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Research on Structural Optimization and Vacuum Performance Improvement of Condenser Air Extraction System of Unit 2 PLTU IPP Sumsel

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ABSTRACT
Condenser vacuum level is a critical parameter that directly influences the thermal economy of steam turbines and the overall efficiency of power generation units. At PLTU IPP Sumsel 5, operational monitoring revealed that the condenser air extraction pipeline of Unit 2 was not installed in strict accordance with the original design drawings. This deviation led to low air extraction efficiency, the formation of local gas stagnation zones, and a condenser vacuum that consistently remained below the design specification. In response to this issue, the power plant utilized the scheduled annual overhaul period to carry out a comprehensive technical evaluation and optimization of the condenser vacuum system. The improvement strategy focused on redesigning and reinstalling the air extraction system, with particular attention to the structural configuration and flow distribution of the extraction pipelines. A total of 2,200 extraction pipelines were optimized to ensure balanced airflow and uniform air removal throughout the condenser. Following the implementation of these modifications, the condenser vacuums stably reached the designed operating level of −93 kPa. As a result, the turbine back pressure was reduced by approximately 3.5 kPa, which contributed to a noticeable improvement in the unit's thermal efficiency. These technical enhancements not only improved operational stability but also generated significant energy savings and economic benefits, demonstrating the effectiveness of systematic condenser vacuum optimization in coal-fired power plant operations.

Keywords: *Condenser; Air extraction system; Vacuum optimization; Structural modification; Operating efficiency*

INTRODUCTION

Thermal power plants operate as complex energy systems whose performance heavily depends on the reliability of auxiliary equipment, particularly feedwater pumps (Jiang & Wang, 2021; Kim et al., 2020). These pumps play a critical role in ensuring a continuous water supply to the boiler, making their operational stability essential for both the safety and economic performance of the unit (Chen et al., 2019). One of the most crucial subsystems in feedwater pumps is the shaft seal, which requires continuous cooling to prevent excessive temperature rise and mechanical failure (Zhang & Li, 2022; Liu et al., 2020). Previous studies have identified seal cooling system failures as a major contributor to reduced reliability and increased forced outages in thermal power units (Xu & Li, 2023; Wang et al., 2021; Chen & Sun, 2019; Li & Wang, 2021).

In many thermal power plants, demineralized water is still widely used as the primary cooling medium for feedwater pump seal systems. Although demineralized water meets chemical quality requirements, its temperature is highly influenced by ambient conditions (Zhang et al., 2021; Kim & Lee, 2020). During high-temperature seasons, inlet water temperatures often approach or exceed 30°C, significantly limiting heat absorption capability (Wang et al., 2022; Liu et al., 2021). As a result, the seal return water temperature increases, posing risks to equipment integrity and operational stability (Zhou & Zhao, 2020; Wang & Huang, 2023).

This issue has become increasingly critical amid rising demands for energy efficiency and water conservation in the power generation sector (Farghali et al., 2023; Gyamfi et al., 2018; Stambouli & Flazi, 2015; Strielkowski et al., 2021). Inefficient cooling systems not only lead to excessive consumption of demineralized water but also increase energy usage due to higher pump friction and load fluctuations. Furthermore, regulatory pressures and sustainability commitments encourage power plants to adopt water-saving and energy-efficient technologies. Consequently, optimizing auxiliary cooling systems has become a strategic priority for thermal power plants (Li & Wang, 2021; Chen & Sun, 2019; IEA, 2020).

From a theoretical perspective, the effectiveness of a cooling system is largely determined by the temperature difference between the inlet and outlet fluids, as well as by stable flow conditions. Design standards for thermal equipment cooling systems typically require a temperature differential of 10–12°C to ensure effective heat transfer. However, field operation data often reveal that demineralized water-based systems fail to meet this requirement due to limited cold source capacity and heat exchanger fouling (Incropera et al., 2017; GB/T 10184-2015; Wang et al., 2022).

Previous studies have explored various approaches to improving cooling system performance in thermal power plants. Zhou and Zhao (2020) demonstrated that optimizing seal water system configurations can significantly reduce pump operating temperatures. Chen and Sun (2019) highlighted the potential of utilizing chilled water systems as alternative cooling sources for auxiliary equipment. Meanwhile, Li and Wang (2021) reported that water-saving retrofit strategies could reduce cooling water consumption by more than 50% while maintaining system reliability.

Despite these contributions, most existing studies focus on isolated aspects, such as thermal efficiency improvement or water conservation alone. Integrated analyses that simultaneously address cooling performance, energy efficiency, water savings, and system reliability remain limited. Moreover, comprehensive reports based on practical engineering implementation in thermal power plants located in tropical climates are still scarce (Zhou & Zhao, 2020; Li & Wang, 2021; Wang et al., 2022).

