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Enhancing Reliability in Marine Energy Systems: Integrated Mitigation Strategies for Biofouling-Induced Overheating

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Abstract. Tugboats play a crucial role in the maritime industry by providing towing and maneuvering services, especially in confined harbor environments. At the Port of Aden, the tugboat Wadi Hassan has experienced persistent issues related to elevated low-water temperatures in its port-side main engine. This study investigates the root causes of these thermal anomalies, with a focus on the impact of marine biofouling and potential failures in the cathodic protection system. A comprehensive analysis was conducted using operational data, inspection reports, and a comparative assessment of the port and starboard engines. The findings reveal that the ineffective cathodic protection system led to extensive marine fouling on the heat exchanger surfaces, compromising the engine's cooling performance. Existing maintenance and protection strategies were evaluated and found to be insufficient in preventing biofouling under the harsh marine conditions of the Red Sea and Gulf of Aden. Based on these findings, the study proposes an integrated mitigation plan to enhance marine energy systems. Key recommendations include upgrading cathodic protection mechanisms, applying advanced anti-fouling coatings, incorporating real-time monitoring systems, and optimizing maintenance schedules. Implementation of these measures is expected to enhance engine reliability, reduce unplanned downtime, lower maintenance costs, and extend the operational lifespan of critical systems.

Keywords. Tugboat, Engine Cooling, Biofouling, Cathodic Protection, Maintenance Optimization, Marine Energy Systems.

INTRODUCTION

The Crucial Role of Tugboats in Modern Maritime Logistics

International marine trade constitutes almost 80% of the worldwide trade volume, hence facilitating international commerce [1]. Ports are the most important part of this network. These complex places require careful maneuvering of large cargo ships, tankers, and bulk carriers in limited spaces [2]. Tugboats are the main operational tools, especially in the challenging conditions of a harbor. Modern tugboats, such as those with Azimuth Stern Drive (ASD) and Schottel Siemens Propulsor (SSP) systems, are essential for docking, undocking, and guiding ships. Their agility is impressive, and they can exert a surprising amount of power given their dimensions [3]. The Port of Aden is a major maritime hub, mainly because of its strategic location at the intersection of important global shipping routes [4]. Due to its location, it serves as a crucial waypoint for vessels navigating between the Mediterranean Sea and the Indian Ocean via the Suez Canal and the Gulf of Aden. The Wadi Hassan and her fellow tugboats in Aden need to be ready to go, all the time. This isn't just about keeping them in good working order; it's about keeping the world's supply chains running smoothly. When big ships break down, especially in busy areas, the consequences can be dire. These events can lead to serious accidents, disrupt port operations, and have a negative impact on the economy. These operational conditions must adhere to international maritime regulations, which are designed to ensure the safety and efficiency of machinery.

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Thermal Management in High-Performance Marine Engines

Modern marine diesel engines, exemplified by the Wartsila medium-speed engines aboard the Wadi Hassan, represent intricate systems engineered to function amidst considerable thermal and mechanical stresses [5]. The efficacy of cooling mechanisms is of utmost importance; a significant fraction of the energy generated during combustion necessitates dissipation to avert thermal strain, component deterioration, and the possibility of catastrophic failure [6]. Conventional marine cooling designs employ a "multi-circuit" configuration, generally partitioned into High-Temperature (HT) and Low-Temperature (LT) freshwater loops. The high-temperature (HT) circuit cools components that experience the highest temperatures, such as cylinder liners and heads, thus keeping coolant temperatures within a range of roughly 80–90 ˚c. This study focuses on the low-temperature (LT) circuit, which cools the charge air through intercoolers and the lubricating oil. The efficacy of the LT circuit is paramount for two principal considerations: (a) Combustion Efficiency: The cooling of the charge air enhances its density, thereby permitting a larger mass of oxygen within the combustion chamber. Consequently, this results in enhanced combustion efficiency, a boost in power output, and a decrease in thermal Nitrogen Oxide (NOx) emissions. (b) Lubricant Integrity: Maintaining lubricating oil within a narrow temperature band (typically 35–45 ˚c) at the cooler outlet) is essential to preserve the oil's viscosity and load-carrying capacity, thereby minimizing wear and extending engine life. In the Wadi Hassan, the LT circuit rejects heat to the ultimate heat sink—the surrounding seawater—via a sea-chest-mounted heat exchanger. In the aggressive tropical conditions of the Gulf of Aden, where seawater temperatures frequently exceed 30 ˚c, the margin for thermal inefficiency is exceptionally slim.

