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Original Article

Experimental Investigation for Optimization of Fluidization in AFBC Boiler while Operating it at Lower Steam Generation

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Abstract *- An industrial-scale Atmospheric Fluidized Bed Combustion (AFBC) boiler with a capacity of 66 TPH has been developed by Aarti Industries Limited, located in the Dahej region of Gujarat. In coal-fired AFBC boilers used in chemical industries, a decrease in chemical production reduces steam demand, leading to higher energy losses and increased specific coal consumption. To maintain operation above the recommended turndown ratio, industries often vent excess steam, which ultimately increases production costs. This study focuses on reducing dry flue gas losses in boilers operating below the recommended turndown ratio. Key parameters-fluidizing air flow, bed material height, and coal conveying air pressure-were analyzed to achieve an optimal flue gas exhaust temperature of 140°C at reduced steam loads of 20, 23, and 26 TPH. The exhaust flue gas temperature was reduced from 150°C to 140°C by selecting an optimized combination of operating parameters. The flue gas temperature dropped to as low as 133°C, leading to cold-end corrosion in the boiler's Induced Draft (ID) fans. The flue gas temperature dropped to as low as 133°C, resulting in cold-end corrosion of the boiler Induced Draft (ID) fans. Maintaining the flue gas temperature above 140°C helps prevent the formation of corrosive sulfur compounds, thereby extending the lifespan of the boiler cold-end components.*

Keywords *- AFBC boiler, Furnace fluidization, Windbox pressure, Steam generation pressure*.

1. Introduction

The persistent reliance on non-renewable energy, especially coal, significantly shapes global energy consumption patterns. In response to the diminishing availability of this crucial resource, initiatives are underway to enhance plant efficiency and optimize coal utilization [1]. Despite the global shift towards cleaner energy alternatives, coal is projected to remain a primary electricity generation source, particularly in numerous developing nations [2]. A key challenge within this domain involves improving the performance of large-scale coal-fired utility boilers, specifically concerning the enhancement of fluidization at reduced steam output rates. This particular challenge substantially influences both energy efficiency and operational expenses.

While considerable research has focused on enhancing combustion processes and mitigating emissions, insufficient attention has been devoted to optimizing fluidization within these particular operational parameters. This deficiency results in diminished boiler efficiency, increased energy consumption, and elevated operational expenses.

Consequently, the chemical sector has prioritized the enhancement of energy efficiency and the reduction of environmental impact associated with coal-fired boilers through performance optimization, with a specific emphasis on minimizing dry flue gas losses [3].

The operational characteristics of Atmospheric Fluidized Bed Combustion (AFBC) boilers under reduced steam generation are of considerable interest, given the need for effective and adaptable operation [23]. This investigation, therefore, focuses on the bed dynamics under conditions of limited fluidization, specifically when the bed is subjected to a reduced weight [18]. This study examines bed behavior by gradually reducing steam production while keeping fuel and air supply rates constant. Key operational parameters, including bed temperature, airflow rate, steam generation, and pressure fluctuations, are monitored to assess their influence on fluidization stability. Furthermore, a comprehensive evaluation of system performance necessitates an assessment of fuel efficiency, heat utilization, flue gas properties, and pollutant emissions. Consequently, maintaining the appropriate fuel-air mixture and mitigating issues such as incomplete combustion or inadequate fluidization are particularly critical during low-load operational scenarios. This approach allows us to understand how to keep the boiler operating effectively and efficiently, even when it's not under maximum demand.

The principal objectives of performance optimization encompass the improvement of combustion and thermal efficiency, the reduction of energy wastage, the enhancement of reliability and safety, and the mitigation of pollution [4].

2. Novelty of the Research

The present work is aimed to fill an important gap in the operational tuning of Atmospheric Fluidized Bed Combustion (AFBC) boilers at low steam demand conditions. Prior research has mainly concentrated on enhancing combustion efficiency, decreasing emissions and enhancing the overall boiler performance, while less attention has been paid to the integrated optimization of fluidization parameters for reducing dry flue gas losses in part-load operation.

In contrast to the previous studies which generally study individual operating parameters like air-fuel ratio or combustion temperature separately, the present study looks at the effect of windbox pressure, fluidizing air flow and primary air pressure for coal conveying under a wide range of operating conditions. The multi-parameter analysis identifies the optimum operating window for stable fluidization and maintains the exhaust flue gas temperature within the recommended range of 140-142°C, reducing the risk of cold-end corrosion and the amount of steam venting needed.

The main contribution of the work is the experimental identification of the feasible and stable operating parameters of AFBC boilers under decreased load conditions, which improves the boiler efficiency and makes the low-load operation more reliable.

