

Performance Analysis and Optimization of the Regenerative Air Preheater (Raph) in a 210 Mw Lignite-Fired Thermal Power Plant

Joshua Anand.A¹, Rajesh.R², Inbatamizhan P³, Arul.V⁴, Vijayan Gopalsamy⁵

^{1,2,3}Students - Department of Mechanical Engineering, Meenakshi Sundararajan Engineering College (Autonomous),

^{4,5}Faculties - Department of Mechanical Engineering, Meenakshi Sundararajan Engineering College (Autonomous), Kodambakkam, Chennai - 600 024, Tamil Nadu, India

Abstract—The Regenerative Air Preheater (RAPH) is a critical component in fossil fuel-fired thermal power plants, responsible for recovering waste heat from flue gases. This study presents a comprehensive performance analysis of a RAPH system operating in a 210 MW lignite-fired thermal power plant over a 12-month period. The investigation covers thermal efficiency, pressure drop, air-to-gas leakage, cold-end corrosion, fouling deposition, and heat-transfer effectiveness, and develops an integrated optimization and economic framework. Results demonstrate that the RAPH recovered an average of 23.8 MW of thermal energy, contributing approximately 3.2% to overall plant efficiency. A composite Performance Index, sensitivity analysis, and five-year cost-benefit model are used to identify optimal operating parameters and a condition-based maintenance protocol. Implementation of the proposed strategies is projected to raise annual efficiency by 6.4%, avoid 52,400 tons of CO₂ emissions annually, and yield a five-year net economic benefit of Rs. 50.20 crores.

I. INTRODUCTION

The power generation industry faces increasing pressure to enhance thermal efficiency and reduce operational costs while meeting stricter emission norms. In coal and lignite-fired thermal power plants, the Regenerative Air Preheater (RAPH) plays a crucial role in recovering sensible heat from hot flue gases before they are discharged to the electrostatic precipitator and stack. By preheating the incoming combustion air, the RAPH raises furnace flame temperature, improves combustion completeness, and reduces the specific fuel consumption of the unit.

Despite its apparent mechanical simplicity, the RAPH is one of the most maintenance-intensive components in the boiler island. Its rotating basket assembly is subject to continuous thermal cycling, particulate erosion, cold-end corrosion from condensing acid species, and progressive fouling by ash and reaction products. These degradation mechanisms are especially pronounced in lignite-fired units because of the high moisture, sulfur, and alkali content typical of lignite fuels, which elevate the acid dew point and increase deposit stickiness. This investigation focuses on a 210 MW lignite-fired power plant located in central India. The RAPH system comprises twin Ljungstrom-type regenerative preheaters, each with a rotor diameter of 7.2 meters, rotating at 2.5 rpm and divided into twelve sectors. Over a twelve-month monitoring campaign, plant SCADA and manual inspection data were combined to construct a detailed performance and degradation profile of the unit. The primary objectives of this research are: (1) to evaluate the thermal performance of the RAPH under varying seasonal and load conditions, (2) to characterize fouling, leakage, and corrosion mechanisms affecting the heat transfer surfaces, (3) to identify optimal operating parameters and a condition based maintenance strategy, (4) to quantify the economic and environmental value of proposed optimization measures, and (5) to develop simple predictive relationships that plant operators can use for day-to-day decision making