The Challenge of Biofouling and Corrosion in Tropical Waters

The ocean's corrosive properties are mainly due to the high levels of chloride and electrical conductivity found in seawater [7]. Therefore, the metal components within this electrolyte are vulnerable to various electrochemical degradation processes, including galvanic and pitting corrosion. To detect and mitigate these effects, marine engineers utilize acoustic emission techniques [8, 9], Cathodic Protection (CP) systems, including sacrificial anodes and Impressed Current (IC) systems, which alter the metal's electrochemical potential to a level that suppresses oxidation [10]. Conversely, in tropical and subtropical areas, the problem is exacerbated by aggressive biofouling [11]. In addition to microbial corrosion and its impact on offshore structures in dynamic systems [12], biofouling, characterized by the unwelcome accumulation of biological organisms on submerged surfaces, initiates with a microscopic biofilm and advances to include macro-organisms like barnacles, mussels, and tubeworms [13].

This biological layer acts as a potent thermal insulator. In heat exchangers, the presence of "fouling resistance" (R_f) substantially diminishes the overall heat transfer coefficient (U). A relatively thin layer of biofouling can, in fact, hinder heat rejection by more than 50%, thereby precipitating swift temperature increases during operational periods [14, 15]. Although cathodic protection (CP) systems are primarily implemented for corrosion mitigation [16], they can, in an indirect manner, impede larval settlement through the alteration of the local pH at the cathode surface. Furthermore, recent advancements in surface protection technologies indicate that specialized "foul-release" coatings offer a non-toxic alternative by reducing the adhesion strength of these organisms [17, 18]. Nevertheless, these are rarely sufficient as a standalone anti-fouling solution in high-growth environments like the Port of Aden.

Problem Statement and Research Rationale

The Wadi Hassan tugboat's port-side main engine is experiencing a recurring technical issue. Specifically, during periods of high operational demand, the LT cooling water temperature has been observed to reach 48–50 °C, which is considerably above the standard operational range of 35–40 °C. These temperature spikes activate automatic engine alarms and require operational shutdowns to avert potential damage, thereby directly affecting the safety and operational effectiveness of port activities. Preliminary diagnostic assessments have excluded internal mechanical malfunctions, as cooling pumps, pipes, and thermostatic valves were all determined to function correctly. Moreover, the problem has persisted even after a comprehensive maintenance overhaul performed in Djibouti, implying that the underlying cause is linked to localized environmental factors rather than a fundamental engine defect. In contrast, the starboard main engine, which operates under identical conditions, has demonstrated normal thermal performance. This difference suggests a localized failure in the port side's protective systems. Therefore, an investigation is underway to determine the connection between the failure of cathodic protection and increased biofouling on the sea-chest heat exchanger.

Objectives and Scope of the Investigation

This study aims to identify the main causes of the low-temperature cooling problems in Wadi Hassan and to suggest a practical solution. The research will cover several areas: analyzing temperature data from different engine speeds (RPM) to measure thermal damage; assessing the condition of the submerged heat exchangers with diver inspections; evaluating how well the current cathodic protection systems work on both the port and starboard sides; and developing recommendations for system improvements and a shift to a proactive, condition-based maintenance (CBM) approach. By addressing the aforementioned issues, this study aims to enhance the reliability of the Port of Aden's tugboat fleet, reduce maintenance expenditures, and ensure the continued safety of maritime logistics in the region.

METHODOLOGY

The following describes the systematic methodology used to investigate the ongoing low-water temperature problems in the port-side main engine of the tugboat Wadi Hassan. This approach was mainly based on data, using existing operational data and observations, along with structured diagnostic and comparative analyses.

Data Collection and Analysis

The study started by gathering operational data, specifically focusing on the low cooling water temperature measurements from the port-side main engine. Data acquisition was facilitated through the engine monitoring system, which provided both standard and atypical temperature readings. A range of operational scenarios were examined, with a particular emphasis on maneuvers at varying engine speeds measured in revolutions per minute (RPM), to ascertain the impact of engine load on cooling system efficacy. The analysis sought to establish the normal operating range (35-40°C), quantify temperature anomalies (48-50°C), identify operational parameters associated with elevated low-water temperatures, and uncover temporal trends linked to maintenance activities.

