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DESIGN OF AN AUTOMATED ONLINE BOILER CLEANING SYSTEM FOR IMPROVED THERMAL EFFICIENCY

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ABSTRACT

This research paper introduces an automated online boiler cleaning system using compressed air as the cleaning medium to address the challenges posed by deposits on boiler surfaces in thermal power plants. These deposits, such as fouling and slagging, have a significant impact on plant performance, leading to reduced electricity generation capacity, decreased boiler efficiency, and increased maintenance costs. The proposed system utilizes real-time conditions within the boiler to initiate the cleaning process, ensuring effective heat transfer without causing damage to internal components. It consists of a monitoring and control system, along with a deposition removal technology. The monitoring system continuously assesses the level and distribution of deposits, providing feedback for optimal cleaning. The control system activates the cleaning process during boiler operation, maximizing cleaning efficiency while minimizing downtime. A case study conducted at the XYZ Thermal Power Plant in Zimbabwe validates the effectiveness of the system, demonstrating a remarkable improvement in plant availability by reducing forced outages caused by tube failures. Additionally, the system contributes to improved thermal efficiency, resulting in lower specific coal consumption and reduced emissions. The successful implementation of this automated online boiler cleaning system offers several benefits, including increased plant availability, reduced operational and maintenance costs, and enhanced environmental sustainability.

Keywords: Automated Online Boiler Cleaning, Compressed Air Cleaning, Fouling And Slagging Deposits, Real-Time Boiler Monitoring, Thermal Power Plant Efficiency.

I. INTRODUCTION

The efficiency of thermal power plants is pivotal to a nation's growth and development. One of the primary factors affecting this efficiency is the accumulation of fouling and slagging deposits on boiler surfaces. These deposits reduce electricity generation capacity, lowers boiler efficiency, and increase maintenance costs. Therefore, planning effective strategies to monitor and eliminate these deposits is paramount for power plant operators [1, 2].

The XYZ Thermal Power Plant stands as an example to these challenges. In 2017, the plant experienced a plant availability rate of just 30.59%, against a target of 80%. This decline was primarily attributed to forced outages and tube failures, consequences of boiler plant unavailability. Such outages not only reduced the plant's production capacity but also inflated maintenance expenses.

Historically, the plant relied on steam jet soot blowers for online boiler surface cleaning. However, this conventional method has shown its limitations. It overlooks critical parameters like load and fuel alterations. Moreover, steam blowers come with elevated operating costs, introduce unwanted moisture into the boiler, and pose risks of tube erosion and other damage.

To counter these challenges, this paper introduces an automated online boiler cleaning system that employs compressed air as its cleaning medium. This innovative system promises enhanced efficiency and cost-effectiveness in deposit removal, thereby augmenting the overall performance of the power plant. By integrating an intelligent mechanism that monitors boiler conditions in real-time and triggers cleaning as required, the system aims to reduce forced outages, streamline the cleaning process, and cut down on maintenance costs.

Our research focuses on the XYZ Thermal Power Plant, offering a comprehensive case study on the design, implementation, and benefits of the proposed cleaning system. The main goal is to boost the power plant's efficiency by crafting an intelligent system capable of initiating timely cleaning, ensuring optimal heat transfer without imposing damage to internal components.

II. LITERATURE REVIEW

Boiler cleaning is a critical aspect of maintaining efficient heat transfer in boiler systems. This literature review aimed to explore the design and efficiency of online boiler cleaning systems. It covered various topics such as slag and soot formation, the effects of accumulation, different removal methods, and the overall impact of boiler cleaning on system performance. By understanding these factors, operators can enhance heat transfer efficiency, reduce maintenance costs, and improve overall plant productivity.

Soot and Slag Formation: During the combustion of solid hydrocarbon fuels, such as coal, soot and slag can form on heat transfer surfaces, leading to decreased heat transfer efficiency. Slag, which is molten ash that has solidified into a rock-like mass, is particularly difficult to remove using traditional soot blowing devices. The temperature profiles and design properties of boilers also influence the deposition of these materials. Coals contain various mineral materials that transform into fly ash during combustion and deposit on boiler surfaces. Understanding the characteristics of soot and slag formation is crucial for effective cleaning strategies [3].

