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Performance Analysis of Circulating Fluidized Bed Boilers in Steam Power Plants Using the Direct Method

[1]*M. Munadi, [2]Mochammad Ariyanto

[1,2]Mechanical Engineering Department, Faculty of Engineering, Diponegoro University, Jl. Prof. H. Soedarto, SH, Tembalang-Semarang 50275, Indonesia
*Corresponding Author's E-mail: munadi@ft.undip.ac.id

***Abstract -* Electricity demand in Indonesia continues to increase in line with population growth, infrastructure development, and industrial sector growth. Power plants, including coal-fired power plants, remain the backbone of the national energy supply despite the ongoing transition to renewable energy. In coal-fired power plants, boilers play an important role as producers of high-pressure steam to drive turbines. Boiler efficiency is a key indicator of operational performance, where a decrease in efficiency results in increased fuel consumption, operational costs, and emissions. Therefore, monitoring and evaluating boiler efficiency is very important for optimizing the power generation system. This practical work report analyzes the performance of circulating fluidized bed boilers by calculating thermal efficiency based on actual operational data using the direct method. The direct method is the calculation of boiler efficiency by comparing the heat generated by steam to the heat from fuel. From the calculation results, an average efficiency value of 72% was obtained. The calculation results showed a decrease in boiler efficiency compared to design conditions. To identify the causative factors, Fault Tree Analysis (FTA) was used as a systematic identification method. Based on the observations, the decrease in efficiency was primarily caused by plugging at the coal feeder outlet, leaks in the drain valve, and damage to the air preheater (APH) tube due to chemical attack, which emphasizes the importance of preventive maintenance and ongoing performance evaluation to maintain the efficiency and reliability of the generating system.**

Keywords: Boiler Efficiency, Fault Tree Analysis, Power Generations.

I. INTRODUCTION

Electrical energy is one of the primary needs supporting modern life and a key factor in national development. Amidst economic growth, urbanization, and increasing use of technology, demand for electrical energy in Indonesia continues to increase annually[1]. To ensure the reliability of the national electricity supply, various types of power plants are operated, ranging from renewable energy-based plants to fossil fuel-based plants such as Steam Power Plants. To date, Steam Power Plants remain the backbone of Indonesia's electricity system due to their ability to generate large amounts of power and operate stably[2].

Steam Power Plants utilize the process of converting thermal energy into mechanical energy and then into electrical energy. One of the main components in a Steam Power Plants system is the boiler, a device used to produce high-pressure steam from the combustion of fuel, usually coal. This steam is then used to drive a turbine connected to a generator. Therefore, the performance and efficiency of the boiler significantly impact the overall efficiency of the plant[3]As a vital component, the boiler in a Steam Power Plants must be maintained to ensure optimal operation. Decreased boiler efficiency can lead to increased fuel consumption, decreased plant performance, and increased exhaust emissions, which negatively impact the environment.

To understand and control boiler performance, a comprehensive evaluation of its efficiency is required. One common method for calculating boiler efficiency is the direct method, which compares the heat energy carried by the outgoing steam to the heat energy supplied by the fuel. Further analysis is also required to determine the causes of the decline in efficiency. In this case, the Fault Tree Analysis (FTA) approach is used to systematically and logically map the possible causes of the decline in efficiency[4]. Efficiency calculations are performed using the direct method to obtain the actual thermal efficiency value. Furthermore, an analysis of the causes of potential efficiency decline is carried out using Fault Tree Analysis (FTA). This approach is expected to provide a comprehensive overview of the factors affecting boiler efficiency and provide a basis for recommendations for operational improvements to support the efficiency and sustainability of electricity generation at coal-fired power plants.

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II. RESEARCH OBJECT

This research aims to contribute to a comprehensive understanding of boiler efficiency and performance, thus providing a basis for developing system optimization strategies to improve boiler efficiency and reliability. Through boiler efficiency analysis, it is hoped that the relationship between data sheets and calculations based on operational data can be established and the causes of the decline in boiler performance can be identified.[5].

