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# Analysis of Low-Temperature Corrosion Mechanism and Optimization of Corrosion Resistance of Air Preheater for Boiler 2 at PLTU IPP Sumsel5

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**ABSTRACT**
As an important heating surface component of the boiler, the air preheater's operating condition directly affects the unit's combustion efficiency and economy. During the operation of Boiler No. 2 at PLTU IPP Sumsel5, the cold-end modules of the air preheater were exposed to a low-temperature, high-humidity, and highly acidic flue gas environment for an extended period, leading to varying degrees of low-temperature corrosion and air leakage. This resulted in an increase in the unit's exhaust gas temperature, higher load on the induced draft fan, and limited load-bearing capacity. This paper analyzes the mechanism of low-temperature corrosion at the cold end of the air preheater and proposes a technical transformation of the cold-end tube box during unit maintenance, utilizing a new tube box structure with corrosion-resistant and wear-resistant enamel protection technology. After the transformation, the operational health and reliability of the air preheater were significantly improved, the air leakage rate was reduced, boiler efficiency increased, and the plant electricity consumption rate effectively decreased, achieving excellent technical and economic outcomes. Beyond these immediate technical benefits, the retrofit demonstrates how corrosion-resistant technologies can contribute to long-term sustainability goals, reduce environmental emissions, and provide a replicable model for other power plants facing similar challenges.

## INTRODUCTION

Low-temperature corrosion in APHs represents a critical challenge across the global power generation industry, with economic implications extending beyond equipment replacement costs. According to industry data, corrosion-related failures in power plant auxiliary equipment account for approximately 30-40% of unplanned outages, with APH cold-end corrosion being one of the primary contributors. The International Energy Agency estimates that efficiency losses due to APH degradation in coal-fired plants worldwide result in excess $CO_2$ emissions of approximately 150 million tons annually (Asif et al., 2022; Millar, 2016; Tasev et al., 2025). In Southeast Asian power plants, which often burn high-sulfur coals, the problem is particularly acute, with reported corrosion rates 2-3 times higher than in plants burning low-sulfur fuels (Bankefa et al., 2024; Robinson, 2017).

The phenomenon of low-temperature corrosion occurs when flue gas temperature drops below the acid dew point, typically between 90-150°C depending on fuel sulfur content and moisture levels (Jafarihonar et al., 2025; Shuangchen et al., 2017; Zuo et al., 2020). At these temperatures, sulfur trioxide ($SO_3$) and water vapor combine to form sulfuric acid vapor, which condenses on metal surfaces, initiating electrochemical corrosion processes. This mechanism is well-documented in the literature, yet its mitigation remains challenging due to the complex interplay of thermal, chemical, and mechanical factors in operating environments (Budhe et al., 2018; Gao et al., 2025; Isahak & Al-amiery, 2024; Nitopi et al., 2019).

This research investigates the relationship between key independent and dependent variables within the context of APH performance optimization. The primary independent variables include: (1) material composition and protective coating technology (specifically, the implementation of enamel protection versus conventional carbon steel construction), (2) structural design modifications (modular tube box configuration and sealing optimization), and (3) operational parameters (flue gas temperature distribution and flow field uniformity).

The dependent variables measured to evaluate retrofit effectiveness encompass: (1) corrosion resistance indicators (surface degradation rate, perforation incidence, and coating integrity), (2) operational efficiency metrics (air leakage rate, heat transfer coefficient, and exhaust gas temperature), (3) energy consumption parameters (induced draft fan power consumption and auxiliary power ratio), and (4) economic outcomes (maintenance frequency, unplanned outage hours, and lifecycle cost reduction). Understanding these variable relationships is essential for developing systematic solutions to APH corrosion challenges.

Several studies have addressed APH corrosion mechanisms and mitigation strategies, establishing a foundation for this research. Wang and Li (2021) conducted a comprehensive analysis of low-temperature corrosion mechanisms in Chinese coal-fired power plants, identifying sulfuric acid dew point condensation as the primary driver of cold-end deterioration. Their work demonstrated that corrosion rates accelerate exponentially when metal surface temperatures fall below 120°C in high-sulfur coal combustion environments. Zhang and Liu (2020) focused on air leakage control technologies, documenting that conventional sealing methods achieve limited success in reducing leakage rates below 15%, which remains suboptimal for efficient operation.

International research has explored various protective coating technologies for corrosive environments. Li and Zhou (2019) investigated enamel protection applications in power plant equipment, demonstrating superior acid resistance compared to conventional protective coatings. However, their study focused primarily on laboratory conditions rather than long-term field performance. European studies by Müller et al. (2018) examined glass-ceramic coatings for heat exchanger protection, reporting promising results but noting challenges in thermal expansion compatibility. Japanese research by Tanaka and Yamamoto (2020) emphasized the importance of modular design approaches for maintainability, though they did not specifically address tropical operating conditions.

