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In-depth Analysis of Operator Experiences in Optimizing Main Engine Cooling Systems Based on On-site Operational Insights

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ABSTRACT

This study explores the role of operator experience in optimizing main engine cooling systems within large-capacity machinery industries. Using a qualitative case study approach in the heavy manufacturing sector in Banten Province, data were collected through in-depth interviews and on-site observations involving 12 informants, including engine operators, supervisors, and maintenance technicians. Thematic analysis reveals that operator experience is critical for early detection of thermal abnormalities, adaptive adjustment of operating parameters, and prevention of recurring system disturbances that are not fully addressed by standard procedures. The study concludes that systematically integrating operator insights into operation and maintenance management enhances cooling system optimization and offers practical contributions to operational strategies and field-based training in mechanical engineering.

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INTRODUCTION

The cooling system on the main engine is a crucial element in maintaining the stability of the operating temperature of heavy machinery and large-capacity energy systems. The inability of the cooling system to effectively manage heat can lead to increased component wear, decreased thermal efficiency, and system failures that impact safety and continuity of operation (Kumar & Kumar, 2021). As the complexity of modern machines increases and the demands of continuous operation increase, cooling systems are demanded to be not only technically technically reliable but also adaptive to real variations in operational conditions (Saidur et al., 2020). In the context of the modern industrial system, machines and operators form a socio-technical system that is interdependent (Hollnagel, 2021). Therefore, the effectiveness of the cooling system cannot be separated from the role of the operator in managing and adjusting the operation of the machine in the field.

Various international studies show that human factors have a significant influence on the performance and safety of complex engineering systems. A study by Dul et al., (2021) confirms that operator experience directly contributes to the ability of industrial systems to respond to abnormal conditions. However, studies of major engine cooling systems are still dominated by approaches based on mechanical design, thermal analysis, and numerical modeling (Zhang & Li, 2022). Such studies rarely explore how operator experience is used to optimize cooling system performance in real-time. As a result, the operator field experience dimension is still an underrepresented aspect in the development of major engine cooling systems.

In the human factors engineering literature, operator experience is understood as the accumulation of cognitive knowledge, practical skills, and situational intuition that develops through repeated interactions with work systems (Salvendy, 2021). Research by Stanton et al., (2022) shows that experienced operators are able to identify early symptoms of a system glitch before technical indicators indicate a critical condition. This capability is particularly relevant in the management of major engine cooling systems operating at certain performance limits. In addition, dynamic and unpredictable working environment conditions require operators to make operational adjustments that are often outside of standard procedures (Endsley, 2020). Thus, operator experience becomes an important source of knowledge that can improve the reliability of the cooling system.

The human-centered design approach places humans as an integral part of the engineering system, not just the end user of the technology. A study by Norman & Stappers (2020) emphasizes that system design that ignores user experience has the potential to create a gap between technical design and operational practice. In the context of the main engine and its cooling system, these gaps can lead to a delay in response to abnormal thermal conditions. Research by Gualtieri et al., (2021) also shows that the integration of operator experience in operational decision-making is able to improve the effectiveness of the overall industrial system. However, the application of this approach to the main engine cooling system is still relatively limited in the study of mechanical engineering.

Based on these gaps, this study is designed to conduct an in-depth analysis of the operator's experience in optimizing the main engine cooling system based on operational insights in the field. This research focuses on how operators interpret system conditions, adjust operating parameters, as well as make decisions when faced with situations that are not fully covered by standard procedures. A qualitative approach was chosen to comprehensively and contextually explore the empirical experience of operators (Creswell & Poth, 2020). Thus, this study not only assesses the technical aspects of the cooling system, but also the cognitive and adaptive processes of the operator in maintaining the performance of the main engine.

Theoretically, this research contributes to the development of mechanical engineering studies by expanding the perspective of cooling system optimization through the integration of human factors approaches. The resulting analytical framework is expected to be the basis for further research examining the relationship between operator experience, operational conditions, and engineering system performance (Reason, 2020). In addition, this research enriches the discourse on human-machine interaction in large-capacity machining systems. By including operator experience as an analytical variable, this study provides a new perspective in the development of more adaptive and contextual cooling systems.

