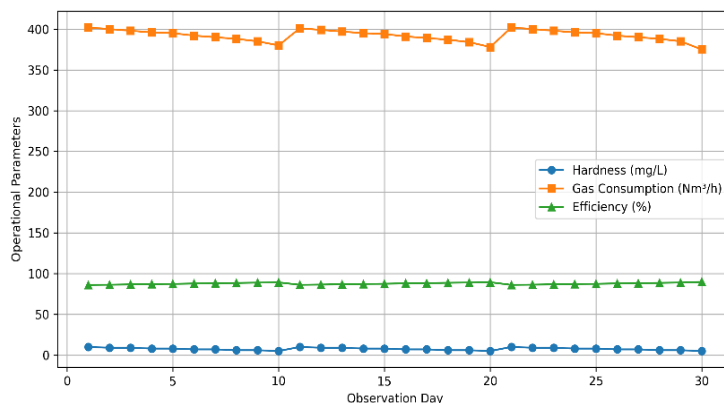


Fig. 3. Daily operational trends of feedwater hardness, boiler thermal efficiency, and natural gas consumption during the 30-day observation period

Previous studies investigating feedwater treatment systems have also reported that the regeneration process and flow rate conditions significantly influence water softener performance. Proper regeneration procedures ensure that the ion exchange resin maintains high removal efficiency and prevents premature saturation of the resin bed [19]. Therefore, maintaining optimal resin regeneration cycles is essential for ensuring stable feedwater quality and preventing a hardness breakthrough into the boiler system [6].

3.2 Feedwater hardness and boiler performance

The results show a gradual increase in boiler thermal efficiency as feedwater hardness decreased (Table 1). At hardness levels close to 10 mg/L, the boiler efficiency was observed in the range of approximately 86–86.5%, whereas at hardness levels near 5 mg/L, the efficiency increased to approximately 89–89.8%. Simultaneously, lower hardness levels were associated with reduced natural gas consumption and lower gas-to-steam ratios.

This trend is consistent with the thermodynamic behavior of boiler systems, where lower concentrations of hardness-forming minerals reduce the potential for scale formation on heat transfer surfaces. Reduced scale deposition can improve heat transfer effectiveness and lower thermal resistance inside the boiler tubes [20][21][22]. However, the present study does not directly measure scale thickness or fouling resistance; therefore, the observed trend should be interpreted as an operational association rather than direct proof of a causal mechanism.

3.3 Correlation analysis

Fig. 4 presents the correlation heatmap of the main operational parameters observed during the 30-day monitoring period, including feedwater hardness, steam production, natural gas consumption, and boiler thermal efficiency. The heatmap visually illustrates the

strength and direction of the linear relationships among the variables using Pearson correlation coefficients.

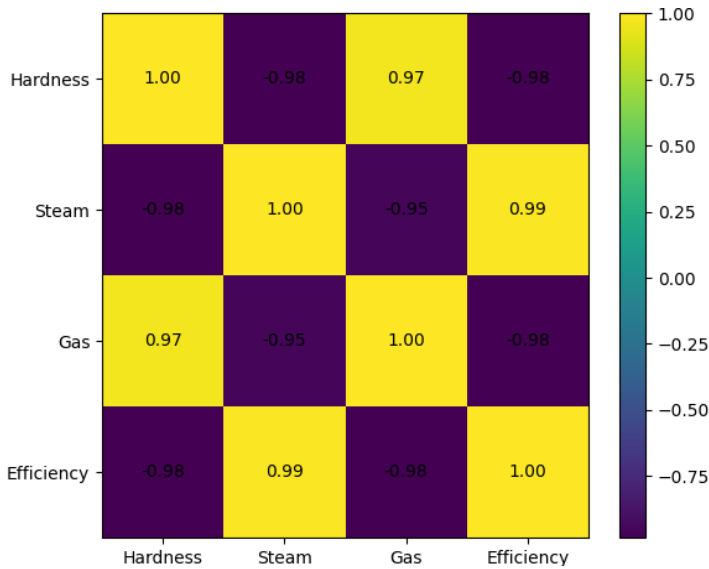


Fig. 4. Correlation heatmap of operational parameters

The analysis shows that feedwater hardness exhibits a very strong negative correlation with boiler thermal efficiency ($r = -0.98$). This indicates that lower hardness levels are strongly associated with higher boiler efficiency under the observed operating conditions. This finding supports the regression analysis presented in the previous section and suggests that improved feedwater quality contributes to better thermal performance.