Effects of Slag Accumulation: Slag and fouling deposits pose significant economic and environmental challenges for power plants. These deposits decrease heat transfer efficiency, increase pressure drop, reduce fuel efficiency, and damage mechanical components. As the ash layer thickness increases, the thermal conduction resistance rises, resulting in higher slag surface temperatures. Slagging deposits impact the conductivity of the system between the fireside and the water-steam side, leading to decreased efficiency and increased corrosion problems. Furthermore, increased fouling can cause planned or unplanned outages, resulting in substantial maintenance costs and lost production [4].

Slag Prevention Technologies: Several technologies can help minimize slag formation and reduce fouling in boilers. Chemical treatment technology, which involves injecting chemicals into the flue gas system, has been successful in controlling slagging, fouling, and tube cracking. Mineral additives, such as kaolin, have shown promise in reducing ash-related problems when mixed with coal. Wet pretreatment techniques and coal blending can also help optimize the combustion process and reduce slag formation. Additionally, anti-fouling coatings applied to internal surfaces of boilers have been effective in reducing molten ash particles sticking to the surfaces [5, 6].

Fouling Monitoring Technologies: To ensure optimal cleaning efficiency, monitoring the extent of ash buildup and accumulation levels is essential. Internal cameras, slagging indices, strain gauges, heat flux sensors, cordial thermocouples, infrared instruments, and acoustic instruments are among the technologies used for fouling monitoring. These devices provide valuable data on the condition of heat transfer surfaces, enabling operators to determine the effectiveness of cleaning methods and optimize cleaning frequencies [7, 8].

Boiler Cleaning Methods: Boilers require both offline and online cleaning methods to remove slagging and fouling deposits. Offline cleaning involves planned outages, while online cleaning enables continuous operation. Mechanical soot blowers, which use steam or air to blow off flue gas circuit deposits, are commonly used for online cleaning. Steam soot blowers have been widely employed, but they have disadvantages, including high capital and maintenance costs, potential oil leaks, and erosion issues. Air soot blowers offer a more cost-effective solution with greater cleaning efficiency. Other emerging methods, such as water cannon soot blowers, acoustic horns, and pulse detonation wave technology, show potential in improving cleaning effectiveness [9, 10].

Component Requirements for Automated Cleaning Systems: An integrated system for automated online boiler cleaning typically consists of instrumentation to determine boiler condition, algorithms to interpret instrumentation data, controls to act upon feedback, and appropriate cleaning equipment. These systems can optimize cleaning frequencies, prevent ash buildup, and clinker formation, and reduce maintenance costs. Additionally, advanced systems provide flexible responses to fuel variations and integrate seamlessly with existing plant systems.

Efficient heat transfer in boilers relies on effective removal of slag and soot deposits. The literature review conducted explored various aspects of online boiler cleaning systems, including slag and soot formation,

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removal methods, monitoring technologies, and component requirements for automated cleaning systems. Further research and development in this field have the potential to drive innovation and improve the performance of boiler cleaning systems in the future.

III. METHODOLOGY AND CONCEPT GENERATION

The conceptual design process that was employed in this project followed a cross-method approach, incorporating both divergent and convergent steps. The divergent step involved generating multiple design alternatives, while the convergent step focused on evaluating and screening these alternatives to identify the final design concept. The objective was to generate design concepts that aligned with the customer needs identified through plant audits and interviews. These concepts were then weighed against technical and economic criteria to determine the best solution.

Design Needs: When designing a solution, it was crucial to consider the chemical composition of coal as it greatly influenced the formation of slagging and fouling. Factors such as ash deposits, sintered and fused deposits on elements, loose ash, and acid corrosion were considered. The more detailed information that was available, the better the selection of cleaning devices or combinations of devices for an overall coordinated system. Various selection factors, including boiler design, flue gas conditions, operating pressures, blowing medium conditions, and physical and operating restrictions, contributed to ensuring the optimum choice of product.

Customer Needs: The customer needs for this project were specific to the XYZ power plant and were divided into two categories: production needs and engineering needs. These needs aimed to minimize the cost of design and possible modifications to existing designs. They were derived through questionnaires and interviews with key personnel at the XYZ Power Station, including operations engineers, shift charges, control room technicians, operators, plant chemists, lab technicians, and postgraduate trainees. Figure 1 below shows the selection criteria for the soot blowing system.