Boilers function to generate heat energy to heat the working fluid flowing within them by converting the energy contained in the fuel into heat[6]. This heat is used to heat water until it turns into steam at a high temperature and pressure. The resulting steam is then used as mechanical energy to turn a turbine system and is connected to a generator, which generates electricity. Boilers come in several types, such as Circulating Fluidized Bed Boilers, Once-Through Boilers, and others[7].

Circulating Fluidized Bed (CFB) boilers operate on the principle of burning fuel in a fluidized state. In this process, fuel is mixed with materials such as sand and fed into the combustion chamber (furnace) along with a flow of air from below. This airflow is strong enough to lift and mix the fuel particles and bed material, creating a fluidized state that allows for even combustion. The heat energy from combustion is used to heat water in the boiler tubes until it turns into steam[8].

Boiler efficiency is a measure of boiler performance calculated by comparing the energy absorbed by the working fluid in the boiler to the heat energy supplied by the fuel. According to USA Standard ASME PTC 4: Power Test Code for Fired Steam Generator Units, there are two methods for evaluating boiler efficiency: direct and indirect[9].

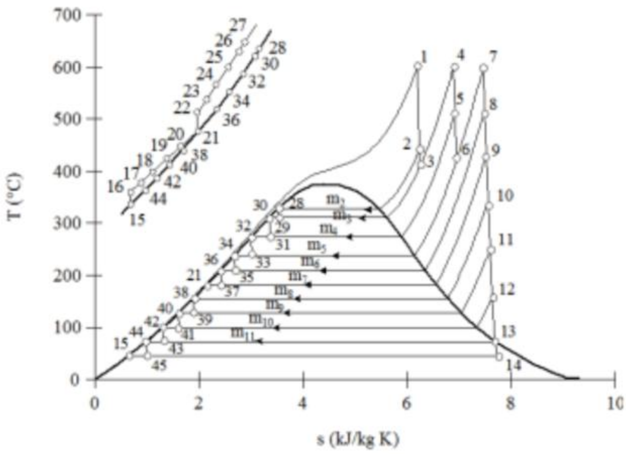
The Steam Power Plants uses a Circulating Fluidized Bed (CFB) boiler from Dongfang Boiler (Group) CO., LTD, type DG430/9.81-II2. This boiler has a production capacity of 430 t/h, an operating pressure of 9.81 MPa, and a steam temperature of 540°C. Figure 2.1 shows the Steam Power Plants's circulating fluidized bed boiler.

Figure 2.1: Circulating Fluidized Bed Steam Power Plants

The method used is the direct method. The direct method, also known as the input-output method, assesses boiler efficiency simply by comparing the heat received by the working fluid with the heat available from the fuel. The output energy is the heat absorbed to produce steam in the superheater, while the input energy comes from the heat content of the boiler fuel [10].

III. DATAFOR ANALYSIS

The boiler used is a Circulating Fluidized Bed (CFB) boiler from Dongfang Boiler (Group) CO., LTD, type DG430/9.81-II2. This boiler has a steam production capacity of 430 tons per hour, an operating pressure of 9.81 MPa, and a steam temperature of 540^{0}C. The following is Figure 3.1, which shows the CFB boiler sheet.



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	Main steam pressure Mpa	Main steam temperature °C	Average Efficiency	CO_2 emissions g/kWh	Power generation Cost US¢ /kW	Total plant capital cost USD /kW
Subcritical	<22,1	≤ 565	36	766-789	4,0-4,5	1095-1150
Supercritical	22,1-25	540-580	45	722	3,5-3,7	950-1350
Ultra Supercritical	>25	>580	>45	<722	4,2-4,7	1160-1190

Specification:

- Capacity: 2 x 110 MW
- Type : Circulation Fluidized Bed
- Natural circulation, SingleDrum, Balanced Ventilation and Steel frame
- Superheater outlet steam flow: 430 t/h
- Superheater outlet steampressure : 9.81 Mpa.g
- Superheater outlet steam temperature : 540 ºC
- Feed-water temperature : 232ºC
- Exhaust gas temperature : 140ºC

Figure 3.1: CFB Boiler Sheet

Based on the data sheet in Figure 3.1, several boiler parameter data can be presented as shown in Table 3.1.