In addition, feedwater hardness shows a strong positive correlation with natural gas consumption ($r = 0.97$), indicating that higher hardness levels tend to be associated with increased fuel usage. This trend may be related to reduced heat transfer effectiveness caused by scale formation inside the boiler tubes, which can increase the energy required to generate steam. The heatmap also indicates that steam production has a very strong positive correlation with boiler efficiency ($r = 0.99$) and a negative correlation with gas consumption ($r = -0.95$). These results suggest that more stable and efficient steam generation is associated with lower fuel consumption and improved boiler performance.

Overall, the correlation heatmap provides quantitative evidence that the operational variables are strongly interrelated. However, because the analysis is based on observational industrial data, the identified relationships should be interpreted as statistical associations rather than definitive causal relationships.

3.4 Regression analysis

In Fig. 5, the x-axis represents feedwater hardness (mg/L), while the y-axis represents boiler thermal efficiency (%). The blue data points indicate the actual operational observations, whereas the regression line represents the statistical model obtained from the linear regression analysis. The regression equation is shown in Eq. (2).

$$\eta = 92.95 - 0.70H \quad (2)$$

Indicates that an increase of 1 mg/L in feedwater hardness is statistically associated with an approximate decrease of 0.70% in boiler thermal efficiency. The negative slope of the regression line demonstrates an inverse relationship between the two variables, where higher hardness levels tend to correspond to lower boiler efficiency.

Fig. 5 illustrates the linear regression relationship between feedwater hardness and boiler thermal efficiency. The negative slope of the regression line indicates that increasing feedwater hardness is statistically associated with decreasing boiler efficiency. The relatively close distribution of the data points around the regression line demonstrates a strong fit between the regression model and the

operational dataset, which is consistent with the high coefficient of determination (R^2) obtained from the analysis.

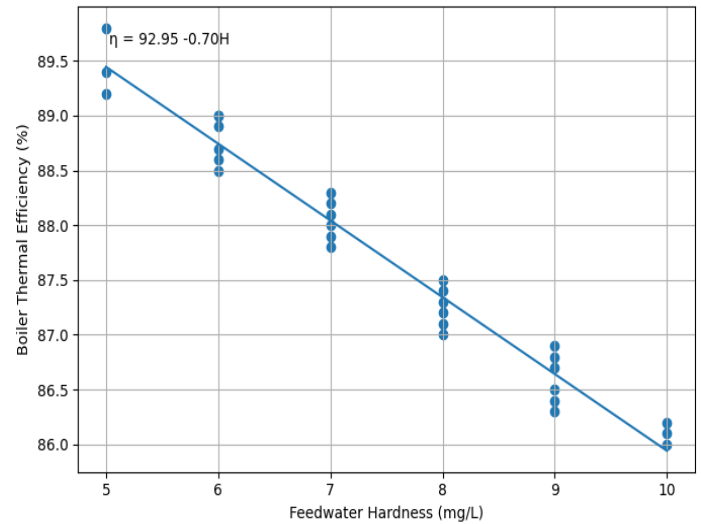


Fig. 5. Linear regression analysis between feedwater hardness and boiler thermal efficiency

The regression model further suggests that lower feedwater hardness levels are associated with improved thermal performance and reduced fuel consumption under relatively stable operating conditions. However, because the study is based on observational industrial data, the relationship should be interpreted as a statistical association rather than definitive causality.