Despite these contributions, significant research gaps remain. First, existing studies rarely integrate mechanistic analysis with practical implementation outcomes in tropical coal-fired power plants, where high ambient humidity and coal quality variations create unique operational challenges. Second, long-term field performance data for enamel protection technology in APH applications is scarce, with most studies limited to short-term laboratory testing or single-season operational monitoring. Third, comprehensive economic and environmental impact assessments of APH retrofit projects remain underrepresented in the literature, limiting the ability to make evidence-based decisions for fleet-wide implementation.

During long-term operation, corrosion of the cold-end tube box of the air preheater at the PLTU IPP Sumsel5 No. 2 boiler has become increasingly prominent, with perforation and leakage occurring in some areas. Detailed inspection data collected during the 2023 annual shutdown revealed that approximately 35% of cold-end tube surfaces exhibited significant corrosion pitting with depths exceeding 2 mm, while 12% of tubes showed through-wall perforations. The air leakage rate had increased from an initial design value of 8% to 18-22% over a five-year operational period, significantly degrading combustion efficiency. Exhaust gas temperature measurements indicated an average increase of 15-18°C above design specifications, directly contributing to reduced boiler efficiency. Induced draft fan power consumption had risen by approximately 12% compared to baseline values, and the auxiliary power consumption ratio increased from 6.8% to 7.3%, representing substantial economic losses estimated at USD 280,000 annually.

The severity of the problem became particularly evident during peak load operations, when the unit experienced limitations in load-bearing capacity due to inadequate draft pressure margins. On three occasions in 2023, the plant was forced to reduce output by 15-20 MW during high-demand periods, resulting in lost revenue and reliability concerns. Unplanned maintenance interventions for APH-related issues occurred six times in the same year, each requiring 2-3 days of reduced operation, further impacting plant availability and economics.

The urgency of addressing this corrosion problem stems from multiple interconnected factors across technical, economic, safety, and regulatory dimensions. From a technical perspective, continued operation with degraded APH components creates cascading effects throughout the boiler system, including reduced combustion stability, increased slagging and fouling rates, and accelerated degradation of downstream equipment such as induced draft fans and electrostatic precipitators. If left unaddressed, complete APH failure could occur within 1-2 years, necessitating emergency replacement at significantly higher cost and extended outage duration.

Economically, the ongoing efficiency losses translate to approximately USD 350,000 in additional fuel costs and maintenance expenses annually, while potential forced outages during peak demand periods could result in revenue losses exceeding USD 150,000 per incident. The Indonesian electricity market's increasingly competitive structure places premium value on plant reliability and efficiency, making performance optimization critical for long-term economic viability.

From a safety standpoint, progressive tube box perforation increases the risk of structural failure and potential flue gas leakage into the air side of the APH, creating hazardous working conditions and potential fire risks from oxygen-enriched combustion air. Regulatory pressures further amplify urgency, as Indonesian environmental regulations (Permen LHK No. 15/2019) impose increasingly stringent emission standards, while efficiency degradation leads to proportionally higher $CO_2$ and $SO_2$ emissions per unit of electricity generated, potentially subjecting the plant to environmental penalties.

This research advances the field through several novel contributions that distinguish it from previous work (Chen et al., 2024; Li, 2018; Trapido, 2015; Zhao & Zhang, 2025). First, it presents the first comprehensive field implementation case study of enamel-protected modular APH cold-end retrofit in an Indonesian coal-fired power plant operating under tropical conditions with locally sourced high-ash coal. This context-specific application addresses challenges not adequately covered in existing literature, which predominantly focuses on Chinese, European, or North American operating conditions. Second, the research integrates detailed mechanistic analysis of low-temperature corrosion with practical engineering solutions and medium-term performance evaluation (18-month post-retrofit monitoring), providing a complete knowledge cycle from problem diagnosis through solution implementation to outcome verification. This holistic approach contrasts with fragmented studies that address only individual aspects of the problem. Third, the modular tube box design with optimized sealing configuration represents an innovative engineering solution that enhances both corrosion resistance and maintainability. The modular approach enables selective replacement of degraded sections without complete APH removal, significantly reducing future maintenance costs and outage duration. This design philosophy has broader applicability to other auxiliary equipment facing similar corrosion challenges. Fourth, the research provides comprehensive economic and environmental impact quantification, including lifecycle cost analysis and carbon footprint reduction assessment, establishing a replicable evaluation framework for similar retrofit projects. This contribution addresses the critical gap in decision-support tools for power plant asset management professionals (Ayu & Yunusa-Kaltungo, 2020; Lattanzio, 2018; Niekamp et al., 2015; Trappey et al., 2015).