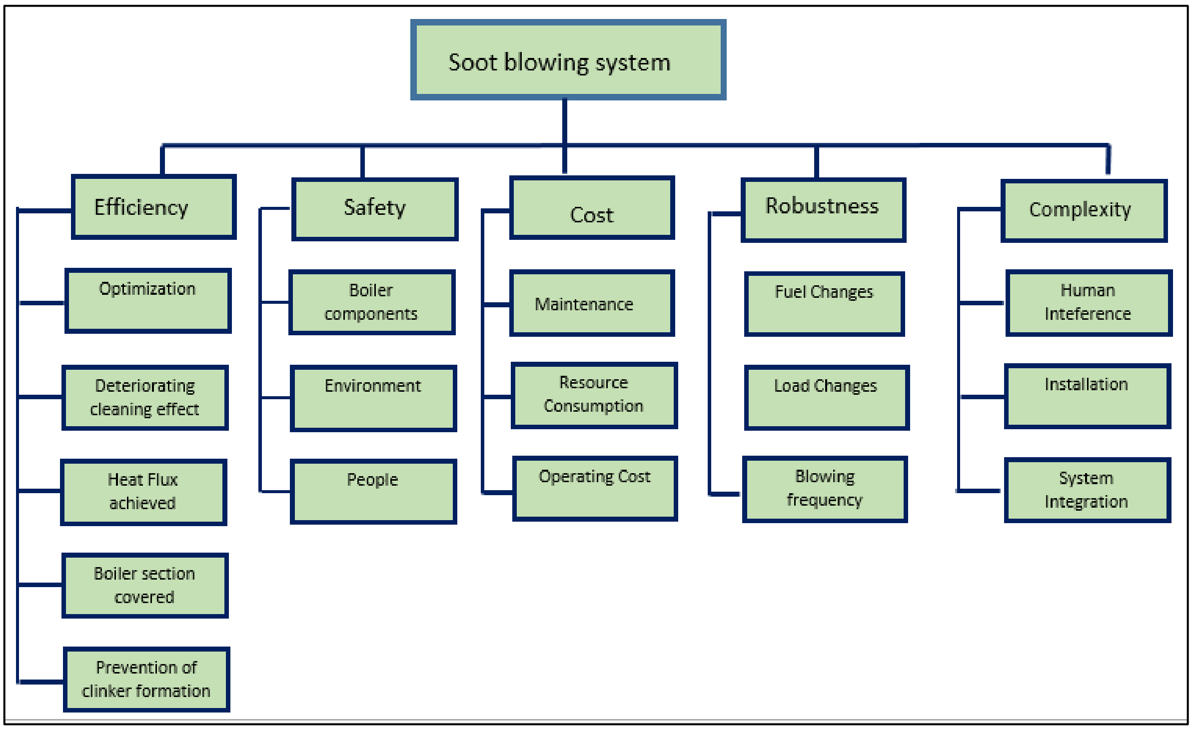

Figure 1: Selection Criteria For soot blowing system.

Concept Screening for soot blowers: Concept screening aimed to identify a few viable cleaning technologies from a range of options. The screening criteria for these technologies were derived from a literature review and customer requirements obtained through questionnaires. The screening matrix had evaluated multiple cleaning technologies, including steam soot blowers (Concept A), acoustic horn soot blowers (Concept B), pulse detonation wave soot blowers (Concept C), air soot blowers (Concept D), and water cannon soot blowers (Concept E). The concept screening matrix is shown in Table 1 below.

Table 1: Concept Screening Matrix

Selection Criteria	Soot blowing Technology				
	A	B	C (Reference)	D	E
Efficiency	+	–	0	+	+
Safety	–	0	0	+	–
Cost	+	+	0	0	0
Robustness	+	–	0	+	0
Complexity	+	+	0	+	+
Sum +'s	4	2	0	4	2
Sum 0's	0	1	5	1	2
Sum –'s	1	2	0	0	1
Net Score	3	0	0	4	1
Rank	2	4	4	1	3
Continue?	YES	NO	REVISE	YES	NO

Key

"0"	**Same as**
"+"	Better than
"-"	Worse than

Concept Scoring for soot blowers: Concept scoring involved a detailed analysis of a few selected concepts (such as Concepts A, C, and D) to determine the single concept most likely to meet the project's objectives. Each criterion was assigned a weight based on its importance. The concept scoring matrix was shown in Table 2.