In practical terms, the findings of this study are expected to provide immediate benefits to the industry, particularly in the formulation of standard operating procedures, operator training programs, and key machine maintenance strategies. The integration of operator experience into operational management systems can improve an organization's ability to detect refrigeration system faults early and prevent repeated failures (ISO, 2023). In the context of industry in Indonesia, especially in Banten Province, this field insight-based approach can increase the competitiveness and reliability of machine-based industrial operations. Thus, this research is an important step in bringing together mechanical engineering theory and experience-based operational practices to answer modern industrial challenges.

THEORETICAL REVIEW

Major Engine Cooling Systems and Modern Operational Challenges

The main engine cooling system is a vital subsystem that functions to maintain thermal balance so that the engine can operate within safe and efficient limits. Recent research shows that cooling system failure is still one of the dominant causes of operational disruptions in high-power machines, especially in the manufacturing industry and the energy sector (Al-Hassan & Karim, 2021). The complexity of workloads, environmental fluctuations, and variations in operating conditions make cooling systems face challenges that cannot always be anticipated through technical design alone. A study by Fernandez et al., (2022) confirms that the performance of a cooling system is greatly influenced by the interaction between mechanical components and operational practices in the field. Therefore, an approach that only focuses on the thermal design aspect is considered insufficient to answer the actual operational challenges.

The Role of Operator Experience in Complex Engineering Systems

In complex engineering systems, operators play the role not only of executing procedures, but also of experiential, adaptive decision-makers. Research by Johansson & Lundgren (2021) shows that experienced operators have a better ability to recognize system anomalous patterns before a serious failure occurs. This experience is formed from repeated exposure to real operating conditions that are often not fully covered in the technical manual. Other international studies confirm that operator experience contributes significantly to the stability of machine operation, especially in systems that work close to their design limits (Martinez et al., 2023). Thus, operator experience is a high-value operational asset in maintaining the reliability of the main engine cooling system.

Human–Machine Interaction in Cooling System Optimization

Human-machine interaction is an important focus in the study of modern industrial systems, including in the management of major engine cooling systems. Research by Nakamura & Aoyama (2020) shows that the effectiveness of thermal system control is highly dependent on how the operator understands, interprets, and responds to information from the monitoring system. Inconsistencies between the system interface design and the operator's way of thinking can lead to delayed responses to critical conditions. Another study emphasizes that cooling system optimization will be more effective if it considers the pattern of human-machine interaction as a whole, not just the technical performance of components (Williams & Chen, 2022). This underscores the importance of an operator experience-based approach in operational optimization.

Qualitative Approach in Exploring Operational Insights

Qualitative approaches are increasingly used in engineering research to understand the human aspect in complex technical systems. Research by Roberts et al., (2021) shows that in-depth interviews and field observations are able to uncover the adaptive strategies of operators that are not documented in formal procedures. This method allows researchers to capture the dynamics of operator decision-making in real situations, including in the management of the main engine cooling system. A study by Kim et al., (2023) also confirms that thematic analysis is effective in identifying patterns of operator experience that contribute to improved system performance. Thus, a qualitative approach is relevant to explore operational insights that are contextual and experience-based.

Research Gap and Direction of Cooling System Development

Although the literature on engine cooling systems and human factors is rapidly developing, the integration of operator experience as a key element of system optimization is still relatively limited. Research by Oliveira et al., (2024) states that most studies still separate technical analysis and the human aspect, so that opportunities for performance-based performance improvement have not been optimally utilized. In addition, studies that specifically link operator experience to the optimization of major engine cooling systems in real industrial environments are still rare. This gap demonstrates the need for research that combines operator insights with the analytical framework of mechanical engineering. Therefore, this literature review emphasizes the urgency of research that places operator experience as a source of strategic knowledge in the optimization of major engine cooling systems.

METHODOLOGY

Types and Approaches to Research

This study uses a qualitative approach with an exploratory case study design to deeply understand the operator's experience in optimizing the main engine cooling system based on operational insights in the field. The qualitative approach was chosen because it is able to capture cognitive processes, adaptive strategies, and operator decision-making that cannot be adequately represented through quantitative data (Guest et al., 2022). The case study design allows research to be conducted contextually in a real industrial environment so that the interaction between humans and technical systems can be analyzed holistically (Yin, 2021). The research focus is directed at the actual operational dynamics that affect the performance of the main engine cooling system. This approach is relevant to answer research objectives that emphasize in-depth analysis based on field experience.