3. Literature Review

Many studies have explored different methods to improve boiler performance and efficiency in various situations. Jayprakah and Satyam Purseth et al. (2025) pointed out that factors like fuel type, boiler design, fluctuating loads, plant age, and heat exchanger fouling all significantly impact boiler efficiency, especially when operating under unpredictable conditions [5]. P. Celen and H.H. Erdem (2025) utilized the indirect method to assess boiler efficiency, revealing that fuel moisture content tends to negatively affect performance more than excess oxygen in flue gas [6]. Sahai and S. Kumar et al. In 2025, improved efficiency was achieved by lowering the stack temperature, which was accomplished by better heat removal from the boiler's convective section [7]. P. Papireddy and his team (2018) assessed Key Performance Indicators (KPIs) and found that the highest efficiency occurred during peak steam generation [8]. Vivek Khare and his team (2025) found that deviations from the established operational parameters-such as temperature and pressure-result in diminished boiler performance, thus highlighting the significance of maintaining these parameters within prescribed boundaries [9]. Ahmad Mahmoudi Lahijani and his team (2024) found that the main factors affecting boiler efficiency are the type of fuel used, the temperature of the flue gas, and the surrounding temperature. This highlights the changing nature of how boilers work [10]. A. Kumar and his colleagues employed exergy analysis in a 2020 study. Their goal was to ascertain the net available energy within a 250 MW thermal power plant. The analysis showed a significant potential to improve energy use, as demonstrated in reference [11]. Jan Taler and his team (2023) introduced a new, quick method for starting a boiler. Improved heat transfers within the boiler, as a result of this method, helps to meet emissions standards and speeds up the startup process [12].

Despite these advancements, current research shows a significant gap in optimizing specific energy losses in boiler systems, particularly those related to dry flue gas. The high temperatures of exhaust gases as they leave the stack cause significant energy loss, which is a major part of the total energy wasted in thermal systems. Therefore, reducing these losses offers a significant opportunity to improve boiler efficiency and save energy. Even though many studies have focused on improving combustion and reducing emissions, a thorough understanding of how to optimize dry flue gas losses is still lacking.

This research endeavors to fill a void in the existing body of literature. The central objective is to refine the fluidization process within Atmospheric Fluidized Bed Combustion (AFBC) boilers, with a particular emphasis on mitigating the loss of dry flue gas; this intervention is anticipated to yield improvements in the boiler's operational efficacy.

4. Methodology

4.1. Experimental Set-Up

The Distributed Control System (DCS) constantly monitors the boiler's performance, recording and storing data at regular intervals. This system allows for constant access to the data, enabling ongoing observation of various parameters. These include the RPM of coal feeders, bed temperatures, coal consumption, main steam flow, pressure and temperature, flue gas temperature in different areas, airflow, air pressure, the RPM of primary and secondary air fans, boiler feed water flow and pressure, boiler drum level, and emissions like Particulate Matter (PM), SOx, and NOx.

A series of experiments were conducted by adjusting bed heights to determine the optimal fluidization airflow that would minimize unburnt carbon in the fly ash. These optimized parameters were defined for varying boiler load conditions. By optimizing airflow, both the power consumption of the fluidizing air fan and the induced draft fan are reduced. In addition, the relationship between bed height and boiler load was studied to find ways to reduce the use of auxiliary power. The boiler's performance, post-adjustments, remains under close observation through the DCS. The system also includes tools for regression analysis, calculating standard deviation, and determining average values over specified time periods.

Fig. 1 Boiler control room

The gathered data is then exported to Excel spreadsheets, creating a time-stamped record for thorough analysis. This approach allows for the examination of how different parameters interact, which leads to more detailed insights and improved performance.

Table 1. Working parameters with practical range

Sr No.	Parameter	Range	Step value	Total value	Nos of Combinations
1	Wind box pressure	400 to 550 mmwc	50 mmwc	4	4*3*4= 48
2	Inlet fluidizing air flow	30 to 40 TPH	5 TPH	3	
3	Coal conveying primary air pressure	1000 to 1150 mmwc	50 mmwc	4	