Table 2: Concept Scoring Matrix

Selection criteria	**Weight (%)**	**Concept**					
		A		C		D (Reference)	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Safety	25	1	0.25	2	0.5	3	0.75
Robustness	10	4	0.4	4	0.4	3	0.3
Cost	20	2	0.4	1	0.2	3	0.6
Complexity	20	2	0.4	1	0.2	3	0.6
Efficiency	25	4	1	4	1	3	0.75
	Total Score		2.45		2.3		3.0
	Rank		2		3		1
	Continue?		NO		NO		YES

Key

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2

Same as reference	3
Better than reference	4
Much better than reference	5

The matrix had evaluated the selected concepts based on the criteria of safety, robustness, cost, complexity, and efficiency, assigning a rating and weighted score for each criterion. The total scores, ranks, and continuation decisions were then determined.

Monitoring System: In addition to the cleaning technologies, a monitoring system had also been essential to assess the extent of ash buildup and levels of accumulation. This system had enhanced the efficiency of slag removal when implemented alongside the cleaning methods. The technologies considered for the monitoring system included strain gauge sensors (Concept A), heat flux sensors (Concept B), thermocouples (Concept C), slagging indices (Concept D), and internal cameras (Concept E). The screening matrix for the monitoring system concept screening is shown in Table 3.

Table 3: Monitoring system concept Screening

Selection Criteria	Monitoring Technology				
	A	B	C	D	E
Effectiveness	+	+	0	_	–
Reliability	+	+	0	_	–
Cost	+	+	0	+	+
Maintainability	_	+	0	+	+
Ease of installation	_	+	0	+	0
Compatibility	+	0	0	0	+
Robustness	+	+	0	+	+
Sum +'s	5	6	0	4	4
Sum 0's	0	1	0	3	1
Sum –'s	2	0	0	2	2
Net Score	3	6	0	2	2
Rank	2	1	5	3	3
Continue?	NO	YES	NO	NO	NO

Concept scoring was conducted to determine the most suitable monitoring technology. The concept scoring matrix had evaluated Concepts A, B, and E, assigning ratings and weighted scores for each criterion. The total scores, ranks, and continuation decisions were then determined as shown in Table 4.

Table 4: Concept Scoring Matrix

Selection criteria	Weight (%)	Concept					
		A		B		E (Reference)	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
effectiveness	20	5	1	5	1	3	0.6
cost	25	4	1	4	1	3	0.15
robustness	25	4	1	5	1.25	3	0.75
compatibility	5	4	0.2	5	0.25	3	0.15
reliability	10	3	0.3	4	0.4	3	0.3

ease of installation	5	2	0.1	4	0.2	3	0.15
maintainability	10	3	0.3	4	0.4	3	0.3
	Total Score		3.9		4.75		2.4
	Rank		2		1		3
	Continue?		NO		YES		NO

Based on the results of the concept screening and scoring matrices, air soot blowing technology (Concept D) had been chosen to design an automated online boiler cleaning technology. Heat flux sensors (Concept B) were employed for monitoring the extent of fouling. To enhance efficiency, the cleaning process was automated, creating a real-time, boiler condition-based cleaning system.

In this methodology, an organized approach was followed to generate and evaluate design concepts for an optimized cleaning and monitoring system. The process involved understanding the design and customer needs, screening and scoring the concepts, and selecting the most suitable options based on defined criteria. The chosen concepts formed the basis for the subsequent detailed design and development stages of the project.

IV. DETAILED DESIGN

The detailed design section for the automated online boiler cleaning system focused on two main components: the air soot blower system and the control system.

The air soot blower system consisted of several components. It had the compressed air supply system, which included a multi-stage centrifugal compressor capable of delivering a maximum volume flow rate of $1246m^3/hr$. The piping system was designed to efficiently deliver the compressed air to the service areas, taking into consideration factors such as maintaining an air velocity of less than or equal to 6.10m/s to avoid carrying moisture beyond drainage drop legs and minimizing pressure drop.

The soot blower itself was composed of a tube to carry the cleaning medium and a soot blower nozzle. The design of the nozzle considered factors such as the change in pressure, the density of air, the discharge coefficient, and the throat area. Through calculations and assumptions, the appropriate throat diameter was determined to optimize the cleaning process.

In determining the number of soot blowers per boiler, it was found that for large boilers with a capacity of around 1500t/hr., a total of approximately 120 soot blowers would be required, with around 90 of them being wall blowers. Since the XYZ boiler capacity was 72t/hr., the number of wall blowers was determined to be 20.

Moving on to the control system design, the primary objective was to develop a system capable of monitoring process variables, estimating the fouling status of heat exchange surfaces, evaluating the impact on economy, and triggering the soot blowing sequence. The design incorporated the use of heat flux sensors placed strategically in various sections of the boiler, which would measure heat flux and send the measurements to a microcontroller.