The regression statistics presented in Table 2 indicate that the developed regression model provides a strong statistical representation of the relationship between feedwater hardness and boiler thermal efficiency. The high coefficient of determination ($R^2 = 0.96$) suggests that approximately 96% of the variation in boiler efficiency can be statistically associated with changes in feedwater hardness under the observed operating conditions. In addition, the negative regression slope indicates that increasing hardness levels are associated with decreasing thermal efficiency.

Table 2. Regression statistics for the relationship between feedwater hardness and boiler thermal efficiency

Parameter	Value
Regression equation	$\eta = 92.95 - 0.70H$
Dependent variable	Boiler thermal efficiency (%)
Independent variable	Feedwater hardness (mg/L)
Pearson correlation coefficient (r)	-0.98
Coefficient of determination (R^2)	0.96
Adjusted R^2	0.96
Regression slope (β_1)	-0.70
Intercept (β_0)	92.95
Standard error	0.12
p-value	< 0.001
Number of observations (n)	30

Furthermore, the Pearson correlation coefficient ($r = -0.98$) and the statistically significant p-value (< 0.001) demonstrate a very strong negative association between the two variables. These results strengthen the analytical interpretation of the operational dataset and support the conclusion that feedwater quality is closely related to boiler thermal performance. Nevertheless, due to the observational nature of the industrial data, the identified relationship should be interpreted as a statistical association rather than definitive causality.

The ANOVA results presented in Table 3 indicate that the regression model is statistically significant, as demonstrated by the high F-value (640.25) and the p-value below 0.001. These results confirm that the developed regression model provides a meaningful statistical representation of the relationship between feedwater hardness and boiler thermal efficiency under the observed operating conditions.

Table 3. ANOVA results for the linear regression model between feedwater hardness and boiler thermal efficiency

Source of Variation	Degrees of freedom (df)	Sum of squares (SS)	Mean square (MS)	F-value	p-value
Regression	1	26.48	26.48	640.25	< 0.001
Residual (Error)	28	1.16	0.041		
Total	29	27.64			

In addition, the relatively small residual error compared to the regression sum of squares indicates that the model explains a substantial proportion of the variability in the operational dataset. This finding supports the reliability of the regression analysis and strengthens the quantitative interpretation of the relationship between feedwater hardness and boiler thermal performance. Nevertheless, because the study is based on observational industrial data, the identified relationship should be interpreted as a statistical association rather than definitive causality.

3.5 Variability and uncertainty analysis

An uncertainty and variability analysis was conducted to evaluate the consistency of the operational dataset. The standard deviation values of the key parameters indicate relatively low operational variability throughout the observation period, particularly in steam production and fuel consumption. This result supports the assumption that the boiler system operated under sufficiently stable conditions for comparative statistical analysis. Fig. 6 shows that the variability of boiler thermal efficiency remained relatively low throughout the observation period, as indicated by the limited standard deviation values. This suggests that the operational conditions were sufficiently stable to support comparative statistical analysis.

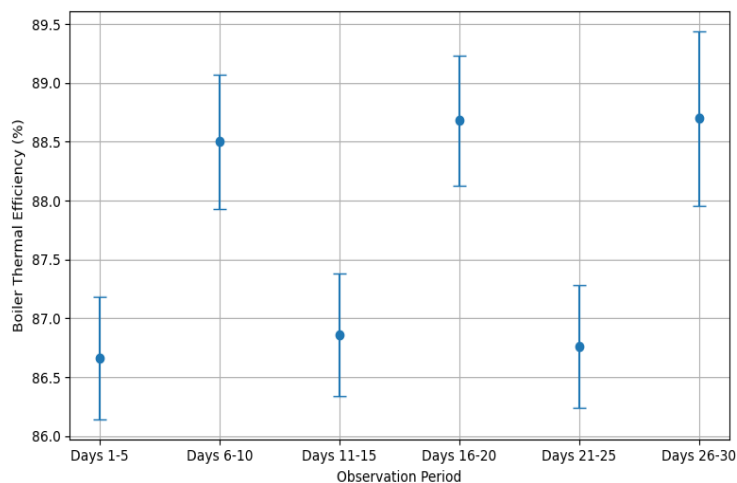


Fig. 6. Variability analysis of boiler thermal efficiency

Fig. 6 shows that the variability of boiler thermal efficiency remained relatively low throughout the observation period, as indicated by the limited standard deviation values. This suggests that the operational conditions were sufficiently stable to support comparative statistical analysis. In addition, graphical analyses equipped with error bars demonstrate that the observed trends between hardness and efficiency remain consistent despite minor operational fluctuations. The inclusion of variability analysis strengthens the reliability of the dataset and reduces uncertainty in the interpretation of the regression results.