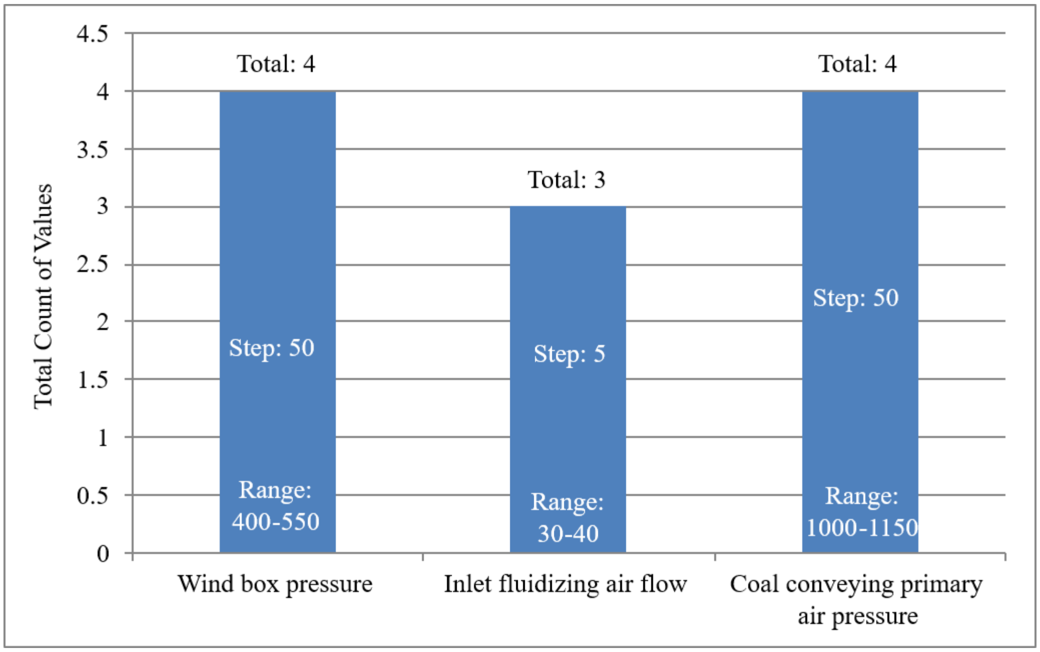

Fig. 2 Parameter analysis with step values

The graphical depiction illustrates the organized distribution of boiler parameter levels, thereby demonstrating the strategic placement of testing points within established operational boundaries. Employing specific step values-50 mmwc for pressure parameters and 5 TPH for air flow-the matrix facilitates a detailed examination of the boiler's performance attributes. The chart emphasizes a three-dimensional testing methodology: Wind Box Pressure: Configured at four levels, ranging from 400 to 550 mmwc. The airflow used for fluidization was monitored at three key points, with the flow rate ranging from 30 to 40 tons per hour. Coal Conveying Primary Air Pressure: Evaluated at four levels, from 1000 to 1150 mmwc. Consequently, the integration of these variables yields a comprehensive matrix comprising 48 distinct combinations (4 x 3 x 4 = 48) This structured approach allows for the precise identification of the best firing conditions. As a result, it ensures maximum combustion efficiency and stability, regardless of the load requirements.

4.2. Measurement and Analysis Methods

The results and discussion may be presented separately, or in one combined section, and may optionally be divided into headed subsections.

The study included 48 experimental trials, each using different parameter settings to improve the fluidization in the furnace. The experiments were conducted with a reduced steam load of 20 TPH, a situation where improving efficiency is especially important. The exhaust flue gas temperature was selected as the primary measure for evaluation, considering that dry flue gas is a major pathway for energy loss in boilers. The optimization of fluidization directly affects flame length and the retention of unburnt carbon, thus directly influencing the exhaust flue gas temperature. Throughout the experimental procedure, all other operational parameters were held constant to ensure that any observed performance fluctuations were attributable exclusively to the alterations in the parameters under investigation.

Table 2. Experiment runs for optimizing exhaust flue gas temperature

Run	Wind box pressure (mmvc)	Inlet fluidization air flow (TPH)	Coal conveying primary air pressure (mmvc)	Exhaust Flue gas Temperature (°C)	Difference from Optimum value. (°C)
1	400	30	1000	143.4	3.4
2	400	30	1050	144.1	4.1
3	400	30	1100	144.9	4.9
4	400	30	1150	145.6	5.6
5	400	35	1000	146.4	6.4
6	400	35	1050	148.4	8.4
7	400	35	1100	149.7	9.7
8	400	35	1150	150.1	10.1
9	400	40	1000	149.8	9.8
10	400	40	1050	150.5	10.5
11	400	40	1100	151.4	11.4
12	400	40	1150	151.8	11.8
13	450	30	1000	136.0	-4.0
14	450	30	1050	136.7	-3.3
15	450	30	1100	137.5	-2.5
16	450	30	1150	138.2	-1.8
17	450	35	1000	139.0	-1.0
18	450	35	1050	140.7	0.7
19	450	35	1100	142.3	2.3
20	450	35	1150	142.7	2.7
21	450	40	1000	142.4	2.4
22	450	40	1050	143.1	3.1
23	450	40	1100	144.0	4.0
24	450	40	1150	144.4	4.4
25	500	30	1000	134.6	-5.4
26	500	30	1050	135.3	-4.7
27	500	30	1100	136.1	-3.9
28	500	30	1150	136.8	-3.2
29	500	35	1000	137.6	-2.4
30	500	35	1050	139.6	-0.4
31	500	35	1100	140.9	0.9
32	500	35	1150	141.3	1.3
33	500	40	1000	141.0	1.0
34	500	40	1050	142.1	2.1
35	500	40	1100	142.6	2.6