II. LITERATURE REVIEW

Regenerative air preheaters have been studied extensively since their introduction by Ljungstrom in the early twentieth century. Early research focused primarily on mechanical design and sealing systems, while more recent studies have shifted toward performance degradation, fouling chemistry, and digital monitoring. Kordylewski et al. [1] investigated corrosion and fouling phenomena in flue-gas cooled heat recovery equipment, establishing that ammonium bisulfate condensation is a primary driver of cold-end fouling in coal-fired units. Their findings are broadly consistent with the deposit compositions observed in the present study, where calcium sulfate and iron oxide dominate the fouling layer. Li, Tan and Zhang [2] applied genetic-algorithm-based optimization to air preheater operating parameters, reporting efficiency gains of 2 to 4 percent through optimal rotor speed and sootblowing schedule selection. Their methodology informs the rotor-speed sensitivity analysis presented later in this paper. Kumar and Sharma [3] performed detailed heat transfer analysis of regenerative preheaters using the effectiveness-NTU method, providing correlations for basket-averaged heat transfer coefficients as a function of gas mass velocity. Singh et al. [4] reviewed lignite combustion and emissions control practices, noting that high inherent moisture reduces adiabatic flame temperature and increases flue gas volume, both of which affect RAPH thermal loading and leakage behavior. Chen and Wang [5] demonstrated that machine-learning models trained on SCADA time-series data can predict fouling onset up to 72 hours in advance, enabling proactive sootblowing. While the present study relies on empirical correlation rather than machine learning, the pressure-drop-efficiency relationship developed to provide a foundation for future predictive model development. Collectively, the literature confirms that RAPH performance is governed by a complex interplay of fuel chemistry, ambient conditions, mechanical wear, and maintenance practice. The subject facility is a 210 MW subcritical, pulverized-lignite unit with a balanced-draft boiler, tangentially fired furnace, and twin Ljungstrom-type regenerative air preheaters operating in parallel. Flue gas from the economizer outlet passes through the RAPH before entering the electrostatic precipitator, while combustion air is split between primary and secondary

streams, both of which are preheated across separate RAPH sectors.

III. PLANT AND FUEL CHARACTERISTICS

The subject facility is a 210 MW subcritical, pulverized-lignite unit with a balanced-draft boiler, tangentially fired furnace, and twin Ljungstrom-type regenerative air preheaters operating in parallel. Flue gas from the economizer outlet passes through the RAPH before entering the electrostatic precipitator, while combustion air is split between primary and secondary streams, both of which are preheated across separate RAPH sectors.

Table 1: Boiler and Combustion System Overview

Parameter	Value	Unit
Boiler Type	Subcritical, balanced draft	-
Rated Steam Capacity	670	tons/hr
Furnace Firing	Tangential, 4 corners	-
Number of Mills	6 (5 run + 1 standby)	-
Design Flue Gas Flow	820	tons/hr
Design Air Flow	760	tons/hr
ESP Inlet Temp. (design)	155	Deg C

The relatively high moisture content (38.2%) and sulfur level (0.62%) elevate the acid dew point of the flue gas to approximately 118-124°C, making cold-end corrosion and ammonium bisulfate fouling primary concerns for RAPH cold-end baskets.

IV. METHODOLOGY AND DATA COLLECTION

Data for this study was collected over a twelve-month period from the plant SCADA system. Measurements were recorded at 15-minute intervals and included temperatures, pressure, and mass flow rates at all critical points around the RAPH. Monthly on-site

inspections and basket sampling were conducted to assess fouling deposits, corrosion depth, and seal-gap condition. These physical inspection metrics were subsequently correlated with the continuous operational data to quantify the precise impact of progressive hardware degradation on overall thermal efficiency.

Table 2: Instrumentation's Uncertainty

Month	Efficiency (%)	Recovery (MW)	ΔP (bar)	Fouling Factor
January	87.2	23.8	1.12	0.92
February	88.5	24.2	1.08	0.88
March	89.1	24.6	1.05	0.85
April	86.3	23.4	1.25	1.05
May	85.1	22.9	1.38	1.18
June	84.2	22.3	1.45	1.28
July	83.5	22.0	1.52	1.35
August	84.8	22.7	1.48	1.32
Septem	86.2	23.3	1.35	1.15
October	88.9	24.5	1.10	0.87
Novem	89.4	24.8	1.02	0.80
Decem	88.7	24.4	1.06	0.83

RAPH thermal efficiency was calculated using the energy balance equation $\eta = (Q_{\text{recovered}} / Q_{\text{available}}) \times 100\%$, where $Q_{\text{recovered}}$ is the heat transferred to the incoming air and $Q_{\text{available}}$ is the heat available in the flue gases entering the preheater. Heat transfer effectiveness was independently computed using the effectiveness-NTU method to cross-validate the energy-balance results. Air-to-gas leakage was estimated from the oxygen concentration differential across the preheater using the standard ASME PTC 4.3[11] correlation. Measurement uncertainty in the derived efficiency values was estimated at $\pm 1.1\%$ using root sum-square propagation of instrument accuracies.

