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Optimization of Injector Performance on the Combustion Process in the Generator Engine to Support Operational Continuity on Board MT. Semar 77

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Abstract

The fuel injector is a critical component of the diesel generator engine, responsible for atomizing fuel into the combustion chamber to achieve complete and efficient combustion. This study investigates the causes of injector performance degradation on the Anqing Daihatsu 6DL-20 diesel generator engines on board MT. Semar 77, an oil tanker, and proposes optimized maintenance strategies to restore and sustain optimal injector function. During the author's sea practice period, two significant incidents were recorded: on February 22, 2022, the exhaust gas temperature of cylinder no. 3 on generator no. 3 rose from the normal range of 350–450°C to 495°C, and the injector fuel pressure had dropped from the specified 300 kg/cm² to 190 kg/cm²; on April 22, 2022, cylinder no. 2 on generator no. 2 exhibited an abnormal exhaust gas temperature of 490°C despite normal fuel pressure readings, indicating a different failure mode. Investigation using a descriptive qualitative approach identified two principal causes. First, the injector failed to atomize fuel uniformly due to spring fatigue causing loss of nozzle needle seating pressure, compounded by inaccurate adjusting screw settings during pressure testing that resulted in improper needle valve lift timing. Second, the nozzle orifices became clogged by carbon deposits from combustion residues and contaminant particles in the fuel that bypassed the filtration system, obstructing fuel passage and converting the intended atomized spray pattern into irregular droplets. The recommended corrective measures include periodic injector pressure testing at 1,500 running-hour intervals with target atomization pressure of 300 kg/cm², systematic spring inspection and replacement, precise adjusting screw calibration procedures, routine nozzle cleaning and replacement according to the Planned Maintenance System (PMS) schedule, and improvement of fuel quality management from bunker reception through purifier and filter maintenance.

Keywords: *fuel injector, atomization pressure, nozzle clogging, generator engine, combustion optimization, planned maintenance system*

I. INTRODUCTION

Maritime vessels rely on diesel generator engines as the primary source of electrical power for all onboard systems, including navigation equipment, communication systems, cargo handling machinery, deck machinery, accommodation services, and safety installations. The continuous and reliable operation of these generators is fundamental to the operational safety and commercial efficiency of the vessel. The combustion process within the diesel generator engine is the mechanism by which chemical energy stored in fuel oil is converted to mechanical energy, which in turn drives the alternator to produce electrical power. The quality and completeness of this combustion process directly determine the engine's power output, fuel consumption rate, exhaust gas composition, and overall operational efficiency.

Among the various components that influence combustion quality, the fuel injector holds a particularly critical role. The injector is responsible for atomizing liquid fuel into a fine mist of microscopic droplets that are introduced into the combustion chamber at precisely controlled timing, pressure, and spray pattern. According to Handoyo (2014), the finer the atomization of fuel to the point of approaching gaseous state, the more complete the combustion will be, and consequently the greater the thermal efficiency and power output of the engine. Complete combustion produces maximum power from minimum fuel consumption, while incomplete combustion results in power loss, excessive fuel consumption, elevated exhaust gas temperatures, carbon deposit formation, and visible exhaust smoke — all indicators of suboptimal engine performance.

During the author's sea practice period on board MT. Semar 77, an oil tanker equipped with three Anqing Daihatsu 6DL-20 diesel generator engines, two significant incidents related to injector malfunction were observed. The first incident occurred on February 22, 2022, while the vessel was sailing from Merak to Palembang, when the exhaust gas temperature of cylinder no. 3 on generator no. 3 rose abnormally from the normal operating range of 350–450°C to 495°C during the 00:00–04:00 watch. Investigation revealed that the injector's atomization pressure had dropped from the specified 300 kg/cm² to 190 kg/cm² due to spring failure and incorrect adjusting screw settings. The second incident occurred on April 22, 2022, during cargo discharge operations at Jetty Plaju, when the exhaust gas temperature of cylinder no. 2 on generator no. 2 reached 490°C. In this case, the fuel pressure reading remained at the normal 300 kg/cm², but the nozzle orifices were found to be blocked by carbon deposits, preventing proper fuel atomization.

Based on these operational experiences, this research was conducted to analyze the root causes of injector performance degradation and to propose optimized maintenance strategies that would prevent recurrence of similar problems. The study addresses two primary research questions: (1) Why does the injector fail to atomize fuel uniformly, resulting in uneven spray patterns? (2) Why do the nozzle orifices become clogged with contaminants?