Analysis of Maintenance Records and Diver Observations

Qualitative and semi-quantitative data derived from maintenance records and diver observations were essential to this study. An examination of maintenance logs, which documented routine inspections, troubleshooting efforts, and significant maintenance activities, was conducted to ascertain the problem's historical context and frequency of occurrence. Diver observations, gathered during underwater inspections, furnished crucial information regarding the state of submerged components, specifically concerning marine fouling and the efficacy of the cathodic protection system. The relationship between escalating fouling levels and increasing low-water temperatures was instrumental in pinpointing the physical basis of the cooling inefficiency.

Inspection and Diagnostics Procedure

Figure 1 illustrates the systematic inspection protocol, which commenced with an examination of the cooling system's internal elements. Preliminary assessments yielded no apparent defects, thereby directing attention to external components, particularly the heat exchanger within the water cooler box. Underwater investigations conducted by divers subsequently revealed substantial marine fouling, which was determined to be the principal impediment to effective heat transfer.

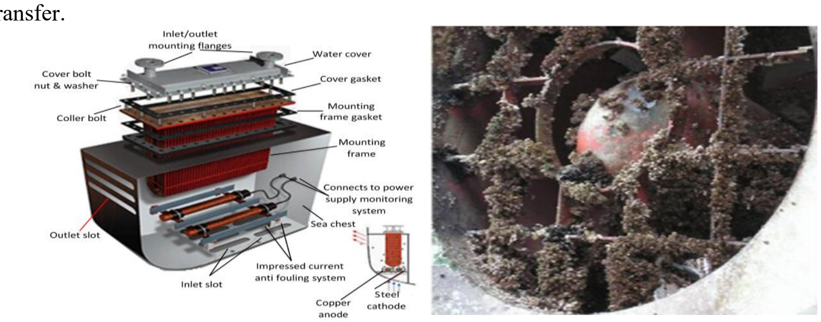

FIGURE 1. Inspection protocol for cooling system components.

Comparative Analysis of Port and Starboard Main Engines

A comparative analysis of the port and starboard main engines was undertaken to ascertain the precise locus of the problem. Operational data revealed persistently elevated low-water temperatures on the port side, whereas the starboard side's temperatures were within the acceptable parameters. Subsequent diver inspections corroborated these findings, revealing significant disparities in the physical state of the cooling systems. Consequently, this observation supported the initial hypothesis that the port engine's increased low-water temperature stemmed from a defective heat exchanger.

Evaluation of Fouling Levels and Cathodic Protection Efficiency

Diver inspections were combined with ongoing evaluations of marine fouling and cathodic protection effectiveness. The port side demonstrated elevated fouling levels and a more rapid accumulation rate, which implied diminished efficacy of the cathodic protection system. The inspections provided semi-quantitative data, which supported this assessment. Therefore, the results suggest that future research should include several experimental studies, such as tests of anti-fouling coatings and evaluations of alternative cathodic protection materials.

Furthermore, the validation of real-time monitoring systems for cathodic protection and thermomechanical parameters is recommended to improve the early detection of potential problems. The employed methodology constituted a thorough, empirically grounded approach, synthesizing quantitative data analysis with qualitative perspectives gleaned from maintenance records and diver observations. The comparison of the port and starboard engines confirmed the earlier findings, which helped identify the underlying cause. This multifaceted approach not only helped identify the problem but also highlighted possible paths for future experiments to confirm the suggested solutions.

RESULTS AND DISCUSSION

The subsequent analysis elucidates the principal outcomes obtained through the implementation of the methodology outlined in section 2. A comprehensive examination and interpretation of these findings follow, elucidating their implications and validating the underlying cause of the persistent high low-water temperature problems observed in the port-side main engine.

Analysis of Operational Temperature Data

Figures 2 and 3 show the operational temperature data at normal and abnormal conditions. Data analyses revealed significant findings: Under normal operating conditions (500-1000 RPM), the low-water temperature remained at 35-40°C. However, at higher engine speeds (700 RPM and above), temperatures surged, reaching 41°C at 700 RPM and peaking at 48-50°C during full-speed maneuvers, indicating a failure of the cooling system to manage increased heat rejection rates.