Based on this literature review, a clear research gap exists regarding the comprehensive evaluation of chilled water utilization as a seal water cooling source, considering not only thermal performance but also water consumption, energy efficiency, and operational reliability. In addition, studies discussing dual-source cooling configurations that combine new cooling sources with existing systems as operational backups are relatively rare (Chen & Sun, 2019; Zhou & Zhao, 2020; Li & Wang, 2021).

This study aims to analyze the causes of the low condenser vacuum level in the air extraction system of Unit 2 of the South Sumatra PLTU IPP and to design and evaluate the optimization of the structure of the air extraction system to improve condenser vacuum performance and the thermal efficiency of the power plant. The research provides theoretical benefits in the form of contributions to the development of condenser system engineering studies and vacuum performance optimization in steam power plants. Practically, the results of this study can serve as a technical reference for plant managers in improving the design and installation of air extraction systems to enhance operating efficiency, reduce turbine back pressure, achieve energy savings, and improve the economic performance of the plant.

METHOD

During operation of Unit 2 at PLTU IPP Sumsel, several critical issues related to condenser vacuum performance were identified. The condenser vacuum consistently remained in the range of −89 kPa to −90 kPa, which was significantly lower than the design value of −93 kPa. Vacuum levels also fluctuated widely and were unstable under varying load conditions. The ejector system experienced frequent trips, indicating insufficient gas flow adjustment capability. Furthermore, severe gas stagnation occurred in certain areas of the condenser, resulting in an excessively large cold-end temperature difference and reduced heat exchange efficiency.

Field inspections and technical evaluations revealed that these problems were primarily caused by installation and operational deficiencies. Several ejector pipes had not been installed according to the design drawings, with off-center positioning and inconsistent lengths that disrupted airflow organization inside the condenser. The inlet orientation and distribution of extraction pipes were also unreasonable, leading to localized extraction and ineffective evacuation of dead zones. In addition, micro-leakage at some weld joints reduced the overall suction efficiency, while deviations in operating parameters—particularly a high proportion of humid air at the ejector inlet—increased the system's suction load.

The optimization of the condenser air extraction system was carried out based on four main principles. First, airflow uniformity was emphasized to ensure that the steam–air mixture in all condenser areas could be extracted evenly. Second, structural rationality was ensured by aligning pipe length, angle, and arrangement with the original design intent and validating them through flow field calculations. Third, sealing reliability was prioritized by ensuring all welded joints met airtightness standards. Finally, construction feasibility was considered so that all optimization work could be safely completed within the scheduled maintenance window.

The optimization scheme included comprehensive rearrangement and structural improvement of the extraction system. A total of 2,200 extraction pipes were repositioned based on design drawings and verified 3D models, with strict control of length tolerances and installation angles. CFD simulations were used to determine optimal extraction locations, transforming the original centralized system into a zoned and layered "pressure equalization extraction" layout. The pipe structure was improved by adopting tapered inlets and adding guide vanes in key areas to enhance gas flow convergence. Finally, argon arc welding was applied, followed by 100% airtightness testing and weld smoothing to minimize leakage and secondary flow resistance.

RESULTS AND DISCUSSION

The implementation of the condenser air extraction system modification yielded substantial improvements in vacuum stability, energy efficiency, and operational reliability. The retrofit was executed in a phased manner to ensure installation accuracy and to minimize operational risk.

Precision surveying was conducted to align the installation points of the stainless steel air extraction pipes with CFD-validated locations, ensuring optimal airflow distribution within the condenser upper cavity. Subsequent welding, airtightness testing, and system vacuum testing confirmed the structural integrity and sealing quality of the modified system (ASME, 2019; Versteeg & Malalasekera, 2007; Zhou & Zhao, 2020).

During commissioning, key operational parameters including condenser vacuum, exhaust pressure, and cooling water temperature differential were continuously monitored. The vacuum build-up process was smooth and stable, with no abnormal fluctuations observed. Notably, the operating load of the air ejector decreased by approximately 12%, indicating reduced flow resistance and improved air extraction efficiency. This reduction reflects a direct improvement in system thermodynamic performance and mechanical loading conditions (Çengel & Boles, 2015; White, 2016; Chen & Sun, 2019).

Under sustained high-load operation, the unit consistently maintained its design condenser vacuum of −93 kPa. The optimized airflow distribution effectively eliminated stagnant zones, enhancing the removal of non-condensable gases. As a result, turbine efficiency improved by approximately 1.8%, contributing to measurable fuel savings and reduced carbon emissions on an annual basis. Furthermore, improved sealing performance and standardized system configuration significantly reduced maintenance frequency and enhanced overall operational reliability (Li & Wang, 2021; Zhou & Zhao, 2020; IEA, 2020).