II. LITERATURE REVIEW

A. Diesel Generator Engine and Combustion Principles

According to Armstrong and Proctor (2019), a diesel engine is an internal combustion engine in which air is compressed to a sufficiently high temperature to ignite diesel fuel that is injected into the combustion chamber. The combustion drives the piston, converting the chemical energy in the fuel into mechanical energy. A generator set combines a diesel engine as the mechanical energy source with an alternator as the electrical power generator. On board MT. Semar 77, the auxiliary engines are Anqing Daihatsu 6DL-20 six-cylinder diesel generator sets.

Van Maanen (2017) defines combustion as the rapid chemical combination of fuel, air, and sufficient temperature for ignition. In the auxiliary engine, air is compressed within the cylinder to create the conditions for this chemical reaction, and the resulting heat energy is converted to mechanical work. The combustion speed depends on the quality of the fuel-air mixture, which is why fuel must be atomized into the finest possible droplets to maximize the reaction surface area and ensure rapid, complete combustion. According to Surbhakty (2012), complete combustion in a diesel engine cylinder depends on four essential conditions: the degree of fuel atomization, sufficiently high temperature for complete combustion of the fuel-air mixture, high relative velocity between fuel particles and air, and thorough mixing of fuel particles with the available air.

B. Fuel Injector: Definition, Components, and Operating Principle

According to Simatupang (2018), the fuel injector is a device used to atomize fuel into the engine cylinder at a specific pressure. The fuel supply system in a diesel engine uses the nozzle injector as the atomizing device in the combustion chamber. Handoyo (2014) further describes the injector as a device that sprays fuel oil into a fine mist to facilitate combustion within the engine cylinder. The principal components of the Daihatsu Anqing DL-20 injector assembly include the nozzle (with precision-machined orifice holes), the nozzle body holder, the pin, push rod, spring seat, nozzle spring, adjusting screw (for pressure calibration), cap nut, gasket, spacer, retaining nut, inlet connector, banjo fitting, eye bolt, and adapter.

According to Karyanto (2012), the injector operates through three sequential phases. In the pre-injection phase, high-pressure fuel flows from the injection pump through the oil passage in the nozzle holder to the oil pool at the base of the nozzle body. During the injection phase, when the fuel pressure in the oil pool exceeds the spring force, the nozzle needle is lifted from its seat by the hydraulic pressure, opening the orifice holes and allowing fuel to spray into the combustion chamber in atomized form. In the end-of-injection phase, when the injection pump ceases fuel delivery, the fuel pressure drops below the spring force, and the spring returns the nozzle needle to its seated position, closing the fuel passage and terminating injection. This precise mechanical sequence ensures that fuel is delivered only during the correct crankshaft angle window for optimal combustion timing.

C. Nozzle Spray Patterns and Atomization Quality

According to Trommelmans (2013), the fuel atomizer must inject a precisely measured quantity of fuel into the cylinder, ensuring complete entry into the combustion chamber for the smallest possible ignition delay and the most complete combustion achievable. The atomizer must close rapidly and completely so that no fuel droplets form before or after the injection event. Poor atomization or droplet formation results in incomplete combustion, smoke formation, and elevated exhaust gas temperatures. A normal spray pattern produces a conical fuel mist with a spray cone angle of approximately 14 degrees (varying by nozzle design), with the fuel uniformly distributed throughout the cone rather than concentrated at any point. Abnormal spray patterns — including asymmetric cones, split sprays, or dripping — indicate nozzle damage, orifice blockage, or insufficient injection pressure, all of which directly degrade combustion quality.

D. Maintenance Strategies for Injector Systems

According to Corder (2013), maintenance is a combination of actions performed to keep equipment in an acceptable operating condition, with objectives including extending equipment lifespan, ensuring operational readiness, reducing unplanned downtime, and minimizing maintenance costs through effective and efficient practices. Arismunandar (2012) specifies the key maintenance procedures for fuel injectors: atomization testing using a nozzle tester to verify spray pressure against the manufacturer's specification, visual inspection of spray pattern quality, nozzle disassembly and cleaning with clean diesel oil when atomization quality is unsatisfactory, and spring adjustment or replacement when injection pressure deviates from the prescribed value. Simatupang (2018) classifies shipboard maintenance into corrective maintenance (performed after failure to restore equipment to operational condition) and preventive maintenance (scheduled activities performed at predetermined intervals to prevent failure, including periodic overhaul according to the Planned Maintenance System and instruction manual book running hour schedules).