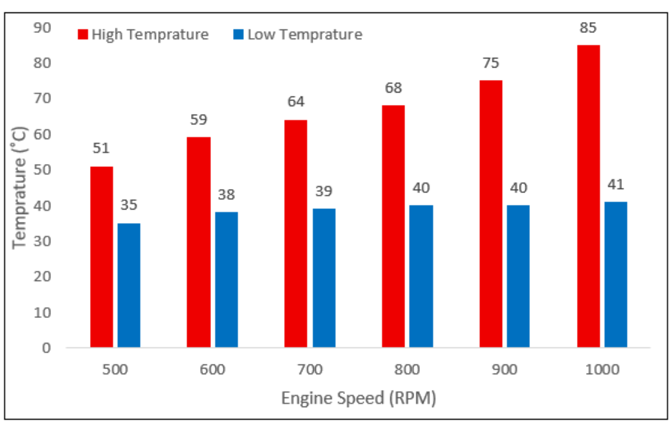

FIGURE 2. Normal temperature reading across multiple engine speeds.

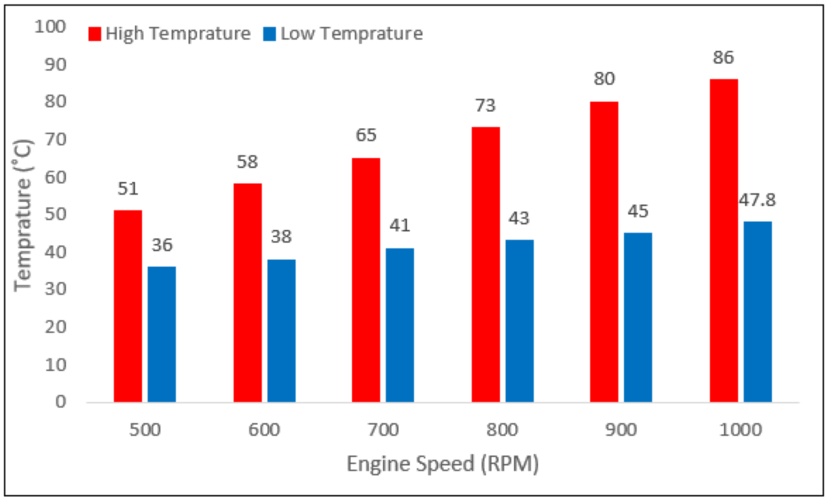

FIGURE 3. Abnormal temperature reading across multiple engine speeds.

Findings from Inspections and Diver Observations

Diver assessments revealed significant problems within the cooling system. The internal elements exhibited no discernible defects, thereby shifting the focus to external influences. A substantial accumulation of marine fouling, as depicted in Figure 4, was evident on the low-temperature heat exchanger pipes, and the cathodic protection system proved inadequate, as evidenced by the swift re-fouling observed following cleaning procedures. The correlation between increased marine fouling and rising temperatures was quantitatively represented, linking fouling progression to thermal behavior.

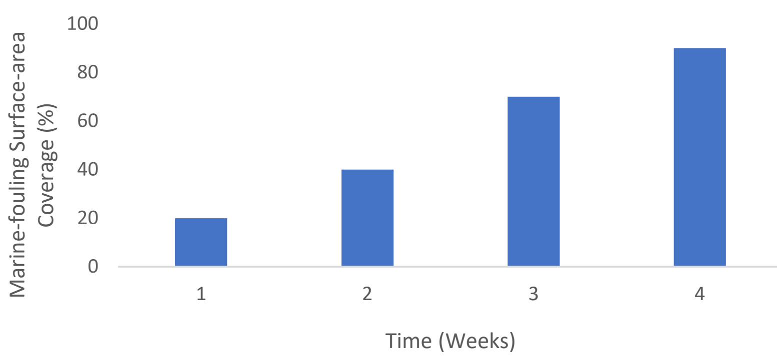

FIGURE 4. Marine-fouling growth percentage during 4 weeks' time.