Table 3.1: Boiler Parameter

No.	Parameter	Nilai	Satuan
1	Steam Generated	430	t/h
2	Steam Pressure	9.81	MPa
3	Steam Temperature	540	°C
4	Feed Water Temperature	232	°C
5	Exhaust Gas Temperature	140	°C
6	Efficiency	91.5	%

To support boiler efficiency analysis, actual operational data is required. This data is obtained directly from the control room in real time and through field reviews with operators, allowing for a picture that accurately reflects the actual conditions in the field. Table 3.2 shows the operational data.

Table 3.2: Operational Data

Parameter	Date			
	25/07/25	30/07/25	04/08/25	06/08/25
Quantity of Coal Consumed (kg/s)	21,8	21,66	21,8	22,1
GCV of Coal (Kj/kg)	15899,2	15899,2	15899,2	15899,2
Heat Input Data				
Feed Water Temperature (°C)	226	226	226	227
Feed Water Pressure (MPa)	11,2	11,4	11,5	11,39
Feed water Flow (kg/s)	100,02	101,72	101,38	101,1
Entalpy of Feed Water (kJ/kg)	952,2	961	965	961
Heat Output Data				
Steam Generated Flow (kg/s)	97	99,5	99,27	101,47
Steam Pressure (MPa)	8,37	8,47	8,52	8,64
Steam Temperature (°C)	532,3	531	531,4	531
Entalphy of Steam (kJ/kg)	3437	3465	3465	3462
Spray Mass Flow (kg/s)	11,325	10,88	11,13	11,27
Spray Mass Pressure (MPa)	9,59	8,47	9,2	11,73
Spray Temperature (°C)	226	226	226	227
Entalphy of Spray	951,4	940	945	965
Steam Drum Flow (kg/s)	100,5	101	100,83	101,6
Steam Drum Pressure (Mpa)	9,39	9,45	9,41	9,64
Steam Drum Temperature (°C)	300	300	300	300
Entalphy of Steamdrum	2950	2785	2783	2786
Blowdown (kg/s)	0,55	0,55	0,55	0,55
Load (MW)	100,3	101,2	101,3	102
Netto (MW)	87,8	88	88	88,8

IV. RESULT AND DISCUSSION

Boiler efficiency indicates how much of the fuel's heat energy is used to produce steam, and the direct method calculates it by comparing the energy absorbed by the working fluid with the total heat energy from the fuel[1].The following is the efficiency formula using the direct method:

$$\eta = \frac{(Q_{mst} - Q_{spray})\, x\, (h_{mst} - h_{spray}) + Q_{spray}\,(h_{mst} - h_{spray}) + Q_{blowdown}\,(h_{steamdrum} - h_{feedwater})}{(Q_{coal\ consumed}\ x\ GCV\ batubara)} \quad (4.1)$$

Dimana:

Q_{mst} = Mainsteam Flow (kg/jam)
$Q_{blowdown}$ = Blowdown flow (kg/jam)
h_{mst} = Mainsteam entalphy (kcal/jam)
h_{spray} = Spray Entalphy (kcal/jam)
$h_{steamdrum}$ = Steamdrum Entalphy (kcal/jam)
$Q_{coal\ Consu\,med}$ = Coal Flow (kg/jam)

Boiler efficiency was calculated using equation (4.1) by entering boiler operational data. The calculation results can be seen in Table 4.1.

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Table 4.1: Boiler Efficiency Data

Parameter	Date			
	25/07/25	30/07/25	04/08/25	06/08/25
Efficiency (%)	70,1	73,02	72,46	72,39

Specific Fuel Consumption is a value used to measure the efficiency of fuel use in generating power[1].SFC indicates the amount of fuel required to produce one unit of energy. The formula for Specific Fuel Consumption is as follows:

$$SFC = \frac{Q_{Coal\ consumed}}{Load_{Gross}} \tag{4.2}$$

The boiler SFC calculation is carried out using equation (4.2) by entering the boiler operational data. The calculation results can be seen in Table 4.2.