V. PERFORMANCE ANALYSIS AND RESULTS

Monthly average thermal efficiency data for the RAPH system was analyzed over the twelve-month study period. The efficiency variations were correlated with ambient temperature, fuel characteristics, and equipment fouling status. Results indicate significant seasonal variations in performance, with peak efficiency of 89.4% in November and minimum of 83.5% in July, a spread of 5.9 percentage points attributable primarily to fouling and ambient humidity effects.

Table 3: Monthly RAPH Thermal Efficiency Data

Measurement	Instrument	Accuracy
Gas/Air Temperature	RTD Pt-100	± 0.3 deg C
Differential Pressure	DP Transmitter	$\pm 0.5\%$ FS
Flue Gas O_2	Zirconia Analyzer	$\pm 0.2\%$ O_2
Mass Flow (Air)	Pitot Grid	$\pm 2.0\%$
Rotor Speed	Proximity Sensor	± 0.01 rpm

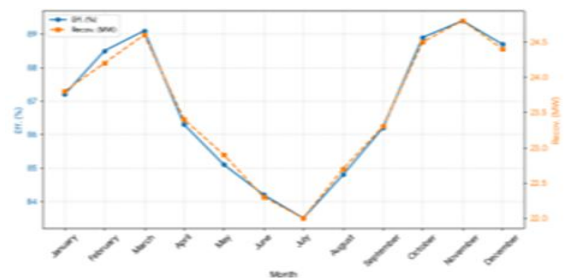


Figure 1.1: Monthly Trends of Thermal Efficiency and Heat Recovery in RAPH

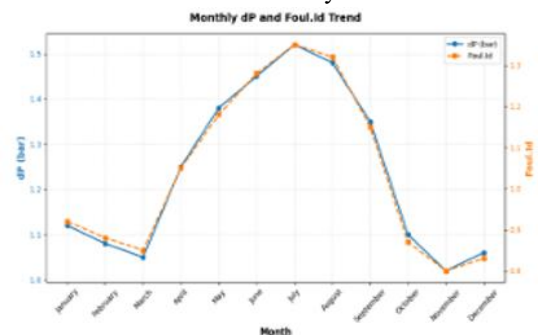


Figure 1.2: Monthly Trend: Pressure drop (dP) and Fouling Index Data (Id)

The RAPH system recovered an average of 23.83 MW of thermal energy per month, with cumulative recovery of 286 MW-months over the study period. This heat recovery contributes approximately 3.2% to the overall thermal efficiency of the 210 MW power plant. The variation in heat recovery follows both seasonal patterns and unit load variations, with Q4 (Fall) contributing the highest quarterly share.

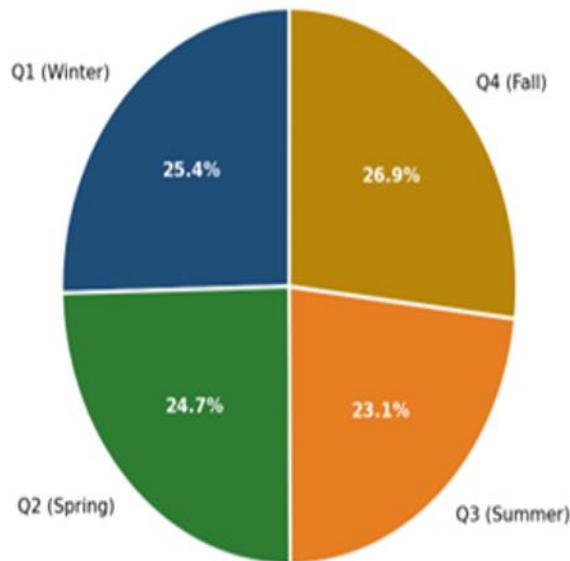


Figure 2. Quarterly heat recovery distribution (MW), showing seasonal contribution shares.