Table 1. Generator No. 3 — Cylinder Performance Data (February 22, 2022)

Cylinder No.	Exhaust Gas Temp. (°C)	Fuel Pressure (kg/cm²)	Remarks
1	360	300	Normal
2	355	290	Normal
3	495	190	Abnormal — spring failure
4	360	290	Normal
5	365	280	Normal
6	360	300	Normal

Source: Engine Room Log and Pressure Test Data, MT. Semar 77 (2022)

Table 2. Generator No. 2 — Cylinder Performance Data (April 22, 2022)

Cylinder No.	Exhaust Gas Temp. (°C)	Fuel Pressure (kg/cm²)	Remarks
1	360	300	Normal
2	490	300	Abnormal — nozzle clogged
3	360	290	Normal
4	360	290	Normal
5	360	300	Normal
6	365	280	Normal

Source: Engine Room Log and Thermo Gun Measurement, MT. Semar 77 (2022)

III. RESEARCH METHODOLOGY

This research was conducted during the sea practice period on board MT. Semar 77, an oil tanker. The vessel is equipped with a Yi Chang MAN B&W 7S35 MC main engine and three Anqing Daihatsu 6DL-20 diesel generator engines. The research period extended from the commencement of the author's sea practice on board the vessel through 2022. The study employed a descriptive qualitative research method, analyzing the observed phenomena through systematic description and correlation with established theories.

A. Data Collection Techniques

Data were collected through four complementary techniques. Direct observation was conducted on the diesel generator engines during normal operation and malfunction incidents, focusing on exhaust gas temperature readings, injector fuel pressure measurements, exhaust smoke color and density, and the physical condition of injector components during overhaul procedures. Interviews were conducted with three Third Engineers (Masinis III) who held direct responsibility for the diesel generator operation and maintenance on board MT. Semar 77, gathering information on injector failure causes, spring function, pressure testing procedures, nozzle clogging mechanisms, and recommended maintenance practices. A literature study was performed using published references on diesel engine theory, injector design and maintenance, and combustion principles. Documentation review encompassed the Daihatsu Anqing DL-20 instruction manual book, the Planned Maintenance System records, running hours logs for the three auxiliary engines, monthly maintenance reports, and performance data records.

B. Data Analysis Method

The collected data were analyzed using the descriptive qualitative technique, systematically describing and analyzing observed events in the field and correlating them with relevant theoretical frameworks. The analysis process followed a structured sequence: identification of the problem manifestation (elevated exhaust gas temperature), determination of the proximate cause (injector malfunction), investigation of root causes through component inspection and data comparison, development of alternative corrective measures, evaluation of each alternative's advantages and disadvantages, and selection of the most effective solution.

IV. RESULTS AND DISCUSSION

A. Non-Optimal Injector Atomization Performance

The analysis of the first incident (Generator No. 3, Cylinder No. 3, February 22, 2022) revealed that the injector failed to produce uniform fuel atomization, resulting in incomplete combustion and a corresponding exhaust gas temperature increase from the normal range of 350–450°C to 495°C. The performance data presented in Table 1 demonstrates the clear correlation between reduced injector fuel pressure and elevated exhaust gas temperature: while all other cylinders maintained normal temperatures (355–365°C) with fuel pressures in the range of 280–300 kg/cm², cylinder no. 3 exhibited a dramatically reduced fuel pressure of only 190 kg/cm² — 37% below the specified 300 kg/cm² — accompanied by the highest exhaust gas temperature recorded.

The root cause investigation identified two contributing factors to the pressure decline. First, the nozzle spring had experienced material fatigue, losing its elastic properties and consequently its ability to maintain adequate seating force on the nozzle needle. When the spring loses its resilience, it cannot return the nozzle needle to its fully seated position after each injection cycle, nor can it maintain the preset cracking pressure required for proper atomization. The weakened spring resulted in premature needle lift at lower-than-specified pressures, producing a coarser spray with larger droplet sizes that could not achieve complete combustion within the available time and space in the combustion chamber.

Second, the adjusting screw — the component used to calibrate the spring preload during injector pressure testing — had been set inaccurately during the most recent maintenance intervention. When the adjusting screw is tightened excessively, the nozzle needle becomes mechanically restricted and cannot lift properly; when it is too loose, the spring preload is insufficient to maintain the required cracking pressure. In both cases, the nozzle needle fails to operate within its designed pressure range, and the fuel injection timing, duration, and atomization quality are all adversely affected. The combined effect of the fatigued spring and the incorrect adjusting screw setting produced an injector that could not atomize fuel into sufficiently fine droplets, resulting in incomplete combustion characterized by grayish exhaust smoke and elevated exhaust gas temperature.