Comparative Engine Analysis

The comparative analysis of the port and starboard engines yielded significant results. The starboard engine's performance remained within the expected low-water temperature parameters, exhibiting no indications of fouling. In contrast, the port engine presented with elevated temperatures, attributable to substantial fouling and insufficient cathodic protection. The available data overwhelmingly suggests that the cathodic protection system's malfunction was the principal cause of the port engine's elevated low-water temperature. This determination is further supported by the significant differences in fouling and temperature characteristics observed between the two engines. Without effective cathodic protection, marine growth increased. This created a thermal barrier, which significantly reduced the efficiency of heat transfer. The insulating properties of the fouling layer subsequently elevated thermal resistance, which in turn impaired the heat exchanger's functionality. As a result, the damaged heat exchanger struggled to release heat effectively as engine loads increased. This led to temperature spikes of 8-15°C above the normal operating range, especially under heavy loads. Moreover, lower water temperatures reduce engine power, operational efficiency, and overall reliability. As a result, this leads to increased thermal stress and more frequent operational problems.

Current maintenance practices mainly focus on reacting to problems, often using simple cleaning methods. This approach doesn't address the underlying causes of failures in cathodic protection systems. Consequently, this approach perpetuates persistent fouling issues, thus demanding a shift toward a more proactive maintenance strategy. These findings align with extant research on marine fouling and cathodic protection, thereby illustrating the consequences of insufficient management of these issues within the domain of marine engineering. To summarize, the investigation substantiates that the recurrent high low-water temperature observed in the port-side main engine is chiefly attributable to significant marine fouling stemming from a compromised cathodic protection system. This fouling functions as a thermal insulator, thereby diminishing heat transfer efficiency, especially under conditions of elevated load. Consequently, current maintenance practices are inadequate, warranting a transition towards addressing the fundamental cause to avert future incidents. Furthermore, the comparative analysis with the starboard engine corroborates these conclusions, underscoring the crucial requirement for effective management of fouling and corrosion within marine environments.

CONCLUSIONS AND RECOMMENDATIONS

The investigation pinpointed the cathodic protection system's malfunction as the primary factor contributing to the increased low-water temperatures, which subsequently fostered substantial marine biofouling on the heat exchanger. This biofouling, in turn, diminished the efficiency of heat transfer, resulting in temperatures that surpassed the typical operational parameters and, consequently, disrupted the vessel's functionality within the Port of Aden.

The main conclusions show a clear cause-and-effect relationship: Cathodic Protection Failure leads to faster Marine Fouling, which then reduces Heat Transfer Efficiency, causing Elevated Low-Water Temperature, and ultimately, Operational Disruption. Current maintenance practices, which are mostly reactive and inadequate, don't address the underlying problem, as seen in the significant performance differences between the port and starboard engines. To tackle these problems, several practical suggestions are put forward:

1. A complete revamp of the Cathodic Protection System is in order. This would require a combined strategy, incorporating both sacrificial anodes and an Impressed Current Cathodic Protection (ICCP) system. Proper installation and commissioning are essential.
2. A real-time monitoring system is essential. This system will track cathodic protection and thermomechanical parameters. The data will be consolidated into a central display, which will provide immediate alerts and allow for historical analysis.
3. Employing Advanced Anti-Fouling Coatings: To reduce the adhesion of fouling agents, apply high-performance, biocide-free coatings to the surfaces of heat exchangers. Evaluating and potentially improving the heat exchanger design requires a careful look at its capacity and the materials used, considering the specific operating conditions.

This study proposes a new approach to preventive maintenance. It emphasizes monitoring based on the current state of the system, regular inspections, proactive cleaning methods, and strict adherence to the maintenance schedule for the cathodic protection system. The primary objectives of this framework encompass enhancing engine reliability, mitigating unforeseen failures, reducing maintenance expenditures, prolonging component lifespan, augmenting operational efficiency, and strengthening safety protocols. Subsequent research initiatives should prioritize the assessment of the proposed systems' efficacy, considering their economic viability, the refinement of predictive modelling techniques, the evaluation of their environmental consequences, and the exploration of novel technological advancements. Implementing these suggestions will significantly enhance the tugboat's cooling system, boosting both its reliability and efficiency. Consequently, this strategy will guarantee the system's proper function, even when faced with the demanding environment of the open sea.

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