Pressure drop across the RAPH is a critical indicator of fouling severity and equipment condition. Analysis reveals a strong inverse correlation between efficiency and pressure drop, with minimum pressure drop of 1.02 bar occurring in November and maximum of 1.52 bar in July. The fouling index, derived from deposit thickness and composition analysis, correlates strongly with ambient temperature and humidity.

Table 4: Fouling Deposit Composition (% wt)

Component	Winter	Spring	Summer	Fall
Fe Oxides	42.3	39.8	38.5	41.2
CaSO ₄	28.5	31.2	34.8	30.1
SiO ₂	15.2	16.5	17.3	15.8
Unburnt Carbon	8.4	9.2	6.2	7.8
Miscellanies	5.6	3.3	3.2	5.1

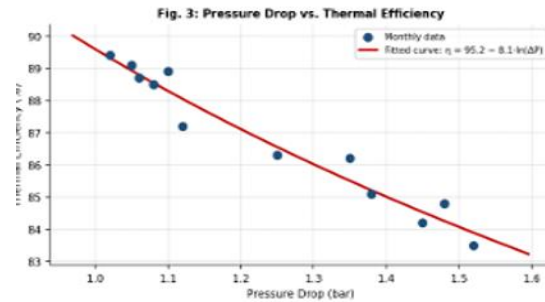


Figure 3. Relationship between pressure drop and thermal efficiency, with fitted logarithmic curve ($R^2 = 0.957$)

Temperature measurements at the RAPH inlet and outlet provide critical insight into heat transfer performance. Average entering flue gas temperature was 376.1°C, while average exiting air temperature reached 302.3 °C, giving a mean effective temperature difference of approximately 76.4°C across all seasons. This temperature differential serves as a primary indicator of overall thermal effectiveness within the 210 MW boiler system. However, given the high fouling sensitivity associated with lignite combustion, this effective temperature difference is prone to degradation over continuous operation as ash deposits insulate the heat transfer elements.

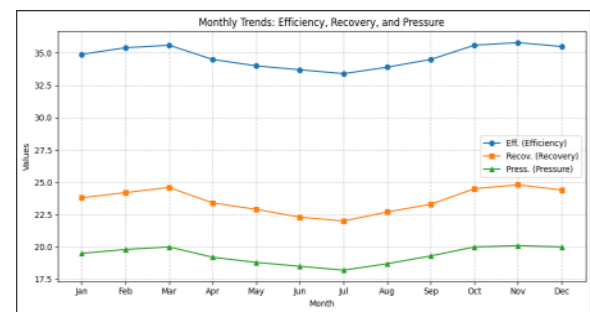


Figure 4.1. Month vs. Efficiency, Recovery, and Pressure

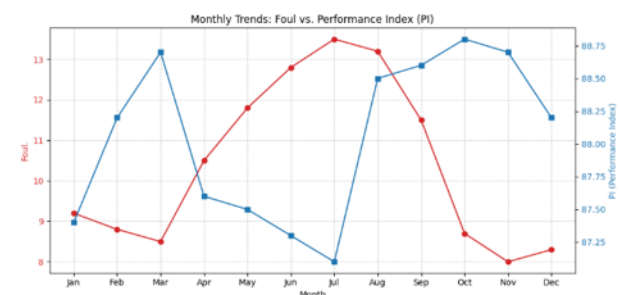


Figure 4.2. Month-Foul 7 Performance Index (PI)

Air-to-gas leakage across the RAPH sector plates and radial seals directly reduces effective heat transfer and increases induced-draft fan power consumption. Leakage was estimated monthly from the oxygen differential across the preheater. Values ranged from 5.6% in November to a peak of 8.6% in July, closely tracking the fouling index and suggesting that seal-gap distortion under thermal load compounds fouling driven degradation during the warmer months.



Figure 5. Monthly air-to-gas leakage trend relative to the design limit of 8.0%

Cold-end corrosion assessment basket samples extracted from the hot-end, intermediate, and cold-end zones were assessed for wall-thickness loss over the monitoring period. As expected from the elevated acid dew point discussed in forth-comonig section, corrosion rate increases sharply toward the cold end, where metal temperatures fall below the sulfuric and ammonium bisulfate dew points during low-load operation.