B. Nozzle Clogging by Carbon Deposits and Contaminants

The analysis of the second incident (Generator No. 2, Cylinder No. 2, April 22, 2022) revealed a fundamentally different failure mode from the first incident. As shown in Table 2, the fuel injection pressure remained at the normal value of 300 kg/cm², confirming that the spring and adjusting screw settings were functioning correctly. However, the exhaust gas temperature had risen to 490°C — well above the normal range — indicating that despite adequate injection pressure, the fuel was not being delivered effectively into the combustion chamber. Upon overhaul and inspection of the injector, carbon deposits were found blocking several of the nozzle orifice holes, confirming that the fuel passage restriction rather than pressure loss was the cause of the malfunction.

The nozzle orifice clogging was attributed to two primary sources of contamination. First, the accumulation of carbon residues from the combustion process itself: during normal engine operation, microscopic quantities of combustion products (soot, carbon particles, and partially burned hydrocarbons) can migrate back toward the nozzle tip between injection cycles, gradually building up on the orifice surfaces and progressively narrowing the effective orifice diameter. Over extended operating periods without cleaning, these deposits eventually reach a critical thickness that significantly restricts fuel flow. Second, contaminant particles present in the fuel supply — including dust, sediment, metallic particles, and water — that pass through the purifier and filter systems can enter the high-pressure fuel circuit and become trapped at the nozzle orifice interface. The fine particles create friction against the nozzle needle and its seat, preventing complete sealing, while larger particles directly block the orifice holes. In both cases, the intended atomized spray cone degenerates into irregular streams or droplets, dramatically reducing the fuel-air mixing quality and producing the incomplete combustion indicated by the elevated exhaust gas temperature.

C. Corrective and Preventive Maintenance Strategies

For the spring failure and pressure deviation problem, the recommended maintenance protocol involves periodic injector pressure testing using the nozzle tester apparatus at intervals of approximately 1,500 running hours, as specified in the Daihatsu instruction manual book and the vessel's Planned Maintenance System. The testing procedure consists of mounting the injector on the pressure test fixture, filling the tester reservoir with clean MDO (Marine Diesel Oil), connecting the fuel supply nipple, gradually operating the test lever while observing the pressure gauge reading, comparing the measured cracking pressure against the specified 300 kg/cm², adjusting the adjusting screw if necessary (tightening to increase pressure, loosening to decrease), verifying that the pressure gauge needle returns slowly (rapid return indicates internal leakage), confirming that the spray pattern is uniformly distributed in a normal conical pattern, and securing the lock nut after final adjustment with a verification test to ensure the pressure setting has not shifted.

Spring replacement must be performed when testing reveals that the spring can no longer maintain the specified pressure even with adjusting screw compensation, or when visual inspection reveals signs of fatigue such as permanent deformation, surface cracking, or reduced free length. All replacement springs must be original manufacturer-specified parts to ensure correct spring rate and preload characteristics. The adjusting screw calibration requires particular precision and attention: the mechanic must apply incremental adjustments while continuously monitoring the pressure gauge, avoiding both over-tightening (which restricts needle movement) and under-tightening (which reduces cracking pressure below the combustion-ready threshold).

For the nozzle clogging problem, the recommended maintenance protocol involves periodic nozzle inspection and cleaning at PMS-specified intervals based on running hours. The procedure includes removing the injector from the cylinder, inspecting the nozzle tip for visible carbon deposits, cleaning deposits using a brass brush and washing with clean diesel oil (MDO), inspecting the orifice holes for blockage using magnification if necessary, checking the nozzle needle for scoring or damage to the sealing surface, and replacing the nozzle assembly with original spare parts when the orifice holes are damaged or worn beyond acceptable tolerances. Additionally, fuel quality management must be improved throughout the supply chain: thorough inspection of fuel quality during bunker reception, regular maintenance of the fuel purifier to maximize contaminant separation efficiency, timely cleaning and replacement of fuel filters at the injection pump intake, and proper settling tank management to allow water and heavy sediment separation before the fuel enters the high-pressure system.