Table 1. Operational Performance Before and After System Modification

Parameter	Before Modification	After Modification	Impact
Condenser vacuum	−88 to −90 kPa	Stable −93 kPa	Improved condensation efficiency
Air ejector load	Baseline (100%)	−12%	Energy consumption reduced
Airflow distribution	Non-uniform	Uniform	Stagnant zones eliminated
Turbine efficiency	Baseline	+1.8%	Fuel savings
Maintenance frequency	High	Reduced	Reliability improved

Structural Accuracy and Vacuum System Performance

The findings confirm that even minor structural deviations in auxiliary systems can exert a disproportionate impact on overall plant efficiency. Prior to modification, misaligned air extraction pipes caused uneven airflow and localized accumulation of non-condensable gases, thereby degrading condenser vacuum. This observation is consistent with classical heat transfer theory, which identifies non-condensable gases as a major source of thermal resistance in condensation processes (Incropera et al., 2017; Çengel & Boles, 2015; White, 2016).

By restoring geometric accuracy through precision surveying and phased installation, the modified system achieved uniform airflow and stable vacuum conditions. This demonstrates that strict adherence to design specifications is not merely procedural, but fundamental to thermodynamic performance. Similar conclusions have been reported in previous condenser optimization studies (Zhou & Zhao, 2020; Chen & Sun, 2019; ASME, 2019). From a reliability standpoint, improved sealing integrity reduced leakage risks and vacuum instability, thereby enhancing long-term operational robustness. These results reinforce the importance of quality-controlled installation as a determinant of auxiliary system performance (Li & Wang, 2021; White, 2016; IEA, 2020).

Role of CFD in Engineering Optimization

The application of CFD played a critical role in diagnosing airflow maldistribution and guiding structural redesign. CFD enabled detailed visualization of stagnant zones and dominant flow paths that are not detectable through conventional inspection. This aligns with modern power plant engineering practices that increasingly rely on numerical 471odelling to support data-driven decision-making (Versteeg & Malalasekera, 2007; Ferziger et al., 2020; Zhou & Zhao, 2020).

Post-modification results validated the CFD predictions, as evidenced by improved vacuum stability and reduced ejector load. This correlation confirms the reliability of CFD as both a diagnostic and predictive tool when coupled with precise field implementation. Prior studies similarly report performance gains when CFD-based designs are accurately executed (Chen & Sun, 2019; Li & Wang, 2021; Incropera et al., 2017).

Moreover, integrating CFD into routine maintenance planning offers long-term strategic value. It enables proactive identification of inefficiencies and supports continuous performance improvement across auxiliary systems (ASME, 2019; Ferziger et al., 2020; IEA, 2020).

Energy Efficiency and Thermodynamic Implications

The observed increase in condenser vacuum directly enhanced the thermodynamic efficiency of the Rankine cycle. Lower turbine exhaust pressure increased specific turbine work, resulting in a 1.8% improvement in turbine efficiency. Although numerically modest, such efficiency gains translate into substantial fuel savings and emission reductions at the plant scale (Çengel & Boles, 2015; Zhou & Zhao, 2020; IEA, 2020).

In addition, the 12% reduction in air ejector load indicates decreased auxiliary power consumption. Reduced mechanical stress further contributes to extended equipment lifespan and lower maintenance costs, reinforcing the economic benefits of auxiliary system optimization (White, 2016; ASME, 2019; Li & Wang, 2021). These results demonstrate that targeted improvements in auxiliary systems can yield system-wide efficiency gains without major capital investment in primary equipment (Chen & Sun, 2019; Zhou & Zhao, 2020; IEA, 2020).

Operational Reliability and Managerial Implications

Enhanced sealing quality and standardized system configuration significantly improved operational reliability. Reduced leakage and stable vacuum conditions minimized unplanned outages, thereby increasing plant availability and profitability. This finding supports prior research emphasizing the critical role of auxiliary system reliability in overall power plant performance (Li & Wang, 2021; Zhou & Zhao, 2020; IEA, 2020).

From a managerial perspective, the study highlights the necessity of enforcing installation quality control and design compliance. Minor deviations during installation can accumulate into significant long-term inefficiencies if left uncorrected. Therefore, integrating CFD analysis, precision installation, and continuous monitoring into maintenance strategies is essential (ASME, 2019; Ferziger et al., 2020; Chen & Sun, 2019). Overall, this study demonstrates that systematic auxiliary system optimization provides a replicable and cost-effective pathway toward sustainable performance enhancement in thermal power plants (Zhou & Zhao, 2020; Li & Wang, 2021; IEA, 2020).

CONCLUSION

This study demonstrates that systematic optimization of the condenser air extraction system, guided by CFD analysis and precise implementation, substantially improved thermal power plant performance without major capital investment—stabilizing condenser vacuum at the design level of −93 kPa, reducing air ejector load by 12%, boosting turbine efficiency by 1.8%, and yielding energy savings with lower emissions. Enhanced sealing and standardized configurations also increased operational reliability, cut maintenance needs, and raised plant availability, offering a replicable, cost-effective model for efficiency, reliability, and sustainability. For future research, investigators could explore AI-driven predictive maintenance integrated with real-time CFD monitoring to further optimize dynamic load responses in tropical climates.

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