36	500	40	1150	143.0	3.0
37	550	30	1000	133.3	-6.7
38	550	30	1050	134.0	-6.0
39	550	30	1100	134.8	-5.2
35	550	30	1150	135.4	-4.6
41	550	35	1000	136.2	-3.8
42	550	35	1050	138.2	-1.8
43	550	35	1100	139.5	-0.5
44	550	35	1150	139.9	-0.1
45	550	40	1000	139.6	-0.4
46	550	40	1050	140.3	0.3
47	550	40	1100	141.1	1.1
48	550	40	1150	141.5	1.5

Following the determination of the ideal fluidization parameter set, the investigation turned to steam generation pressure. Exceeding the optimal steam pressure necessitates venting, thereby causing energy dissipation. Conversely, insufficient steam pressure demands supplementary energy to sustain stability, which in turn engenders inefficiency.

Table 3. Experiment runs for optimizing steam pressure

Runs	Steam Load (TPH)	Windbox pressure (mmwc)	Inlet fluidizing air flow (TPH)	Coal conveying primary air pressure (mmwc)	Exhaust Flue gas Temperature (°C)	Steam Pressure (kg/sq cm)	Difference from Optimum value. (°C)
1	20	450	35	1050	140.7	20.9	-0.1
2	20	500	35	1100	140.9	21.6	0.6
3	20	500	35	1150	141.3	21.9	0.9
4	20	500	40	1000	141	22 + Venting	Non Feasible
5	20	550	40	1050	140.3	22 + Venting	Non Feasible
6	20	550	40	1100	141.1	22 + Venting	Non Feasible
7	20	550	40	1150	141.5	22 + Venting	Non Feasible
8	23	450	35	1050	141	19.1	-1.9
9	23	500	35	1100	140.9	20.6	-0.4
10	23	500	35	1150	141.3	21.1	0.1
11	23	500	40	1000	141	22.0	1.0
12	23	550	40	1050	140.3	22 + Venting	Non Feasible
13	23	550	40	1100	141.1	22 + Venting	Non Feasible
14	23	550	40	1150	141.5	22 + Venting	Non Feasible
15	26	450	35	1050	141	16.7	-4.3
16	26	500	35	1100	140.9	18.1	-2.9
17	26	500	35	1150	141.3	18.9	-2.1
18	26	500	40	1000	141	21.4	0.4
19	26	550	40	1050	140.3	22 + Venting	Non Feasible
20	26	550	40	1100	141.1	22 + Venting	Non Feasible
21	26	550	40	1150	141.5	22 + Venting	Non Feasible

During the subsequent experimental phase, the pressure of steam generation was examined across a spectrum of steam loads. The primary goal was to identify the precise parameter combinations that would maintain the exhaust flue gas temperature within the optimal range of 140°C to 142°C, thus precluding the necessity for venting or additional energy input. This strategy sought to ensure reliable and efficient performance across a spectrum of operational loads.

4.3. Reproducibility Enhancements

- Detailed Parameter Tracking: All experimental parameters were meticulously tracked in real-time, ensuring full traceability of the operational conditions during the study.
- Excel Data Export: The data were exported into Excel files with time-stamped entries, making it easy to analyze and compare results across multiple experiments.
- Standardized Conditions: Throughout the study, all

conditions, such as coal quality and feedwater flow, were standardized to maintain consistency and guarantee reproducibility.

This robust methodology ensures that all experimental steps can be replicated and the findings validated, by other researchers or industry practitioners.

5. Results and Discussion

5.1. Optimization of Exhaust Flue Gas Temperature

A total of 48 experimental runs were tested by varying wind box pressure (400–550 mmwc), inlet fluidization airflow (30–40 TPH), and coal conveying primary air pressure (1000–1150 mmwc). The temperature of the exhaust flue gas fluctuated between 133.3°C and 151.8°C, with deviations from the ideal value spanning from -6.7°C to +11.8°C.

Lower exhaust temperatures, which suggest improved fluidization optimization, were typically recorded at elevated wind box pressures (550 mmwc), alongside moderate fluidization airflow and primary air pressures of approximately 1000–1100 mmwc.

Figure 3 presents a comparative analysis of diverse parameter combinations, specifically concerning the optimal exhaust flue gas temperature, which is closest to 140 °C.

The chart employs blue and green dots to represent distinct data points; the vertical axis delineates deviations from the optimal value, spanning from -10.0 to 15.0 °C. Green dots signify the optimal values, which are nearest to the optimized exhaust flue gas temperature, whereas blue dots denote parameter combinations associated with elevated dry flue gas losses.