3.6 Comparison with previous studies

The results obtained in this study are generally consistent with previous investigations reporting that feedwater quality plays an important role in boiler thermal performance [23][24]. Several studies have reported that increased hardness levels may promote scale formation on heat transfer surfaces, which can reduce heat transfer effectiveness and increase fuel consumption during boiler operation [25][26][27]. The strong negative statistical association identified between feedwater hardness and boiler thermal efficiency in the present study is therefore consistent with the general

thermodynamic behavior reported in earlier boiler performance studies.

However, unlike many previous studies that were primarily conducted under laboratory-scale conditions or based on theoretical calculations, the present work utilizes operational field data collected from an industrial fire-tube boiler operating under actual production conditions over a 30-day observation period. In addition, this study strengthens the conventional engineering evaluation through the incorporation of correlation analysis, regression modeling, ANOVA, and variability assessment. Therefore, the contribution of this study lies not only in confirming previously reported operational trends, but also in providing a statistically supported field-based evaluation framework for analyzing boiler performance under real industrial operating conditions.

3.7 Industrial implications

From an industrial perspective, the results suggest that maintaining low feedwater hardness through effective water treatment contributes to improved thermal performance and lower fuel consumption. However, feedwater quality should not be considered the sole factor affecting boiler efficiency. Other operational aspects, including combustion efficiency, blowdown management, excess air control, and heat losses, remain important factors in achieving optimal boiler performance. Therefore, improving boiler efficiency requires an integrated operational strategy that combines effective feedwater treatment with comprehensive boiler operation and maintenance practices.

4 Conclusions

Based on the operational and statistical analyses conducted in this study, feedwater hardness shows a significant statistical association with the thermal efficiency of the industrial fire-tube boiler system. Lower feedwater hardness levels were consistently associated with improved boiler efficiency, reduced natural gas consumption, and lower gas-to-steam ratios under relatively stable operating conditions. The regression analysis further demonstrated a strong quantitative relationship between hardness and efficiency, as indicated by the high coefficient of determination obtained from the operational dataset. The results also indicate that boiler thermal performance is influenced by multiple operational factors, including steam production rate and fuel utilization. Therefore, feedwater quality should be considered as one important component within a broader boiler performance management strategy. Although this study was based on observational industrial data and did not establish direct causality, the use of real operational data provides practical insights into the relationship between feedwater quality and boiler efficiency. Overall, the findings support the role of effective feedwater treatment in improving thermal performance and energy utilization in industrial boiler systems.

References

- [1] Y. E. Demirel, E. Simsek, E. Ozturk, and M. Kitis, "Selection of priority energy efficiency practices for industrial steam boilers by PROMETHEE decision model," *Energy Effic.*, vol. 14, no. 8, p. 89, Nov. 2021, doi: 10.1007/s12053-021-10007-8.
- [2] P. Saini, M. Ghasemi, C. Arpagaus, F. Bless, S. Bertsch, and X. Zhang, "Techno-economic comparative analysis of solar thermal collectors and high-temperature heat pumps for industrial steam generation," *Energy Convers. Manag.*, vol. 277, p. 116623, Feb. 2023, doi: 10.1016/j.enconman.2022.116623.
- [3] A. Shokri and M. Sanavi Fard, "Principles, operational challenges, and perspectives in boiler feedwater treatment