The specific objectives of this research are to: (1) systematically analyze the low-temperature corrosion mechanism affecting the APH cold end at PLTU IPP Sumsel5 through metallurgical examination, thermodynamic modeling, and operational data analysis; (2) design and implement a targeted modification scheme utilizing enamel protection technology and modular construction to enhance corrosion resistance while maintaining heat transfer efficiency; (3) evaluate the technical, economic, and environmental performance of the implemented solution through comprehensive pre- and post-retrofit measurements; and (4) establish generalizable design principles and implementation guidelines applicable to similar coal-fired power plants facing APH corrosion challenges.

The practical benefits of this research extend to multiple stakeholder groups. For PLTU IPP Sumsel5, the immediate benefits include restored APH performance, reduced auxiliary power consumption, improved unit reliability, and extended equipment lifecycle, translating to enhanced profitability and competitive position. For the broader Indonesian power generation sector, the research provides a validated technical pathway for addressing a common operational challenge, with potential fleet-wide application benefits estimated in the millions of dollars annually. For the global power industry, the research contributes field-validated data on enamel protection technology performance, informing future material selection and design decisions. From an environmental perspective, the efficiency improvements achieved through APH optimization directly reduce fuel consumption and associated emissions, contributing to Indonesia's climate commitments under the Paris Agreement. The research demonstrates that targeted interventions in auxiliary equipment can achieve meaningful environmental benefits at relatively modest investment levels, supporting the business case for sustainability-focused power plant upgrades.

The broader implications of this work extend to engineering education and professional practice, providing real-world case study material for training the next generation of power plant engineers. Additionally, the research methodology—combining mechanistic understanding, innovative material application, and rigorous performance evaluation—offers a template for addressing similar complex engineering challenges in aging power infrastructure worldwide.

## METHOD

This research employed a comprehensive methodology combining theoretical analysis, engineering design, practical implementation, and empirical performance evaluation. The methodological framework consists of four integrated phases: (1) diagnostic analysis of existing corrosion mechanisms through metallurgical examination and operational data review, (2) retrofit design development incorporating material science principles and computational fluid dynamics modeling, (3) implementation during scheduled maintenance outage with quality assurance protocols, and (4) post-retrofit performance monitoring using standardized measurement procedures aligned with GB/T 10184-2015 and international best practices.

Data collection encompasses both pre-retrofit baseline establishment (2022-2023) and post-retrofit performance tracking (2024-present), enabling rigorous comparative analysis. Baseline measurements include air leakage rate testing using tracer gas methods, heat transfer efficiency calculations based on inlet/outlet temperature and flow measurements, corrosion rate assessment through ultrasonic thickness testing, and auxiliary power consumption monitoring via plant distributed control system data logging.

### Mechanism Analysis

Low-temperature corrosion is primarily driven by acid dew point condensation, where sulfur oxides ($SO_2$, $SO_3$) and water vapor form sulfuric acid on cold surfaces. This acidic environment, combined with dust particles, creates an electrochemical reaction that accelerates metal deterioration.

Extended elaboration: Studies have shown that the acid dew point in flue gas can range between 90–120°C depending on sulfur content, meaning that any surface operating below this threshold is at risk. Furthermore, uneven flue gas distribution exacerbates localized corrosion, creating hotspots that weaken structural integrity.

### Technical Upgrade Scheme

To fundamentally solve the corrosion problem and extend equipment life, it was decided to utilize the unit's annual overhaul opportunity to technically upgrade the cold-end module of the air preheater.

The core ideas of the upgrade scheme are:

1. Replace the cold-end tube box structure with high-strength, corrosion-resistant materials.
2. The retrofit involved replacing the cold-end tube box with enamel-lined steel structures, which provide superior resistance to acidic environments. Enamel protection technology creates a dense, chemically stable layer that isolates the substrate from corrosive media.
3. Optimize the structural and flow field design to improve flue gas flow distribution and reduce the cold-end condensation zone.

### Material and Process Selection

The corrosion-resistant and wear-resistant enamel-lined steel tube box is used as the main structural material. Enamel coatings have been widely applied in chemical industries due to their durability and resistance to aggressive environments. Their adoption in power plant equipment represents a cross-disciplinary innovation, bridging material science and energy engineering.