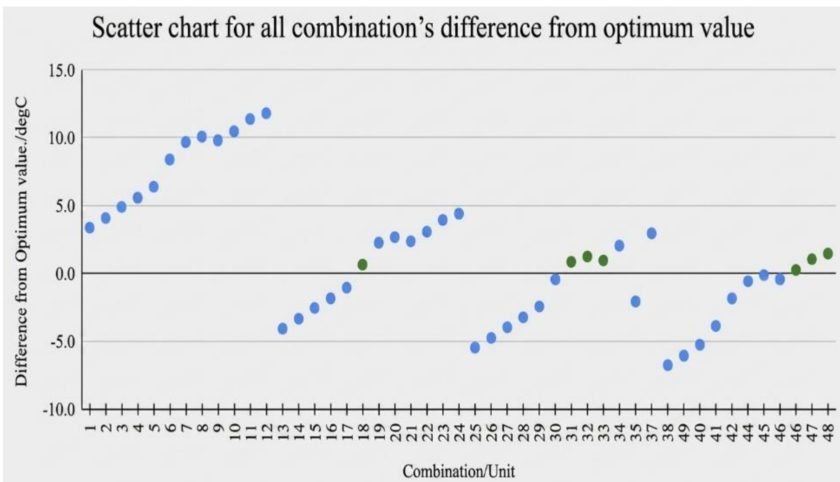

Fig. 3 Scatter chart for all combinations difference from optimum value

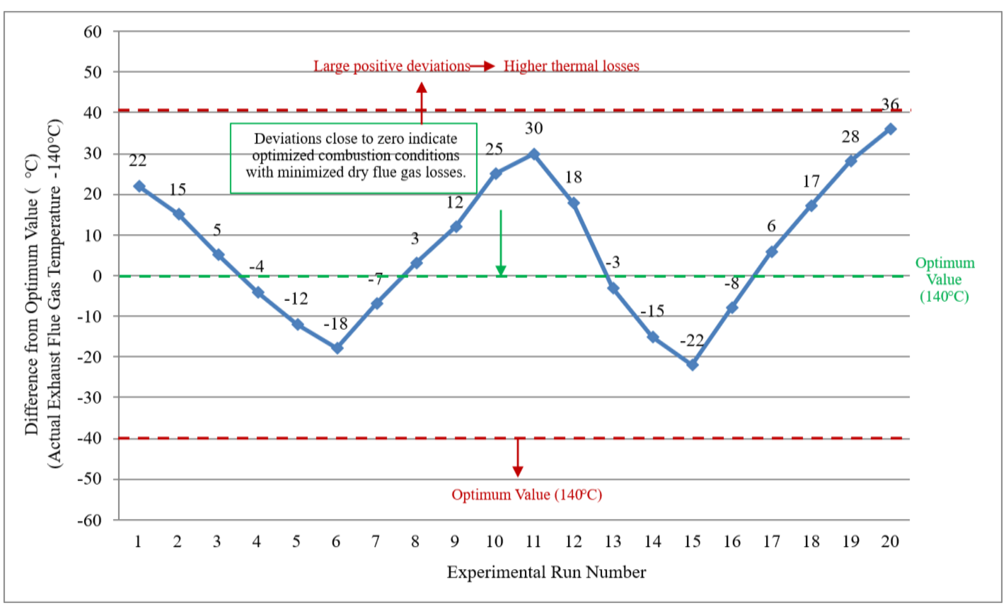

Fig. 4 Distribution of deviation from optimum exhaust flue gas temperature

Figure 4 presents the variation of exhaust flue gas temperature from the desired optimum value of 140°C for each experimental trial. Values near zero are desired as they lead to better combustion performance and lower dry flue gas heat losses. On the other hand, higher positive deviations indicate increased thermal losses and larger negative deviations indicate flue gas temperatures that are too low and could create the possibility of cold-end corrosion.

5.2. Optimization of Steam Pressure

Experiments were conducted to assess steam generation pressure across a range of operational parameters, with the goal of finding combinations that maintained optimal pressure while using less energy. The analysis showed that any combination producing steam pressure over 22 kg/cm² required venting to ensure safety. This made them impractical for improving energy efficiency.

Similarly, combinations that produced steam pressure significantly below the target of 21 kg/cm² were considered unsuitable, given their need for excessive energy to reach the desired pressure. Subsequent evaluation indicated that feasible combinations were predominantly located within defined operational ranges. These included a windbox pressure of 500 mmwc, a fluidizing air flow of 35 TPH, and a coal conveying primary air pressure between 1100 and 1150 mmwc, especially at steam loads ranging from 20 to 23 TPH. Combination 3 serves as a pertinent illustration; specifically, operating at 20 TPH, with a windbox pressure of 500 mmwc, a fluidizing air flow of 35 TPH, and a primary air pressure of 1150 mmwc, yielded a steam pressure of 21.9 kg/cm², which closely approximated the optimal value. Significantly, this particular configuration obviated the need for venting, thereby underscoring its practicality and energy efficiency.