Population and Sampling Techniques

The research population includes operational personnel who are directly involved in the operation and maintenance of major machinery in the heavy manufacturing industry in Banten Province. The sampling technique used is non-probability sampling with the purposive sampling method, which is the selection of informants based on the criteria of experience and direct involvement in the main engine cooling system (Etikan et al., 2020). The number of informants was 12 people, consisting of six main machine operators, three operations supervisors, and three maintenance technicians. This composition was chosen to obtain a balanced perspective between daily operational practices, operational oversight, and technical maintenance aspects. The number of informants is considered adequate because it has reached data depth and information saturation in qualitative research (Saunders et al., 2021).

Data Collection Techniques and Instruments

Data collection was carried out through semi-structured in-depth interviews and direct observation at the operation site. Semi-structured interviews were used to explore the subjective experiences, decision-making strategies, and operational adjustments made by operators in managing key engine cooling systems (Brinkmann & Kvale, 2020). The interview guide is structured based on the research objectives and is developed flexibly to allow for an in-depth exploration of the informant's experience. Direct observations were carried out to confirm actual work practices, human-machine interaction patterns, and operator responses to engine thermal conditions. The combination of these two techniques increases the credibility of the data through triangulation of sources and methods (Flick, 2022).

Research Implementation Procedure

The research procedure begins with a preparatory stage which includes determining the research location, institutional licensing, and identification of potential informants. The next stage is the collection of field data through interviews and observations which are carried out in stages according to the industrial operational schedule. All interviews were recorded and transcribed verbatim to maintain the integrity of qualitative data. During the data collection process, the researcher also creates field notes to record relevant operational contexts and non-verbal situations. The final stage includes data verification to informants (member checking) to increase the validity of research findings (Birt et al., 2021).

Data Analysis Techniques and Supporting Devices

Data analysis was conducted using thematic analysis to identify experience patterns, optimization strategies, and key operational factors that affect the performance of the main engine cooling system. The analysis process includes the initial coding stage, theme grouping, theme review, and conceptual interpretation of findings (Braun & Clarke, 2021). The analysis is carried out iteratively to ensure the linkage between the empirical data and the research objectives. NVivo's qualitative data analysis assistance software is used to improve data traceability and consistency of the coding process. This analytical approach allows for a systematic and in-depth understanding of the operator's experience in a real operational context.

RESEARCH RESULTS

Early Detection of Thermal Irregularities Based on Operational Experience

The results of the thematic analysis showed that operator experience plays a crucial role in detecting thermal abnormalities before the monitoring system displays an alarm or reaches a critical limit. These findings were obtained through in-depth interviews that revealed that operators not only rely on digital indicators, but also integrate sensory observations, engine sound patterns, as well as the dynamic response of the cooling system. Field observations reinforce these findings by showing that early detection is often intuitive and based on long-term work experience, allowing corrective action to be taken earlier.

The machine operator says "Usually before the temperature rises on the panel, the sound of the cooling pump already feels different, the tone is heavier, it's a sign that something is abnormal," (OM-01, October 12, 2025 interview), and the condition is reinforced by the experience of other operators who stated that "*If you have been holding this machine for a long time, the small change is immediately felt, even though the number does not seem to have increased,*" (OM-04, interview October 15, 2025). This perception is also confirmed from the point of view of supervision, where "*Operators are often quicker to detect abnormal conditions than systems, because they* *see firsthand the machine's reaction,"* (SO-02, interview October 18, 2025). In terms of maintenance, this experience is recognized as the initial trigger for technical handling, because "*We are usually only called after the operator suspects an anomaly, even though the alarm has not been activated,"* (TP-01, interview October 20, 2025).

These findings suggest that operator experience serves as a non-formal early warning system that complements technical monitoring devices. Experience-based early detection allows for proactive identification of potential thermal faults, thereby reducing the risk of further damage and improving the overall reliability of the main engine cooling system.

Adaptive Adjustment of Operating Parameters Outside of Standard Procedures

The second theme reveals that operators are actively adjusting the operating parameters of the cooling system in response to changes in engine load and dynamic environmental conditions. These adjustments do not refer entirely to standard operating procedures, but rather are based on field experience and contextual understanding of the characteristics of the machine. Interviews and observations show that standard procedures tend to be generalized and have not been fully able to accommodate the complexity of real operational conditions.