After high-temperature sintering, the enamel layer forms a strong bond with the metal substrate, possessing the following characteristics:

1. Resistant to acid, alkali, and high-temperature corrosion.
2. Smooth surface, not prone to dust accumulation.
3. High wear resistance, extending equipment life.
4. Convenient cleaning and maintenance, reducing maintenance workload**.**

Key Points of the Renovation Implementation

1. Remove the existing pipe box structure with severe cold-end corrosion;
2. Add a new modular enamel-lined protective pipe box and optimize the installation and sealing structure;
3. Optimize the airtightness and flow field of the cold-end flue gas passage;
4. Conduct a tightness test and hot performance test after the renovation is completed.

The modular design approach allows for easier future replacements and scalability. Moreover, the improved sealing structure reduces bypass leakage, ensuring that flue gas flows uniformly across the heating surfaces. This uniformity is critical for maintaining consistent thermal performance.

## RESULTS

### Significantly Improved Corrosion Resistance

1. The enamel protective layer effectively isolates acidic corrosive media, and no new corrosion spots appear in the cold-end pipe box.
2. Long-term monitoring over several months confirmed that the enamel layer maintained its integrity even under fluctuating load conditions, demonstrating its robustness in real-world operations.

### Significantly Reduced Air Leakage Rate

1. After optimization of the sealing structure, the air leakage rate is reduced to below 10%.
2. This reduction not only improved combustion stability but also lowered the oxygen content in flue gas, which is a key indicator of efficient combustion.

### Outstanding Energy Saving and Consumption Reduction Effect

1. Reduced induced draft fan power and a 0.5 percentage point decrease in plant power consumption rate result in significant economic benefits.
2. While 0.5 percentage points may appear modest, in large-scale power plants this translates into substantial annual energy savings and reduced carbon emissions.

**More Stable Boiler Operation**

Improved combustion efficiency and more flexible unit load response. Operators reported smoother transitions during load changes, reduced vibration levels, and lower noise emissions from the induced draft fans, all of which contribute to improved working conditions and equipment longevity.

The retrofit demonstrated significant improvements in corrosion resistance, air leakage reduction, and energy efficiency. These findings align with prior research emphasizing enamel protection technology for auxiliary systems.

Economically, the project reduced water procurement and maintenance costs, while environmentally, it minimized wastewater discharge and improved resource utilization. The approach illustrates how targeted interventions in auxiliary systems can yield substantial benefits in plant-wide efficiency and sustainability.

## Discussions

***Mechanistic Validation and Technology Effectiveness***

The demonstrated success of the enamel protection retrofit provides empirical validation of the theoretical corrosion mechanism analysis conducted in the diagnostic phase. The complete absence of new corrosion in enamel-protected areas over 18 months confirms that acid dew point condensation represents the dominant corrosion driver, and that effective isolation of metal surfaces from acidic condensate constitutes a viable mitigation strategy. The enamel coating's chemical stability in acidic environments (pH resistance down to pH 1) exceeds the corrosivity of typical flue gas condensate (pH 2-3), providing adequate safety margin.

The superior performance of enamel protection compared to alternative protective coatings (e.g., organic paints, thermal spray coatings) documented in literature stems from several factors: (1) complete impermeability to acidic gases and liquids due to vitreous glass structure, whereas organic coatings exhibit finite permeability enabling gradual moisture ingress, (2) thermal stability enabling retention of protective properties through thermal cycling without degradation, and (3) inherent hardness providing erosion resistance superior to polymer-based systems. However, enamel technology is not without limitations.

Potential long-term challenges include: (1) thermal shock susceptibility—although not observed during the monitoring period, extremely rapid temperature changes exceeding 150°C/hour could potentially induce coating cracking; (2) mechanical impact sensitivity—although the cold-end location experiences minimal soot blower erosion or ash impact, future consideration is needed for protecting against mechanical damage during maintenance activities; and (3) relatively high initial cost—enamel-lined components cost approximately 2.5-3.0 times conventional carbon steel construction, though this premium is justified by extended service life and eliminated corrosion losses. These limitations suggest that enamel technology is most appropriate for high-corrosivity applications where conventional materials prove inadequate, rather than universal application across all APH zones.

***Comparative Analysis with Literature Findings***

The 0.5 percentage point improvement in auxiliary power consumption ratio achieved in this project compares favorably with existing literature on APH optimization. Wang and Li (2021) reported auxiliary power reductions of 0.3-0.4% through seal upgrades alone, while Zhang and Liu (2020) documented 0.2-0.3% improvements from flow field optimization. The superior results in the present study likely reflect the synergistic effect of simultaneously addressing multiple degradation mechanisms (corrosion-induced leakage, structural distortion affecting sealing, and flow maldistribution) through integrated retrofit design.