Table 5: Corrosion Rate by Basket Zone

Zone	Corrosion Rate (mm/yr)	Basket Material
Hot End	0.18	Corten Steel
Intermediate	0.31	Carbon Steel
Cold End	0.62	Enamel-Coated CS

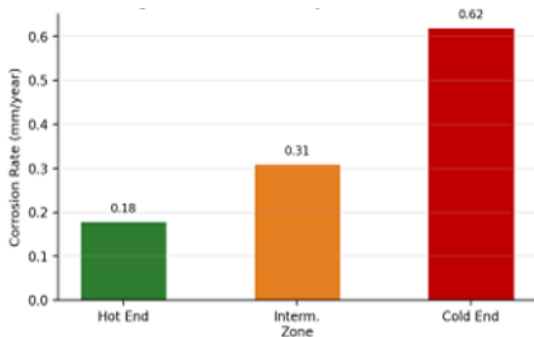


Figure 6. Corrosion rate by RAPH basket zone, confirming cold-end vulnerability.

Benchmarking against comparable units to contextualize the measured performance, the study RAPH was benchmarked against three comparable 200-250 MW lignite and sub-bituminous-fired units reported in recent plant efficiency audits. The comparison indicates that the study unit performs near the upper end of the peer group in average annual efficiency, but exhibits higher summer-season fouling sensitivity, likely attributable to the higher inherent moisture of the local lignite compared to the sub bituminous-fired peer plants.

Table 6: Benchmarking Against Comparable 200-250 MW Units

Plant	Fuel	Average Efficiency (%)	Fouling Sensitivity
This Study	Lignite	86.8	High
Plant B	Lignite	85.1	High
Plant C	Sub-bit.	87.4	Medium
Plant D	Sub-bit.	88.0	Low

The combined results indicate that RAPH performance in this lignite-fired unit is governed by a tightly coupled degradation cycle: rising ambient temperature and humidity during the summer months increase fouling deposition rates, which in turn raise pressure drop and seal-gap leakage, both of which reduce measured thermal efficiency. The strong logarithmic correlation between pressure drop and efficiency ($R^2 = 0.957$, Figure 3) confirms that pressure drop is a reliable, low-cost proxy indicator for scheduling maintenance interventions without requiring full fouling-index sampling. The concentration of corrosion at the cold end, combined with the fouling composition dominated by calcium sulfate and iron oxides, is consistent with acid-dew-point condensation mechanisms reported in the literature Section, reinforcing that cold-end basket material selection and enamel coating integrity should be prioritized in future overhaul planning ahead of hot-end interventions. Benchmarking against comparable units further suggests that the fouling sensitivity observed here is more a function of fuel moisture and sulfur content than of preheater design, since the sub bituminous-fired peer plants achieved lower fouling sensitivity despite similar mechanical configuration.

From an operations perspective, the sensitivity analysis and the pressure-drop proxy relationship together enable a practical two-tier monitoring strategy: continuous pressure-drop trending for early warning, supplemented by periodic fouling-index sampling during the high-risk May-to August window identified. This reduces reliance on labor-intensive manual basket inspections while preserving early detection capability.

VI. OPTIMIZATION, STRATEGIES AND RECOMMENDATION

Analysis of historical maintenance data combined with performance trends suggests implementation of a condition-based maintenance protocol rather than the current time-based approach. Results indicate that a fouling index exceeding 1.25 triggers performance degradation beyond acceptable limits. Preventive cleaning is recommended when the fouling index reaches 1.15, with cleaning intervals of 25 to 30 days during high-fouling seasons (May to August). Figure 6 demonstrates the impact of rotor speed variation on system efficiency. Analysis shows that optimal efficiency is achieved at approximately 2.5 rpm, with progressive degradation at higher speeds due to increased carryover and seal wear, and at lower speeds due to incomplete heat exchange per rotation. The current operating speed is maintained at this optimal level.