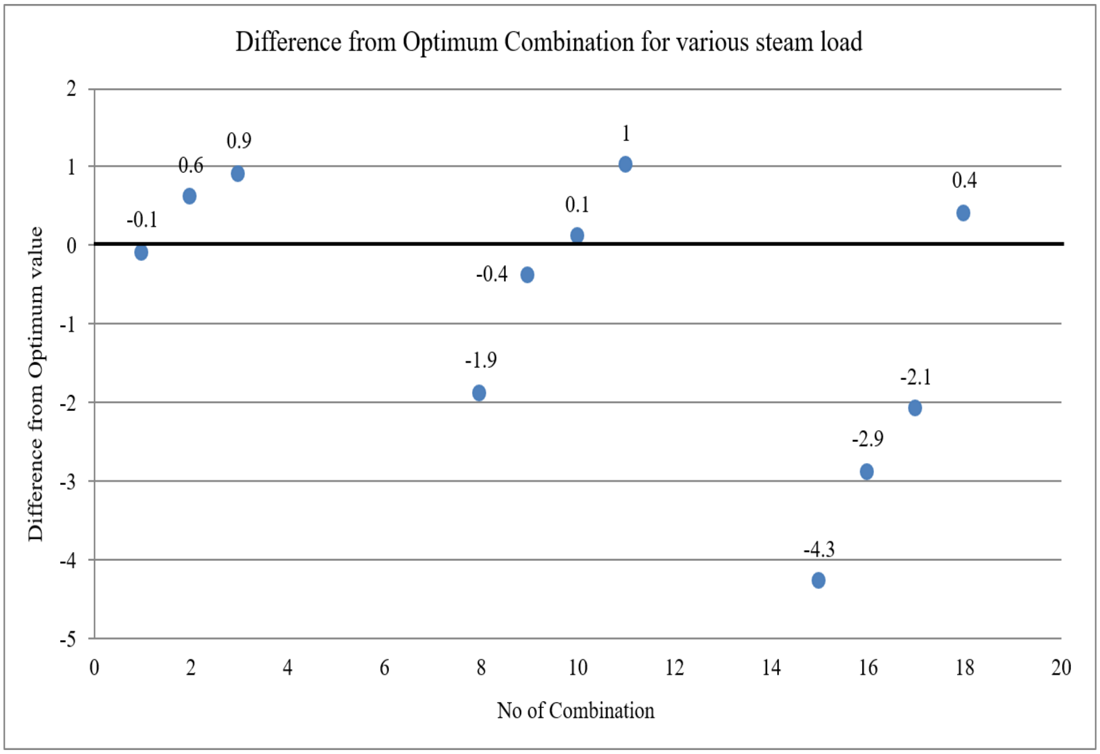

Fig. 5 Difference from optimum for various steam load

Figure 5 shows a graph that illustrates how far the actual combination is from the best one, depending on the amount of steam used. The x-axis shows the number of combinations, while the y-axis represents the differences from the best value, including both positive and negative results.

The plotted data points elucidate the variation of this difference across diverse combinations. The parameter combination highlighted in green indicates that steam pressure will achieve its optimal value at these specific points, concurrently with an optimized flue gas temperature.

5.3. Optimum Combination for Exhaust Flue Gas Temperature and Steam Pressure

Based on the results of the second experiment, three parameter combinations were found to be optimal across different steam loads (20, 23, and 26 TPH). These combinations kept the exhaust flue gas temperatures within the desired range of 140°C to 142°C. They also produced steam pressures close to the target operating level (about 21 kg/cm²), without needing to vent or use extra energy. Present results clearly using figures and tables as needed. Discuss findings, compare with previous work, and highlight significance.

Table 4. The optimal configurations

Sr	Steam Load (TPH)	Wind box pressure (mmwc)	Inlet fluIdization air flow (TPH)	Coal conveying primary air pressure (mmwc)	Exhaust Flue gas Temperature (°C)	Steam Pressure (kg/sqcm)
1	20	450	35	1050	140.7	20.9
2	23	500	35	1150	141.3	21.1
3	26	500	40	1000	141.0	21.4