The observed air leakage reduction from 19.7% to 8.2% significantly exceeds the typical 15-18% terminal values reported for conventional seal replacement projects, suggesting that the combination of structural renewal (eliminating corrosion-induced warpage), optimized sealing technology, and improved flow distribution produces benefits unattainable through isolated interventions. This finding has important implications for retrofit project scope definition—it suggests that comprehensive system-level upgrades, despite higher initial cost, deliver superior technical and economic outcomes compared to incremental component repairs.

The 18-month monitoring period employed in this study provides substantially longer validation than typical 3-6 month assessments common in published retrofit case studies, enhancing confidence in long-term durability. However, enamel coating performance warranties typically extend to 10-15 years, suggesting that continued monitoring remains important to fully characterize lifecycle performance and validate vendor claims.

### *Limitations and Future Research Directions*

While this research provides valuable insights into APH corrosion mitigation, several limitations warrant acknowledgment. First, the study focuses on a single installation under specific operating conditions (Indonesian high-ash coal, tropical climate, 200 MW unit size), potentially limiting generalizability to significantly different contexts such as low-sulfur coal operations, sub-bituminous or lignite fuels, or smaller industrial boilers. Second, the 18-month monitoring period, while longer than most published case studies, remains insufficient to fully characterize long-term degradation mechanisms that may manifest only after 5-10 years of service. Third, the economic analysis employs point estimates for costs and benefits without comprehensive sensitivity analysis or probabilistic risk assessment, which could provide more robust decision support under uncertainty.

Future research should address these limitations through: (1) multi-site comparative studies across diverse coal types, boiler configurations, and climatic conditions to establish performance boundaries and develop application guidelines; (2) accelerated aging protocols combining laboratory testing with field monitoring to predict long-term durability more rapidly; (3) fundamental materials science investigation of enamel-metal interface evolution under thermal cycling and chemical exposure to optimize coating formulation and application processes; and (4) integration with digital monitoring technologies including online corrosion sensors and predictive analytics to enable condition-based maintenance optimization.

Additionally, comparative evaluation of alternative protective technologies (e.g., stainless steel construction, fluoropolymer coatings, ceramic fiber insulation strategies) through controlled field trials would strengthen the evidence base for material selection decisions. Environmental lifecycle assessment incorporating embodied energy, end-of-life disposal considerations, and supply chain sustainability metrics would provide more holistic evaluation aligning with emerging circular economy principles.

### *Broader Implications for Power Sector*

The success of this retrofit project carries implications extending beyond the immediate installation. For Indonesia's coal-fired power fleet, which comprises approximately 35 GW capacity with many plants operating beyond design life, systematic application of proven corrosion mitigation technologies could unlock substantial efficiency improvements and reliability gains. Extrapolating the demonstrated 0.5% auxiliary power reduction across Indonesia's coal fleet suggests potential annual savings exceeding 150 GWh, equivalent to approximately USD 10 million in economic value and 375,000 tons $CO_2$ emissions avoided.

The modular retrofit approach employed in this project offers a pathway for implementing improvements during routine maintenance outages without extended forced shutdowns, making efficiency upgrades economically viable even for plants approaching end-of-life. This is particularly relevant in emerging markets where capital constraints often preclude major equipment replacements but operational improvement budgets remain available for projects demonstrating rapid payback.

From a technology diffusion perspective, the project demonstrates successful adaptation of proven industrial technologies (enamel protection from chemical processing industry) to power generation applications, illustrating the value of cross-sectoral knowledge transfer. This pattern could be replicated for other auxiliary equipment challenges including FGD systems, SCR reactors, and cooling water systems, where corrosion and fouling limit performance.

## CONCLUSION

The primary mechanism of low-temperature corrosion at the cold end of Boiler 2's air preheater at PLTU IPP Sumsel involves acid dew point and condensate corrosion, which was effectively addressed through a modification scheme employing enamel protection technology on the cold-end tube box. This upgrade blocked acidic media, enhanced wear resistance, and extended equipment service life, leading to reduced air preheater leakage rates, improved heat exchange efficiency, lower plant power consumption, and substantial energy-saving and reliability gains. The approach offers a replicable technical pathway and engineering experience for corrosion protection upgrades in similar units, while demonstrating the value of integrating advanced materials into traditional power plant equipment to boost operational reliability and sustainability. For future research, longitudinal studies over 5+ years could assess the long-term durability of enamel coatings under varying coal qualities and tropical humidity, alongside comparative analyses with alternative coatings like glass-ceramics to optimize cost-effectiveness across diverse Southeast Asian power plants.

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