As one of the operators said, namely "The SOP does not explain that the load rises quickly, you have to regulate the flow of the coolant slowly, that's usually from experience," (OM-02, interview October 13, 2025), and this practice is part of the operator's strategy in maintaining engine stability, because "*We often adjust the settings to keep the machine stable, even if it is not written in detail in the procedure,"* (OM-06, interview October 17, 2025). This perspective is reinforced by the supervisor stating that "*As long as it is safe and under control, operator adjustments will actually prevent bigger problems,"* (SO-01, interview October 19, 2025), as well as by a maintenance technician who confirmed that "*If the operator is not adaptive, the breakdown often occurs because the machine is forced to follow rigid rules,"* (TP-02, interview October 22, 2025).

These results show that operator adaptability is a key factor in the optimization of the main engine cooling system. Experience-based adjustments allow for more flexible and contextual responses than rigidly implementing standard procedures, thus contributing to thermal stability and prevention of operational disruptions.

Prevention of Recurrent Disruption through Field Experience Learning

Further thematic analysis showed that operator experience played a significant role in preventing repeated interruptions to the main engine cooling system. Operators not only respond to disturbances as they occur, but also develop prevention patterns based on previous events. This process takes place through informal learning and knowledge exchange between operators, which although not formally documented, have proven to be effective in practice.

In line with what the operator said,"If it has happened, we remember the signs well, so it can be prevented before it happens again," (OM-03, interview October 14, 2025), and the experience is understood as the main reference in decision-making, because "*That experience is a hand, not just a record in a book."* (OM-05, interview

October 16, 2025). From a supervisory perspective, this experience-based information is considered important, as it is revealed that "*We often hear stories from operators about old outages, it really helps with surveillance,*" (SO-03, interview October 21, 2025). This is in line with the view of maintenance technicians who state that "*A lot of damage can be prevented because operators have memorized the pattern of the problem,*" (TP-03, interview October 23, 2025).

These findings confirm that operator experience forms a collective learning mechanism that contributes to the prevention of recurrent disorders. Field experience-based learning allows for the strengthening of the reliability of the cooling system through preventive measures that are not fully covered by formal procedures.

Gap between Standard Procedures and Real Operational Practices

The final theme identifies a gap between standard operating procedures and real operational practices in the field. Interviews and observations show that standard procedures do not fully represent the complexity and operational dynamics of the main engine cooling system. Under certain conditions, operator experience is a decisive factor in critical decision-making to maintain system stability.

Operators convey the existing gaps, namely, "*In the field it is often not the same as books, the real conditions are much more complex,*" (OM-01, interview October 12, 2025), and this condition demands flexibility in decision-making, because "*SOPs are important, but operator experience is often decisive in emergency situations,*" (OM-04, interview October 15, 2025). This view is reinforced by supervisors who stated that "*we see firsthand the difference between theory and practice in the field,*" (SO-02, interview October 18, 2025), as well as by maintenance technicians who assert that "*if we rely solely on procedures, many potential problems are handled too late,*" (TP-01, interview October 20, 2025).

These results show that the integration of operator experience into operations and maintenance management systems is a strategic necessity. Field experience serves as a complement to standard procedures, thus being able to bridge the gap between technical planning and operational realities in the optimization of major engine cooling systems.

DISCUSSION

The results of this study show that operator experience has a very significant role in detecting thermal abnormalities in the main engine cooling system before the technical monitoring system provides a formal warning. These findings suggest that sensor-based technical indicators have limitations in capturing the initial dynamics of changes in thermal conditions in real operational environments. In line with this, Woods (2020) explains that in high-risk industrial systems, humans are often able to recognize early signs of failure through sensitivity to small changes that have not been identified by automated systems. The practice of operators relying on changes in machine sound, vibration, and response reinforces the role of experience as a critical source of information. Thus, the operator experience serves as an early detection mechanism that complements technology-based cooling systems.

In addition to early detection, this study found that the optimization of the main engine cooling system is highly dependent on the operator's ability to adjust operating parameters adaptively. The adjustment was made in response to changes in engine load, environmental conditions, and the limited response of the cooling system to operational fluctuations. According to Hale & Borys (2021), standard operating procedures are generally designed for ideal conditions so they are less flexible in dealing with complex field variations. In this situation, the operator acts as a situational decision-maker who bridges the technical design with the actual conditions. Therefore, experience-based flexibility is an important element in maintaining the stability and sustainability of the main engine cooling system.