D. Evaluation of Maintenance Approaches

The evaluation of corrective measures considered two alternative approaches for each problem. For the spring failure issue, the alternatives were preventive periodic testing and spring replacement according to the PMS schedule versus reactive repair after failure occurrence. The preventive approach was determined to be superior because it enables early detection of spring fatigue before catastrophic failure, maintains consistent injector performance throughout the service interval, prevents unexpected generator shutdowns during critical operations such as cargo handling or maneuvering, and is significantly more cost-effective than emergency repairs that may require additional component replacement due to secondary damage from prolonged operation with degraded atomization.

For the nozzle clogging issue, the alternatives were periodic nozzle inspection and cleaning with preventive replacement at running-hour intervals versus extended operation with nozzle replacement only upon failure detection. The periodic approach was determined to be superior because carbon deposit accumulation is progressive and can be removed when deposits are thin but becomes increasingly difficult and potentially damaging to the nozzle when deposits harden over extended periods. Early cleaning prevents the transition from partial blockage (reduced atomization quality) to complete blockage (loss of fuel delivery to one or more orifice holes), which can cause severe thermal stress on the remaining orifices and accelerated nozzle degradation. The importance of fuel quality management was emphasized as a complementary preventive measure that addresses the contamination source rather than only the symptom, providing systemic protection for all injectors simultaneously.

The advantages of preventive maintenance through the PMS framework over reactive maintenance were clearly demonstrated in both incidents. In the first incident, the spring failure could have been detected during a routine pressure test well before the exhaust gas temperature reached the critical threshold of 495°C, avoiding the need for emergency generator changeover and the associated operational risk during a sea passage. In the second incident, regular nozzle inspection and cleaning at the prescribed running-hour interval would have removed the carbon deposits before they accumulated to the point of causing significant orifice blockage. The estimated cost of preventive maintenance activities — including regular pressure testing, periodic spring replacement, and nozzle cleaning — represents a fraction of the costs associated with unplanned generator failures, which include emergency repair labor, accelerated component wear due to thermal overload on adjacent cylinders, increased fuel consumption during operation with degraded combustion, and potential cargo operation delays.

E. Impact on Generator Engine Operational Continuity

The operational impact of injector malfunction extends beyond the immediate engine performance degradation to affect the overall vessel operation. On MT. Semar 77, the diesel generators supply all electrical power required for vessel operation, including navigation systems, cargo pumps during loading and discharge operations, deck machinery for mooring and anchoring, accommodation systems, and safety equipment. When a generator must be shut down due to injector failure, the standby generator must be started and brought online to assume the electrical load — a process that, while feasible, introduces operational risk during the transition period, particularly if the failure occurs during critical operations such as cargo discharge at a jetty or navigation in congested waterways.

Furthermore, incomplete combustion resulting from injector malfunction produces secondary effects that compound the operational impact. Elevated exhaust gas temperatures accelerate thermal degradation of the exhaust valve, valve seat, and turbocharger components on the affected cylinder. Carbon deposits from incomplete combustion accumulate on the piston crown, cylinder liner surface, and exhaust gas passages, progressively reducing the thermal efficiency of the entire engine and increasing the maintenance burden across multiple component systems. Excessive fuel consumption resulting from poor combustion directly increases the vessel's operating costs and may necessitate unplanned bunkering stops on longer voyages. The visible smoke from incomplete combustion also raises environmental compliance concerns, as MARPOL Annex VI and port authority regulations increasingly restrict visible emissions from vessels in port and coastal areas.

The two incidents documented in this study also highlighted a deficiency in the engine monitoring systems on MT. Semar 77. In both cases, the abnormal exhaust gas temperatures were not detected by the automated instrument control systems in the Engine Control Room (ECR) because the exhaust gas temperature sensors were not functioning properly. The exhaust temperature anomalies were only discovered through manual readings using handheld thermometer gauges and thermo gun devices during routine rounds by the watch-keeping personnel. This finding underscores the importance of maintaining all monitoring and safety devices in proper working condition as part of the comprehensive PMS framework, as early detection of abnormal parameters is the first line of defense against escalating machinery damage. It is recommended that exhaust gas temperature sensor calibration and functional testing be included in the regular maintenance schedule, with alarm set points verified against the instruction manual specifications to ensure that future anomalies trigger immediate automated alerts.