Table 4.2: SFC Data

Parameter	Date			
	25/07/25	30/07	04/08/25	06/08/25
SFC	0,782	0,771	0,775	0,78

NPHR is an indicator of the total efficiency of a power plant in converting fuel energy into clean electrical energy[1]. NPHR indicates the amount of heat energy required to produce one kilowatt-hour of usable electricity. The following is the NPHR formula:

$$NPHR = \frac{Q_{Coal\ consumed} \times GCV}{Load_{Netto}} \tag{4.3}$$

The NPHR calculation is carried out using equation (4.3) by entering boiler operational data. The calculation results can be seen in Table 4.3.

Table 4.3: NPHR Data

Parameter	Date			
	25/07/25	30/07/25	04/08/25	06/08/25
NPHR	3486	3478,1	3478,1	3495,7

GPHR is a generator efficiency parameter based on the total (gross) electrical energy produced before deducting the generator's internal consumption[1]. GPHR indicates the amount of heat energy from fuel required to produce one kilowatt hour of gross electricity.

$$GPHR = \frac{Q_{Coal\ consumed} \times GCV}{Load_{Gross}} \tag{4.4}$$

GPHR calculations were carried out using equation (4.4) by entering boiler operational data. The calculation results can be seen in Table 4.4.

Table 4.4: GPHR Data

Parameter	Date			
	25/07/25	30/07/25	04/08/25	06/08/25
GPHR	3051,5	3005	3021,4	3043,4

Based on boiler efficiency data, the average efficiency value was 71.99%. This value indicates that combustion and heat transfer performance in the boiler is not optimal. Compared to the optimal boiler efficiency of 91.5%, there is a decrease of 19.5%. This decrease in efficiency indicates imperfections in the heat transfer stage from fuel to steam generation, which can be caused by various technical and operational factors.

The Fault Tree Analysis (FTA) method is highly relevant and effective as a systematic approach to identifying the causes contributing to this decrease in efficiency[11]. FTA allows for hierarchical mapping of various possible sources of problems, ranging from component failures to operational errors. Figure 4.1 shows the Fault Tree Analysis.

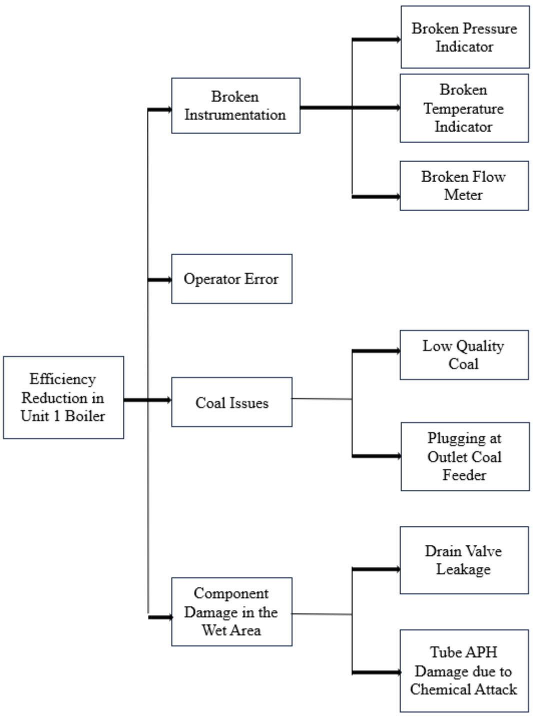

Figure 4.1: Fault Tree Analysis

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Based on field analysis, the probable causes of the problem were plugging at the coal feeder outlet, drain valve leakage, and Tube APH damage due to chemical attack.

1. Plugging at Outlet Coal Feeder

Plugging at the coal feeder outlet is a condition where the coal flow to the pulverizer or combustion chamber is blocked, which can reduce boiler efficiency. This blockage is generally caused by high moisture content, non-uniform particle size, or the accumulation of fine particles that clump together.

Variations in coal specifications from various sources can also worsen flow conditions if not properly adjusted. This results in unstable combustion, uneven heat distribution, and decreased performance of components such as the economizer and superheater.