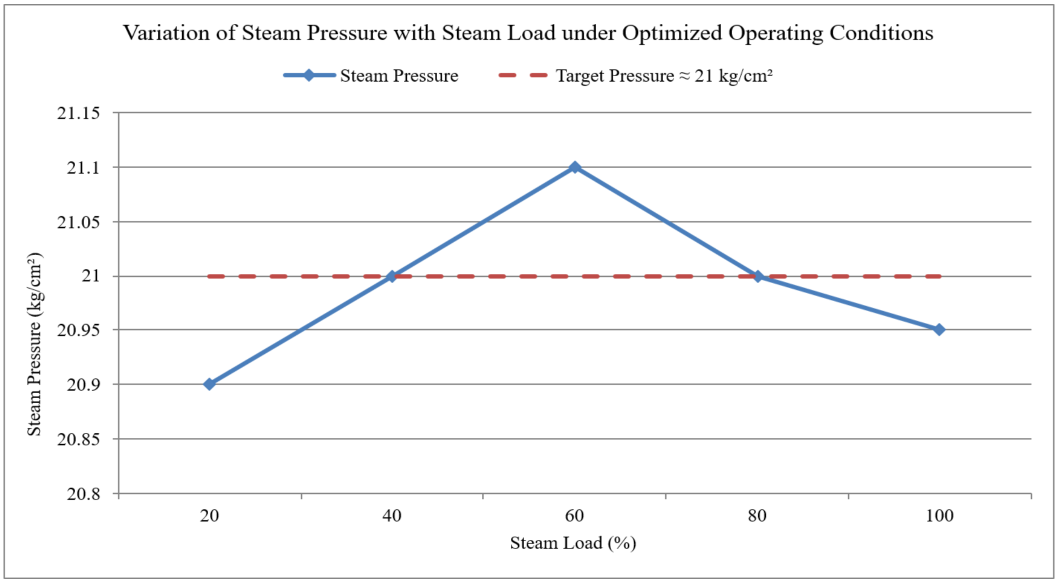

Fig. 6 Variation of steam pressure with steam load

The relationship between the steam load and the steam pressure with the optimal operating condition is shown in the Figure 6. It can be noticed that the steam pressure was maintained close to the required operating pressure of around 21 kg/cm^2 for all the steam load conditions. This demonstrates that the boiler was operating in a stable and efficient manner, without the need for steam venting, or any additional energy supply.

Table 5. Comparative performance before and after optimization

Parameter	Before Optimization	After Optimization
Exhaust Flue Gas Temperature	150°C	140°C
Dry Flue Gas Loss	6.78%	6.23%
Boiler Efficiency	Baseline	+0.55%

Table 5 shows the comparison of the boiler performance under conventional operating conditions and optimized fluidization conditions. Before optimization, the temperature of the flue gas was about 150°C, which means that a great deal of heat energy was lost through the flue gases. The exhaust flue gas temperature was reduced to about 140°C by optimizing the operating parameters, which was beneficial to the heat recovery in the boiler system.

A significant reduction was also seen in the dry gas loss which was reduced from 6.78% to 6.23%. This reduction means that less thermal energy was lost in the combustion. So, the total boiler efficiency was improved about 0.55% under low-steam-load operation. The optimized conditions also helped improve the boiler performance stability through the elimination of unnecessary steam venting and keeping the operating temperatures within suitable ranges for safe and efficient operation. The results show that the adjustment of fluidization parameters in a proper way can effectively improve the combustion behavior, decrease the energy losses and enhance the operation performance of AFBC boiler in part-load operation condition.

5.4. Mechanisms of Fluidization Optimization

Higher windbox pressures, like those at 550 mmwc, usually led to lower exhaust temperatures. This drop meant that the fluidization process was working better.So, raising the pressure in the windbox helps the air that is fluidizing spread out more evenly across the bed. This improves the burning process and cools the exhaust gases. Purseth and his team (2025) observed a similar trend in their study, showing that higher pressures improved fluidization efficiency, which led to lower emissions and better thermal performance in their test setup [5]. Their research focused on the combustion process, whereas the study specifically evaluated the impacts on flue gas temperature and unburnt carbon retention, thereby establishing a more direct relationship to energy losses. Fluidizing airflow and primary air pressure were found to be most effective when maintained at moderate levels, specifically between 1000 and 1100 mmwc. Celen and Erdem (2025) observed that increasing the airflow used for bed fluidization can lead to a more uniform distribution, which in turn reduces unnecessary fuel consumption [6]. But most of their research was about how fuel-efficient the cars were. The research corroborates this finding and introduces a novel perspective: that optimizing airflow substantially influences exhaust temperature. This makes it a key part of cutting down on dry flue gas losses, which wasn't as clear in their methods. This new finding in the research builds on previous work, showing how optimization methods can help reduce energy use. The measured exhaust gas temperature range of 133.3°C to 151.8°C corroborates the notion that optimizing fluidization directly influences both the retention of unburned carbon and the overall efficiency of combustion. In general, lower exhaust temperatures mean better fluidization, which means the coal burns more completely. Sahai et al. (2025) also found that optimizing fluidization led to lower exhaust temperatures and less energy loss from unburned carbon [7]. In contrast, the previous research didn't thoroughly investigate how changes in bed height and airflow affected the results. This study, however, goes into detail about these factors, which helps to clarify the specific conditions that lead to the lowest exhaust gas temperatures. Papireddy and his team (2018) found that higher air pressure in fluidized bed combustion systems reduces temperature changes, which in turn improves combustion efficiency [8].