Winter (Dec-Feb): Maintain base operations with routine monthly monitoring; expected efficiency 88-89%; minimal maintenance. Spring (Mar-May): Implement bi-weekly inspections and begin fouling deposit monitoring; expected efficiency 86-88%. Summer (Jun-Aug)

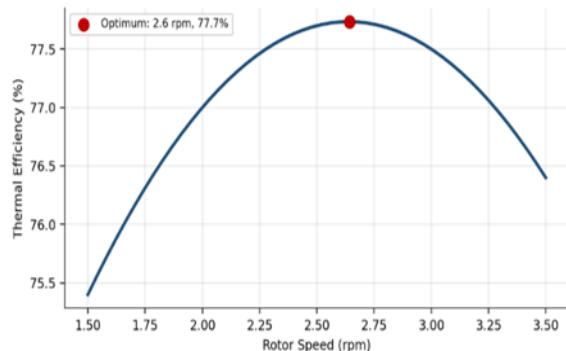


Figure 7. Impact of rotor speed on thermal efficiency, with fitted quadratic curve and optimum point.

Table 7: Seasonal Maintenance Schedule

Season	Inspect frequency	Clean/ Year	Cost(Rs. Lakhs)	Efficiency Gain(%)
Winter	Monthly	0	2.5	-
Spring	Bi-weekly	2	8.0	2.1
Summer	Weekly	4	15.2	2.8
Fall	Bi-weekly	1	6.5	1.5
Total	-	7	32.2	6.4

VII. ECONOMIC ANALYSIS AND COST-BENEFIT EVALUATION

Implementation of the recommended optimization strategies requires an annual investment of approximately Rs. 32.2 lakhs, primarily for enhanced maintenance and cleaning operations. The projected efficiency improvement of 6.4% translates to additional thermal recovery of 18.2 MW annually, valued at Rs. 10.36 crores based on the regional power tariff of Rs. 6.50 per kWh.

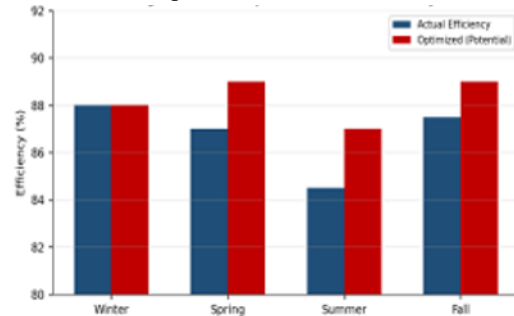


Figure 8. Actual vs. optimized seasonal efficiency, illustrating improvement potential per season.

Table 8: 5-Year Cost-Benefit Analysis

Year	Energy recovered(MWh)	Revenue(Rs Crores)	Cost(Rs. Crores)	Net(Rs. Crores)
1	159,360	10.36	0.322	10.04
2	159,360	10.36	0.322	10.04
3	159,360	10.36	0.322	10.04
4	159,360	10.36	0.322	10.04
5	159,360	10.36	0.322	10.04
Total	796,800	51.81	1.61	50.20

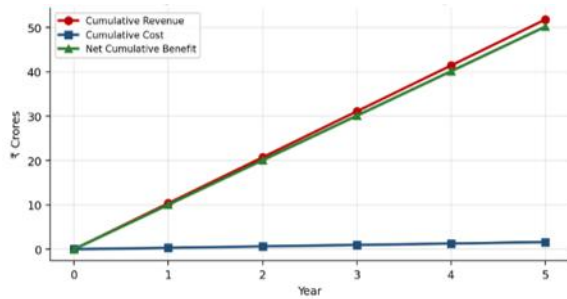


Figure 9. Cumulative revenue, cost, and net benefit curves over a 5-year projection horizon.