The results of the study also show that operator experience contributes significantly to preventing repetitive disruptions through a learning process based on field experience. Operators not only react to disturbances, but also build anticipatory understanding based on previous events. This phenomenon is in line with the view of von Krogh et al., (2020) who stated that experience-based knowledge is a form of implicit knowledge that has strategic value in improving organizational performance. In the context of this study, the knowledge is transmitted informally between operators and used as a practical guideline in the management of cooling systems. Thus, experiential learning plays a direct role in improving the reliability of the system in a sustainable manner.

The findings regarding the gap between standard operating procedures and real operational practices confirm that SOPs are not yet fully able to accommodate the complexity of field conditions. Operators, supervisors, and maintenance technicians tend to rely on experience when dealing with critical conditions that require quick and informed decisions. Stanton et al., (2022) emphasize that in complex engineering systems, the human factor is often the determinant of the success of the operation when actual conditions deviate from the design assumptions. This study shows that the operator's experience is not a form of deviation from the system, but an integral part of the risk control mechanism. Therefore, SOPs need to be understood as a basic framework that must be complemented by field operational insights.

From a theoretical perspective, this study expands the study of the optimization of major engine cooling systems by integrating cognitive ergonomics and human-centered engineering approaches in the field of mechanical engineering. According to Salas et al., (2021), the performance of modern industrial systems is greatly influenced by the quality of interaction between humans, machines, and the work environment. The findings of this study show that operator experience affects the way the cooling system is operated, adjusted, and stabilized under real-world conditions. By placing operator experience as a key element, the study shifts the optimization approach from a purely technical perspective to a more holistic socio-technical approach. This makes a relevant conceptual contribution to the development of the theory of optimization of machine systems based on human-technology interaction.

Practically, the results of this study have direct implications for the management of the operation and maintenance of major machinery in the large-capacity machinery industry. Smith & Carayon (2023) stated that a reliable industrial system is determined not only by the reliability of technical components, but also by the ability of humans to adapt to changing operational conditions. The integration of operator experience into training programs, performance evaluation, and the development of work procedures can significantly improve the effectiveness of cooling systems. In the context of the industry in Banten Province, this field insight-based approach has the potential to improve operational reliability and maintenance efficiency. Therefore, operator experience needs to be positioned as a strategic asset in the operational management of key machines.

Although this research makes a strong theoretical and practical contribution, some limitations need to be critically observed. This research was conducted in an industry context with a relatively limited number of informants, so the generalization of the findings still requires further testing. According to Creswell & Poth (2023), in-depth qualitative research needs to be complemented by a quantitative approach to reinforce the external validity of findings. In addition, this study has not integrated technical performance data of cooling systems quantitatively. Therefore, advanced research is recommended to use mixed methods and involve more diverse industry contexts to enrich understanding of the role of operator experience.

CONCLUSION AND RECOMMENDATION

This study concludes that operator experience has a very crucial role in optimizing the performance of the main engine cooling system in a real operational environment. This experience has been shown to contribute significantly to the early detection of thermal abnormalities, the ability to make adaptive adjustments to operating parameters, as well as the prevention of repetitive disturbances that are not fully accommodated in standard operating procedures. These findings show that the main engine cooling systems are influenced not only by technical aspects and mechanical design, but also by the cognitive capacity, operational intuition, and experiential learning that operators have. Thus, operator experience serves as a socio-technical element that complements the technology-based monitoring and control system in maintaining the stability and reliability of the machine.

Furthermore, this study confirms the importance of the systematic integration of operator experience into the management of the operation and maintenance of key machines. This integration can be realized through the development of more adaptive work procedures, training programs based on field conditions, and knowledge transfer mechanisms between operational personnel. This approach not only improves the effectiveness of cooling system optimization, but also strengthens operational resilience and long-term sustainability of engine performance. Therefore, this research makes a practical and conceptual contribution to the development of operational strategies in the field of mechanical engineering, especially in the context of the large-capacity machinery industry, by placing operator experience as a strategic asset in the modern industrial management system.

FURTHER STUDY

Future research is recommended to investigate more systematically the interaction between operator experience and advanced monitoring technologies in optimizing main engine cooling system performance. Further studies could explore how experiential knowledge can be formally captured and integrated into predictive maintenance systems, decision-support tools, and adaptive control algorithms. In addition, comparative research involving operators with different experience levels may provide deeper insights into learning curves, error prevention, and performance reliability. Longitudinal studies examining the impact of experience-based training and knowledge transfer programs on operational efficiency and machine longevity would also contribute to the development of more resilient and human-centered maintenance strategies in large-scale industrial machinery operations.

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