2. Drain Valve Leakage

The drain valve in a boiler system functions to drain water only during cleaning or maintenance processes. However, in some cases, internal leaks occur due to wear or corrosion on the sealing surface, causing water to continue to leak even when the valve is closed.

This leakage causes water and energy waste because replacement water needs to be reheated to operating conditions, and it disrupts pressure stability and flow rate. As a result, the boiler has to work harder to maintain output[12]. At the power plant, some drain valves are rusted and require further maintenance. Figure 4.2 shows a drain valve.

Figure 4.2: Drain Valve

3. Tube APH Damage due to Chemical Attack

This occurs in the low-temperature zone due to chemical attack when flue gases containing SO_3 condense to form sulfuric acid (H_2SO_4) below the acid dew point. This acid condensate causes severe corrosion, especially at weld joints, leading to tube thinning and leakage. Causes include high coal sulfur content, low APH outlet temperature, and water vapor condensation at the inlet. Figure 4.3 shows corrosion on APH tubes.

Figure 4.3: Tube APH Corrosion

Based on the causes of the boiler performance decline, several repair recommendations are provided to address the existing issues. The repair recommendations are as follows.

1. Anti-Blocking Rotary Knife Implementation

This system works by slowly rotating a knife inside the feeder outlet to prevent clumping. Technically, the rotary knife consists of key components such as a scraper blade, a motor gearbox, and a housing. The system is designed to rotate at a speed of approximately 1 rpm and a torque of 50–150 Nm.

Research by Harahap and Dwiyantoro at the Sepuluh Nopember Institute of Technology supports the effectiveness of this device by designing and analyzing the performance of a rotary anti-blocking system in a coal bunker with a flow rate of 15–25 tons/hour. In the experiment, the system was able to maintain a stable coal supply without the need for manual cleaning for up to 12 hours of operation, compared to only 4 hours with a conventional system without anti-blocking[13].

2. Lapping on Sealing Surface

Lapping is a valve sealing surface repair method using an abrasive compound such as silicon carbide or aluminum oxide to restore smoothness and precision of contact between the valve disc and seat. This process removes micro-defects caused by wear or corrosion that cause internal leaks in drain valves. With sealing results approaching ANSI Class IV–V standards, lapping effectively prevents leaks, maintains system pressure, and improves energy efficiency without the need for component replacement.

3. Anti-Corrosion Coating with Hard-Facing Stellite

The application of hard-facing with Stellite material to the disc and valve seat surfaces is an effective solution to prevent

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internal leaks due to corrosion. Stellite, a cobalt-based alloy with elements of chromium, tungsten, and carbon, has high resistance to heat, corrosion, and abrasion, and maintains a hardness above 40 HRC at temperatures >500 °C. The coating process is carried out through PTAW welding, followed by machining and lapping to restore the sealing geometry[14].

4. Tube APH Coating with Thermal Spray Coating NiCr

Coating Air Preheater (APH) tubes with NiCr thermal spray coating is an effective solution to prevent corrosion caused by sulfuric acid condensation in the cold-end area. This method sprays molten NiCr metal powder onto the tube surface, forming a hard, corrosion-resistant protective layer.

The nickel content provides resistance to sulfidation, while the chromium forms a stable protective oxide. A study by Oksa et al. (2016) showed that NiCr coatings have superior high-temperature corrosion resistance, maintaining the tube's structural integrity and extending the service life of APHs[15].

V. CONCLUSION

Based on the CFB Boiler analysis, the actual boiler efficiency during four consecutive monitoring sessions was 70.10%, 73.02%, 72.46%, and 72.39%, with an average of 71.99%. This value is approximately 19.5% lower than the design efficiency of 91.5%, indicating a decrease in performance compared to optimal conditions. Specific Fuel Consumption (SFC) values measured during the same period ranged from 0.771–0.782 kg/kWh, with a Net Plant Heat Rate (NPHR) ranging from 3478.1–3495.7 kJ/kWh and a Gross Plant Heat Rate (GPHR) ranging from 3005–3051.5 kJ/kWh. This range remains within stable operating conditions, but indicates potential inefficiencies due to variations in operational conditions.