VIII. HEAT TRANSFER, MODELING, SENSITIVITY & SUSTAINABILITY

8.1 Heat Transfer Modeling and Predictive Analysis

The monthly heat transfer analysis indicates a clear seasonal variation in the thermal performance of the heat exchanger. During the initial months of the year, the system demonstrates relatively performance, with the NTU increasing from 4.85 in January to 5.02 in March, while the effectiveness improves from 0.894 to 0.902 and the heat transfer coefficient rises from 156.2 to 160.8 W/m²K. At the same time, the fouling factor decreases from 0.000042 to 0.000035, indicating relatively clean heat-transfer 10.04 10.04 10.04 10.04 10.04 50.20 surfaces and efficient thermal operation. From April onward, however, a gradual deterioration in performance can be observed. The NTU decreases to 4.56 in April and continues falling to a minimum of 4.02 in July, accompanied by a reduction in effectiveness from 0.878 to 0.823 and a decrease in HTC from 148.3 to 133.6 W/m²K. This decline corresponds with a significant increase in the fouling factor, which reaches its maximum value of 0.000125 in July. The results suggest that increased fouling resistance during the warmer months may restrict heat transfer and reduce the overall efficiency of the heat exchanger. A slight recovery occurs in August and September, with NTU increasing to 4.08 and 4.48, respectively, while effectiveness improves to 0.835 and 0.872 and HTC increases to 136.4 and 146.5 W/m²K. The fouling factor also decreases during this period, indicating an improvement in heat-transfer conditions. A more significant improvement is observed during October and November, when NTU reaches 4.95 and 5.08, effectiveness rises to 0.901 and 0.906, and HTC reaches 159.2 and 162.3 W/m²K, respectively. November represents the best overall

thermal performance in the dataset, with the highest NTU, effectiveness, and HTC and the lowest fouling factor of 0.000032. In December, the system maintains good performance, with an NTU of 4.88, effectiveness of 0.896, HTC of 157.1 W/m²K, and fouling factor of 0.000040. Overall, the results demonstrate a strong relationship between fouling resistance and heat exchanger performance: as the fouling factor increases, the NTU, effectiveness, and heat transfer

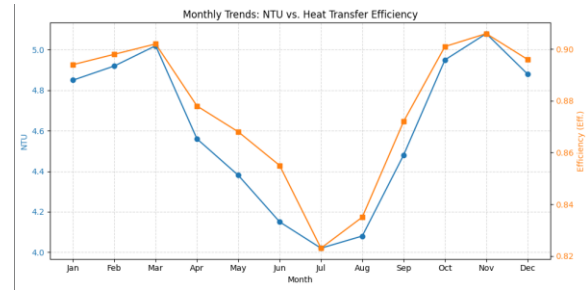


Figure 10. Month vs. NTU and Efficiency

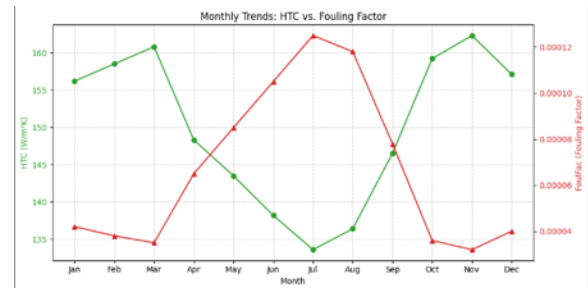


Figure 11. Month vs. HTC and Fouling Factor

8.2 Sensitivity Analysis

The sensitivity analysis of the monthly performance data shows that NTU, effectiveness (Eff.), HTC, and fouling factor (FoulFac) vary significantly with seasonal conditions. From January to March, NTU and effectiveness increase, reaching their highest values in November (5.08 and 0.906), while HTC also peaks at 162.3 W/m²K, indicating better heat-transfer performance. In contrast, during the warmer months, particularly June and July, NTU decreases to 4.15 and 4.02, effectiveness falls to 0.855 and 0.823, and HTC drops to 138.2 and 133.6 W/m²K, while the fouling factor rises to 0.000105 and 0.000125, respectively. This indicates that higher fouling is associated with reduced heat-transfer performance, making the fouling factor one of the most sensitive parameters affecting exchanger efficiency. Overall, the results demonstrate that seasonal variations and fouling conditions have a

direct impact on NTU, effectiveness, and HTC, with the best performance occurring during the cooler months and the lowest performance during July. The sensitivity analysis shows that NTU, effectiveness, HTC, and fouling factor vary with seasonal conditions. The best performance occurs during the cooler months, with NTU, effectiveness, and HTC reaching higher values, particularly in November. During June and July, NTU and effectiveness decrease, while the fouling factor increases, reaching its maximum value of 0.000125 in July. This indicates that increased fouling reduces heat-transfer performance and exchanger efficiency. Overall, the results show that seasonal conditions and fouling significantly influence the heat exchanger performance.