The microcontroller, an Arduino Uno, acted as the central control unit for the system. It was equipped with digital input/output to receive and process sensor data and execute control algorithms accordingly. Additionally, other components such as temperature sensors, the ESP8266 Wi-Fi module for remote access, a relay for controlling power supply to the cooler fans, a power supply for the electronic components, a buzzer for alarms, and cooler fans to simulate the air soot blowing system were integrated into the control system design.

The proposed system also provided the option for internet-based monitoring, allowing authorized personnel to remotely access and monitor the instantaneous boiler condition data. This feature enhanced production planning and eliminated the need to solely rely on information provided by boiler operators.

In a nutshell, the detailed design of the air soot blower system included the compressed air supply system, piping system, soot blower nozzle, and determination of the number of soot blowers per boiler. It also presented the design of the control system, which incorporated the use of a microcontroller, sensors, and other electronic components. The system also provided the capability for internet-based monitoring for remote access to real-time boiler condition data.

V. RESULTS AND DISCUSSION

Table 5 provides the specifications for the equipment selection and sizing of the soot blowing system. The compressor type chosen was a multi-stage centrifugal compressor with a maximum flow rate of 1246m³/hr. The piping system was made of commercial steel with a length of 50m and a diameter of 76.2mm. The air velocity in the piping system was 6.1m/s. The nozzle used had a throat diameter of 42.1mm and an inlet diameter of 56mm. The inlet pressure was 3012.9Kpa, while the exit pressure was 1590Kpa. The cleaning pressure for the nozzle was set at 217Kpa, and the air flow rate was determined to be 4.39Kg/s. A total of 20 soot blowers were recommended for the system.

Table 5: Results for equipment selection and sizing.

	Parameter	Specification
Compressor	Type	Multistage centrifugal
	Maximum flow rate	1246m³/hr
	Power rating	
Piping system	Material	Steel commercial
	Length	50m
	Diameter	76.2mm
	Air velocity	6.1m/s
	Pressure drops	59.81Kpa.
Nozzle	Throat diameter	42.1mm
	Inlet diameter	56mm
	Inlet Pressure	3012.9Kpa
	Exit Pressure	1590Kpa
	Critical Pressure	0.528
	Cleaning Pressure	217Kpa
	Air flow rate	4.39Kg/s
Soot blowers	Quantity	20

Additionally, Table 6 presents the results for the heat flux calculations per section in the boiler. The economizer section had a maximum heat flux of 6052.34 and a minimum heat flux of 4224.36 W/m^2. The F&C generating tubes had a maximum heat flux of 8108.16 $W/m^2$and a minimum heat flux of 5739.11 W/m^2. The rear generating tubes had a maximum heat flux of 8050.76 W/m^2 and a minimum heat flux of 5703.74 W/m^2. Lastly, the superheater section had a maximum heat flux of 5801.67 W/m^2 and a minimum heat flux of 3685.9 W/m^2.

Table 6: Results for heat flux calculations.

Boiler section	Heat flux, q (W/m^2)	
	Max	Min
Economiser	6052.34	4224.36
F&C generating tubes	8108.16	5739.11
Rear generating tubes	8050.76	5703.74
Super heater	5801.67	3685.9

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These results provide valuable information for the design and implementation of the proposed solution, ensuring the selection of appropriate equipment, sizing of the system, and estimation of costs. Figure 5.3 below shows the prototype for the proposed system.

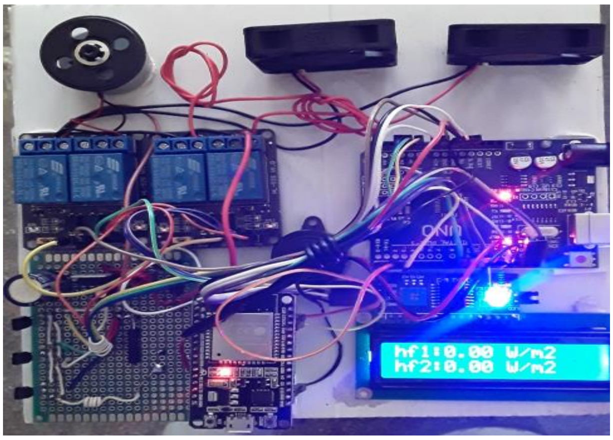

Figure 2: Prototype of the proposed system

Figure 3 below shows a snapshot taken from a mobile device connected to the monitoring system, giving boiler condition.