- process,” *Environ. Adv.*, vol. 13, p. 100389, Oct. 2023, doi: 10.1016/j.envadv.2023.100389.
- [4] R. E. Itika, H. Z. Belachew, D. F. Tegegn, and A. O. Salau, “Improving Industrial Boiler Efficiency With Quantitative Feedback Theory-Based Controllers”, doi: 10.1002/adc2.70010.
- [5] S. Janta-Lipińska, A. Shkarovskiy, and Ł. Chrobak, “Improving the Fuel Combustion Quality Control System in Medium Power Boilers,” *Energies*, vol. 17, no. 12, p. 3055, Jan. 2024, doi: 10.3390/en17123055.
- [6] A. B. Kose, N. V. Nikam, S. B. Jaju, and V. W. Khond, “A review on methods of water softening processes for improving efficiency of bio-mass fired boiler,” *Mater. Today Proc.*, vol. 103, pp. 383–387, Jan. 2024, doi: 10.1016/j.matpr.2023.09.031.
- [7] T. I. Petrova and O. V. Egoshina, “Analyzing the State of Phosphate Water Chemistries in High-Pressure Drum Boilers,” *Therm. Eng.*, vol. 71, no. 11, pp. 1016–1023, Nov. 2024, doi: 10.1134/S0040601524700472.
- [8] D. Wang, H. Li, C. Wang, Y. Zhou, X. Li, and M. Yang, “Thermodynamic analysis of coal-fired power plant based on the feedwater heater drainage-air preheating system,” *Appl. Therm. Eng.*, vol. 185, p. 116420, Feb. 2021, doi: 10.1016/j.applthermaleng.2020.116420.
- [9] Y. Xu, H. Wang, X. Liu, J. Zhu, J. Xu, and M. Xu, “Mitigating CO₂ emission in pulverized coal-fired power plant via co-firing ammonia: A simulation study of flue gas streams and exergy efficiency,” *Energy Convers. Manag.*, vol. 256, p. 115328, Mar. 2022, doi: 10.1016/j.enconman.2022.115328.
- [10] L. Chen, Y. Liao, and X. Ma, “Economic analysis on sewage sludge drying and its co-combustion in municipal solid waste power plant,” *Waste Manag.*, vol. 121, pp. 11–22, Feb. 2021, doi: 10.1016/j.wasman.2020.11.038.
- [11] C. Polski, T. Polski, J. Roman, R. Wróblewski, J. Bartoszewicz, and B. Ceran, “A novel concept to improve the flexibility of steam power plants using an electric feedwater heater,” *Appl. Therm. Eng.*, vol. 236, p. 121661, Jan. 2024, doi: 10.1016/j.applthermaleng.2023.121661.
- [12] Y. E. Demirel, E. Simsek, E. Ozturk, and M. Kitis, “Selection of priority energy efficiency practices for industrial steam boilers by PROMETHEE decision model,” *Energy Effic.*, vol. 14, no. 8, p. 89, Nov. 2021, doi: 10.1007/s12053-021-10007-8.
- [13] A. F. Meese et al., “Opportunities and Challenges for Industrial Water Treatment and Reuse,” *ACS EST Eng.*, vol. 2, no. 3, pp. 465–488, Mar. 2022, doi: 10.1021/acsestengg.1c00282.
- [14] K. Kumar, S. Kumar, and H. S. Gill, “Role of Surface Modification Techniques to Prevent Failure of Components Subjected to the Fireside of Boilers,” *J. Fail. Anal. Prev.*, vol. 23, no. 1, pp. 1–15, Feb. 2023, doi: 10.1007/s11668-022-01556-w.
- [15] R. S. Jha and M. M. Lele, “Dynamic modeling of a water tube boiler,” *Heat Transf.*, vol. 51, no. 7, pp. 6087–6121, 2022, doi: 10.1002/htj.22581.
- [16] E. Mohammadi Zahrani, “Premature Failure of Grade-316Ti Stainless Steel Tubing in a Boiler Feed-Water Heat Exchanger in a Steel Complex,” *J. Fail. Anal. Prev.*, vol. 21, no. 1, pp. 61–73, Feb. 2021, doi: 10.1007/s11668-020-01037-y.