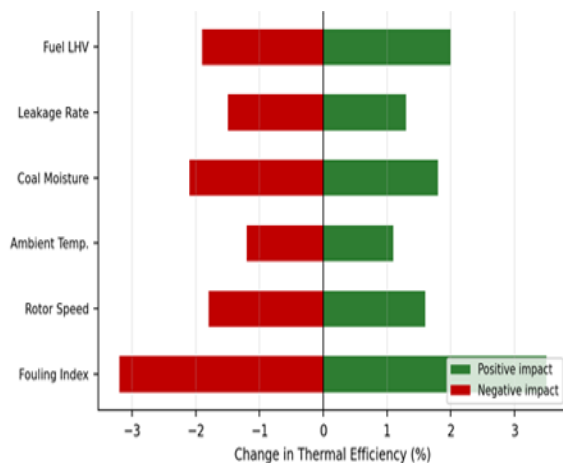


Figure 12. Sensitivity analysis

8.3 Environmental Impact and Sustainability

The monthly performance results indicate that the heat exchanger operates with varying thermal effectiveness and fouling characteristics throughout the year, which directly influence energy consumption and environmental performance. Higher NTU and effectiveness values, particularly during November and March, are associated with performance and a potential increase in energy requirements. Fouling reduces the thermal efficiency of the system and may require additional energy to maintain the desired operating conditions, thereby indirectly increasing the associated environmental impact. Regular monitoring and timely cleaning of heat-transfer surfaces can minimize fouling, improve thermal performance, and reduce unnecessary energy consumption. Maintaining a high heat-transfer.

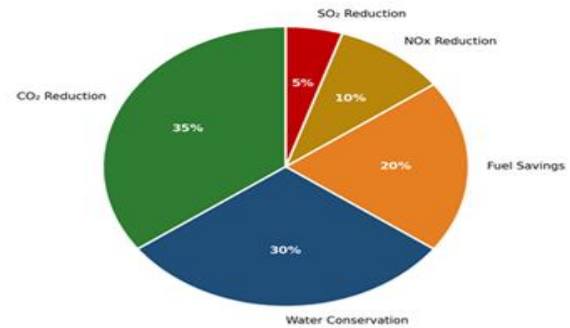


Figure 13. Annual Environmental Benefits

Coefficient also enhances the utilization of recovered thermal energy and reduces the demand for additional fuel or auxiliary energy. Therefore, effective fouling management, periodic performance assessment, and optimized operating conditions can improve overall energy efficiency, reduce emissions associated with energy generation, and contribute to the sustainable operation of the heat-exchange system.

IX. APPLICATIONS, ADVANTAGES AND LIMITATIONS

RAPH is used in thermal power plants to recover heat from flue gases and preheat combustion air. It improves boiler efficiency, combustion performance, and reduces fuel consumption. Performance analysis helps identify air leakage, fouling, corrosion, and heat-transfer losses. Optimization of seals, cleaning methods, and operating conditions improves efficiency. However, lignite ash deposition, seal leakage, and corrosion can reduce RAPH performance.

X. CONCLUSIONS

The RAPH plays a vital role in improving the efficiency of the 210 MW lignite-fired power plant. Parameters such as effectiveness, NTU, heat-transfer coefficient, and air leakage indicate its performance. Fouling and leakage significantly affect heat recovery and boiler efficiency. Proper maintenance, cleaning, and sealing can improve RAPH operation. Overall, optimization reduces energy losses and contributes to efficient power generation.

XI. FUTURE SCOPE

Future studies can implement real-time monitoring of RAPH operating parameters. AI and machine learning can be used to predict fouling and performance deterioration. CFD analysis can help study airflow and temperature distribution within the RAPH. Advanced sealing systems and corrosion-resistant materials can improve reliability. Digital twin and predictive maintenance technologies can further optimize plant performance.

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