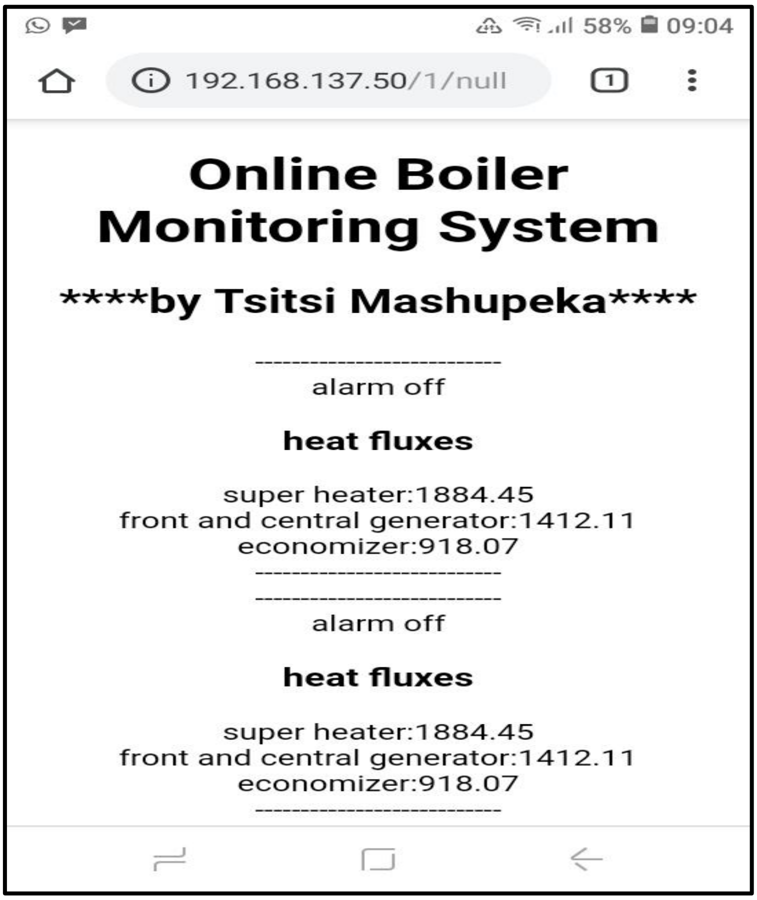

Figure 3: Internet based monitoring

VI. CONCLUSION

In conclusion, the project aimed to design an automated online boiler cleaning system to address the issues of slagging and fouling in the XYZ Power Plant. The project was justified by the high percentage of forced outages and poor thermal efficiency experienced in the plant. A plant audit was conducted to determine the specific areas of concern and to gather data on plant performance.

The audit revealed that the plant had a low boiler plant availability rate of 30.59% against a target of 80%. This resulted in a significant loss of production and increased maintenance costs. It was also found that the specific coal consumption was higher than the target, indicating poor thermal efficiency. The audit further identified tube erosion and leaks as a recurring problem, leading to unplanned outages and water losses.

Based on the audit findings, the project proposed the design of an automated online boiler cleaning system using compressed air as the cleaning medium. The system aimed to remove deposits and prevent slagging and fouling, improving boiler performance and reducing forced outages. The design included the selection and sizing of soot blowing equipment, as well as the development of a monitoring and control system.

In terms of future work, there are several areas that could be explored to further improve the system. Firstly, the effectiveness of the cleaning system could be evaluated through simulation and testing, considering different operating conditions and types of deposits. This would allow for optimization of the cleaning process and the development of predictive maintenance strategies.

Additionally, the integration of the system with other plant control systems could be considered to allow for real-time monitoring and automatic adjustment of the cleaning process. This would further enhance the efficiency and reliability of the system.

Lastly, the cost-effectiveness of the system should be evaluated in terms of capital and operational costs. This would involve conducting a cost-benefit analysis and comparing the savings achieved through improved plant availability and reduced maintenance costs with the investment required for the system implementation.

Overall, the design of the automated online boiler cleaning system presented in this project provides a promising solution for the issues of slagging and fouling in the XYZ Thermal Power Plant. With further research and development, the system has the potential to significantly improve plant performance and reduce downtime, leading to increased efficiency and profitability.

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