The difference between actual and design efficiency indicates potential system losses, both technical and operational. These factors need to be thoroughly identified through a systematic approach such as Fault Tree Analysis (FTA) to identify the root causes of efficiency decline and prioritize improvements. Based on the FTA analysis, several potential causes of efficiency decline were identified, including plugging of the coal feeder outlet, leaking drain valves, and tube damage in the air preheater due to chemical attack. These three factors result in suboptimal combustion, increased fuel consumption, and a decrease in the overall efficiency of the boiler system.

REFERENCES

[1] Tawil E, Ap L. Boiler Classification and Application Credit: 2 PDH. 2009.

[2] Hadi MF, Hidayat M, Widiarsih D, Murialti N. The Role of Electricity and Energy Consumption Influences Industrial Development Between Regions in Indonesia. *International Journal of Energy Economics and Policy* 2021;11:403–8. https://doi.org/10.32479/ijeep.11082.

[3] Tirumala Srinivas G. Efficiency of a Coal Fired Boiler in a Typical Thermal Power Plant. *American Journal of Mechanical and Industrial Engineering* 2017; 2:32. https://doi.org/10.11648/j.ajmie.20170201.15.

[4] Shams OA. Studying Boiler Reliability in a Petroleum Refinery by Using Fault Tree Analysis. 2012.

[5] Keith Burnard, Sankar Bhattacharya. Power Generation from Coal. 2011. https://doi.org/10.1787/5kg3n27ts06b-en.

[6] M Ihsan Riady, Bazlina Dawami Afrah, Nabilla Tania Rahma, Edda Anastasia Oktawina. Effect Analysis of Boiler Feed Water and Exhaust Gas Turbine Generator against Steam Products. *Journal of Mechanical Engineering Manufactures Materials And Energy* 2024;8:59–66. https://doi.org/10.31289/jmemme.v8i1.9766.

[7] Trojan M. Accepted Manuscript Modeling of A Steam Boiler Operation using the Boiler Nonlinear Mathematical Model. 2019.

[8] Arnab Mark. *Journal of Nuclear Energy Science and Power Generation Technology* 2012.

[9] Akademia Baru P, Khattak MA, Mohd Ali NS, Zainal Abidin NH, Azhar NS, Omar MH. Common Type of Turbines in Power Plant: A Review. vol. 3. 2016.

[10] Kareem B, Ewetumo T, Adeyeri MK, Oyetunji A, Olatunji OE. Design of Steam Turbine for Electric Power Production Using Heat Energy from Palm Kernel Shell. *Journal of Power and Energy Engineering* 2018;06:111–25. https://doi.org/10.4236/jpee.2018.611009.

[11] Khoirunnisa L, Basri H. Failure Analysis and Performance Assessment of Tubular Air Heater at PLTU South Sumatra V, 2021. https://doi.org/10.2991/ahe.k.210205.040.

[12] Hwang IS, Lee YL. Study on Performance Change in a Linear Compressor Considering Refrigerant Leakage Through the Suction Valve Clearance. *Journal of Mechanical Science and Technology* 2019; 33:2665–70. https://doi.org/10.1007/s12206-019-0514-8.

[13] Harahap CH, Dwiyantoro BA. Design and Analysis Performance of Rotary Anti Blocking at Coal Bunker Outlet, 2024, p. 080017. https://doi.org/10.1063/5.0208250.

Volume 4, Issue 11, pp 20-26, November-2025
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Article DOI: https://doi.org/10.47001/ICJES/2025.411004

[14] Chang S-S, Wu H-C, Chen C. Impact Wear Resistance of Stellite 6 Hardfaced Valve Seats with Laser Cladding. *Materials and Manufacturing Processes* 2008;23:708–13. https://doi.org/10.1080/10426910802317102.

[15] Oksa M, Metsäjoki J, Kärki J. Corrosion testing of thermal spray coatings in a biomass co-firing power plant. *Coatings* 2016; 6. https://doi.org/10.3390/coatings6040065.

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