F. Recommended Comprehensive Maintenance Program

Based on the analysis of both incidents, a comprehensive injector maintenance program is recommended for the Anqing Daihatsu 6DL-20 generators on MT. Semar 77. The program integrates preventive inspection, testing, cleaning, and replacement activities into a structured schedule aligned with the instruction manual running-hour specifications and the vessel's Planned Maintenance System. The key elements include injector pressure testing at every 1,500 running hours with verification of cracking pressure at 300 kg/cm² and spray pattern uniformity, spring inspection at each pressure testing interval with replacement when fatigue indicators are observed, nozzle removal and cleaning at each pressure testing interval using brass brushes and clean MDO, nozzle replacement with original spare parts when orifice wear or damage is detected, fuel filter cleaning and replacement to minimize contaminant passage, purifier maintenance to ensure maximum separation efficiency, and exhaust gas temperature sensor calibration to ensure reliable early detection of combustion anomalies. All maintenance activities must be documented in the monthly maintenance report and engine log book, with running hours tracked for each generator to ensure timely execution of scheduled tasks.

The spare parts inventory management aboard the vessel must also be addressed as part of the comprehensive maintenance strategy. Adequate stocks of critical injector components — including nozzle assemblies, spring sets, nozzle needles, gaskets, and retaining nuts — must be maintained on board at all times to enable immediate corrective action when component replacement is required during scheduled or emergency maintenance. The Third Engineer responsible for generator maintenance should maintain an up-to-date spare parts inventory list and submit timely requisitions to the company's technical department when stock levels approach minimum thresholds. Furthermore, all replacement parts must be original manufacturer-specified components from Daihatsu to ensure dimensional accuracy, material quality, and performance compatibility with the DL-20 engine design specifications.

V. CONCLUSION

Based on the analysis and discussion presented in this study regarding the optimization of injector performance on the diesel generator engines of MT. Semar 77, the following conclusions are drawn.

The non-optimal atomization performance of the fuel injector was caused by two interrelated factors: spring fatigue leading to loss of nozzle needle seating pressure, and inaccurate adjusting screw calibration during pressure testing that resulted in improper needle valve lift timing and pressure characteristics. These conditions produced a degraded spray pattern with excessively large fuel droplets that could not achieve complete combustion within the cylinder, resulting in elevated exhaust gas temperatures (from the normal range of 350–450°C to 495°C), grayish exhaust smoke, and reduced engine power output. The corrective measure involves systematic injector pressure testing at 1,500 running-hour intervals using the nozzle tester apparatus, with target cracking pressure of 300 kg/cm² as specified in the instruction manual book, combined with spring inspection and replacement according to the PMS schedule and precise adjusting screw calibration procedures.

The nozzle orifice clogging was caused by progressive accumulation of carbon deposits from combustion residues and contaminant particles from the fuel supply that bypassed the filtration system. The blocked orifice holes prevented proper fuel atomization despite normal injection pressure, converting the intended spray cone into irregular droplets and causing incomplete combustion with exhaust gas temperatures reaching 490°C. The corrective measure involves periodic nozzle inspection, cleaning, and replacement at PMS-specified running-hour intervals, supplemented by comprehensive fuel quality management throughout the supply chain from bunker reception through purifier operation and filter maintenance.

Several recommendations are proposed to optimize injector performance and prevent recurrence of similar incidents. First, the engine department crew must conduct injector maintenance, repair, and spare part replacement strictly in accordance with the Planned Maintenance System and instruction manual book schedules, with particular emphasis on the 1,500 running-hour pressure testing interval and the spring and nozzle inspection protocols. All crew members involved in generator maintenance should be trained on proper pressure testing techniques, with specific attention to the precise calibration of the adjusting screw to avoid both over-tightening and under-tightening errors that compromise injector performance. Second, to prevent nozzle orifice clogging, the fuel quality management program must encompass the entire fuel supply chain from bunker reception through storage, settling, purification, and filtration, ensuring that only clean, contaminant-free fuel reaches the high-pressure injection system. The fuel purifier must be maintained at optimal efficiency, fuel filters at the injection pump intake must be cleaned and replaced at prescribed intervals, and settling tank drain procedures must be performed regularly to remove accumulated water and sediment. Third, the exhaust gas temperature monitoring system, including all sensors, wiring, and alarm configurations, must be verified and calibrated at regular intervals to ensure that abnormal combustion conditions are detected promptly through the automated alarm system rather than relying solely on manual thermometer readings during watch rounds. Fourth, adequate spare parts inventory for critical injector components must be maintained on board at all times, with timely requisitions submitted to the company technical department to prevent spare part shortages that could delay essential maintenance activities.

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