- [17] R. Ranjeeth, D. Aditya, A. Gautam, S. P. Singh, and S. Bhattacharya, “Failure investigation of a water-wall tube of fossil-fuel fired boiler,” *Eng. Fail. Anal.*, vol. 155, p. 107727, Jan. 2024, doi: 10.1016/j.engfailanal.2023.107727.
- [18] I. A. Kachalla and C. Ghiaus, “Electric Water Boiler Energy Prediction: State-of-the-Art Review of Influencing Factors, Techniques, and Future Directions,” *Energies*, vol. 17, no. 2, p. 443, Jan. 2024, doi: 10.3390/en17020443.
- [19] A. A. Mohammad and A. Kasmin, “Optimization Of Boiler Feedwater Treatment Through Varies Softener Regeneration Process Inlet Pressure,” *Prog. Eng. Appl. Technol.*, vol. 4, no. 2, pp. 425–435, Dec. 2023.
- [20] H. Park, J. Lee, J. Lim, H. Cho, and J. Kim, “Optimal operating strategy of ash deposit removal system to maximize boiler efficiency using CFD and a thermal transfer efficiency model,” *J. Ind. Eng. Chem.*, vol. 110, pp. 301–317, Jun. 2022, doi: 10.1016/j.jiec.2022.03.004.
- [21] H. Yin, D. Jin, J. Yan, X. Liu, M. Li, and H. Wang, “A comprehensive model for the prediction of boiler platen superheater tube temperature considering the effects of ash deposits and oxide scale,” *Appl. Therm. Eng.*, vol. 269, p. 125953, Jun. 2025, doi: 10.1016/j.applthermaleng.2025.125953.
- [22] S. Tang, L. Ding, Z. Zhao, J. Zhou, and H. Bian, “Dynamic modeling and improvement on ash deposition and thermal–hydraulic characteristics in a waste heat boiler of cement kiln,” *Appl. Therm. Eng.*, vol. 213, p. 118826, Aug. 2022, doi: 10.1016/j.applthermaleng.2022.118826.
- [23] M. V. Chamorro, J. C. Avella, F. G. Barrios, A. M. Ávila, and M. P. Marriaga, “Operational control of the energy performance of a water-tube boiler using intelligent monitoring of operating variables and parameters,” *EUREKA Phys. Eng.*, no. 3, pp. 45–60, May 2024, doi: 10.21303/2461-4262.2024.003222.
- [24] M. R. I. Rusdi, T. Bashkeran, and Z. Ahmad, “Data Driven Technique for Palm Oil Mills Boiler Water Quality Monitoring in State of Perak Malaysia,” *Malays. J. Fundam. Appl. Sci.*, vol. 18, no. 2, pp. 171–183, May 2022, doi: 10.11113/mjfas.v18n2.2242.
- [25] S. Kumar, A. Handa, V. Chawla, N. K. Grover, and R. Kumar, “Performance of thermal-sprayed coatings to combat hot corrosion of coal-fired boiler tube and effect of process parameters and post-coating heat treatment on coating performance: a review,” *Surf. Eng.*, vol. 37, no. 7, pp. 833–860, Jul. 2021, doi: 10.1080/02670844.2021.1924506.
- [26] J. B. Morake, J. M. Mutua, M. M. Ruthandi, and E. O. Olakanmi, “The potential use of laser cladded functionally graded materials to mitigate degradation in boiler tube heat exchangers for power plant applications: A review,” *Surf. Eng.*, vol. 39, no. 6, pp. 677–721, Jun. 2023, doi: 10.1080/02670844.2023.2249653.
- [27] K. Kumar, S. Kumar, and H. S. Gill, “Role of Surface Modification Techniques to Prevent Failure of Components Subjected to the Fireside of Boilers,” *J. Fail. Anal. Prev.*, vol. 23, no. 1, pp. 1–15, Feb. 2023, doi: 10.1007/s11668-022-01556-w.