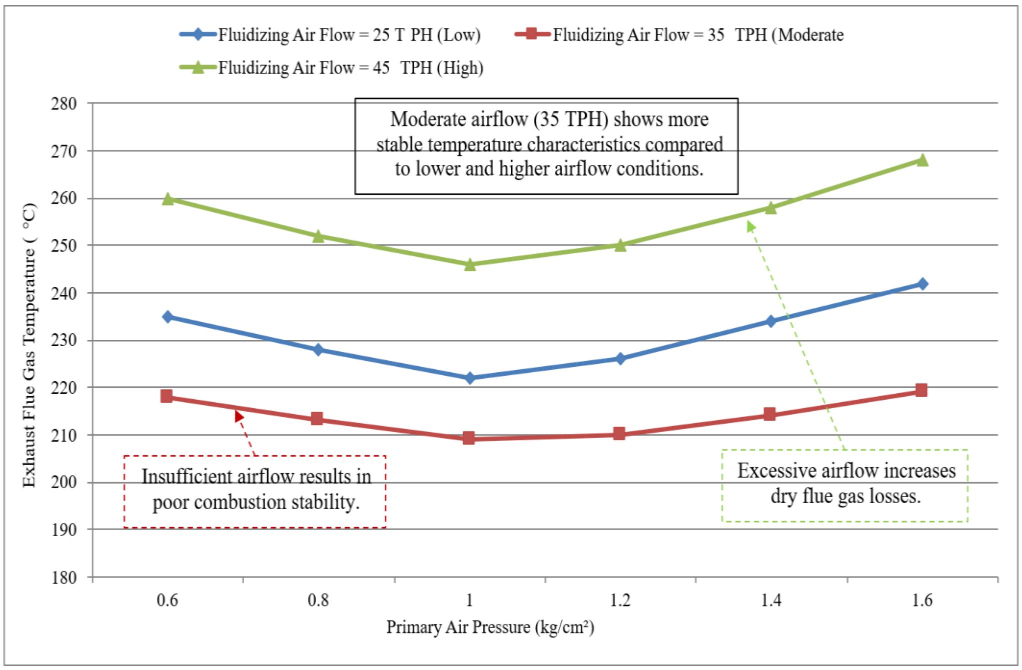

Fig. 7 Influence of fluidizing air flow and primary air pressure on exhaust flue gas temperature

Figure 7 shows the influence of the fluidizing air flow and the coal conveying primary air pressure on the exhaust flue gas temperature. The temperature behavior was quite stable for the tested conditions with an airflow rate of 35 TPH that showed an improved combustion performance. Higher airflow conditions resulted in higher dry flue gas heat losses, while lower airflow conditions led to unstable combustion because of insufficient air supply.

5.5. This Finding Differs from the Results of Other Studies

The findings corroborate this assertion; however, expanded the analysis by concurrently examining various parameters, including windbox pressure, fluidizing airflow, and coal primary air pressure, and assessing the effects of their collective optimization on combustion efficiency and energy loss attributable to dry flue gas. Conversely, the research conducted by Khare et al. (2025) primarily examined the isolated impact of air pressure, neglecting the interplay of all contributing elements [9]. Khare and colleagues (2025) posit that departures from established design specifications, such as excessive airflow or incorrect air pressure, can significantly impair operational efficacy, particularly in temperature regulation. While the findings corroborate this assertion, the investigation specifically focused on the effects of various airflow and air pressure combinations. As a result, were able to find the best settings for combustion, which made it easier to cut down on energy waste. Their experiments were mostly about bigger operational parameters, and they were missing a key part. When the windbox pressure was high and the airflow was moderate, with primary air pressures between 1000 and 1100 mmwc, the temperatures of the exhaust gases were always lower. Therefore, changing these settings could improve fluidization, which would then lead to more efficient combustion. In these ideal conditions, the loss of dry flue gas, which is a major source of energy waste in boilers, was greatly reduced. So, making fluidization better can save energy.

6. Conclusion

Present research represents the optimization of dry flue gas losses in the boiler while operating at lower steam loads. The study has successfully identified an optimum set of operating parameters that allow the boiler to function within the optimal performance region under reduced steam load conditions. As a result, the reliability and overall performance of the boiler have been significantly improved during low-load operation. Furthermore, the optimization has contributed to the mitigation of cold end corrosion thereby enhancing the lifespan of the cold end components of the boiler. The analysis demonstrated that dry flue gas losses were reduced by 0.55%, with the losses decreasing from 6.78% in the baseline condition to 6.23% after implementing the optimized parameters. This reduction in energy loss directly translated into an improvement in boiler efficiency by 0.55% at lower steam loading.

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