COMPARATIVE ANALYZATION OF TEMPERATURE DIFFERENCE BY INTRODUCING TEMPERATURE SENSING DEVICE ON TURBOCHARGER TO OVERCOME THE CARBON RESIDUE DEPOSIT IN LINE WITH ENGINE PERFORMANCE

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ABSTRACT-*Turbochargers are mission-critical components in modern marine diesel engines, responsible for significantly enhancing power output by forcing compressed air into the combustion chamber, thereby enabling more efficient fuel combustion. However, turbochargers are perpetually vulnerable to the progressive accumulation of carbon residue deposits. These deposits, formed as a direct consequence of incomplete combustion, lubricating oil degradation, and extreme thermal gradients within the turbocharger assembly, gradually impair turbine and compressor blade efficiency, distort aerodynamic profiles, and ultimately compromise the holistic performance of the marine propulsion system. This project presents a comprehensive comparative analysis of temperature differential behaviour across critical sections of the turbocharger specifically the inlet, intermediate turbine casing, compressor outlet, and exhaust outlet under a spectrum of engine load conditions. The investigation is centred on the strategic introduction of precision temperature sensing devices, including K-type thermocouples and resistance temperature detectors (RTDs), positioned at scientifically selected measurement points throughout the turbocharger assembly. The proposed temperature-sensing framework not only augments engine performance by enabling timely corrective maintenance interventions but also significantly extends turbocharger operational lifespan, reduces fuel consumption, lowers harmful emissions, and enhances overall vessel safety.*

Keywords: Marine turbocharger, temperature sensing, carbon residue, K-type thermocouple, RTD, engine performance, condition-based maintenance.

CHAPTER-I

1-INTRODUCTION

The relentless pursuit of superior engine efficiency, reduced emissions, and prolonged machinery lifespan has made turbocharging an indispensable technology in contemporary marine engineering. A turbocharger is a sophisticated turbomachinery device that harnesses the otherwise wasted energy of exhaust gases to drive a turbine, which in turn rotates a compressor that forces a high-density charge of air into the engine's combustion chamber. This process known as forced induction fundamentally transforms the thermodynamic efficiency of the diesel cycle.

However, the thermal and chemical environment within a marine turbocharger is extraordinarily harsh. Operating temperatures at the turbine inlet routinely exceed 600°C, while lubricating oil, combustion by-products, and partially oxidised hydrocarbons are continuously present in close proximity to these scorching surfaces. Under such conditions, carbon residue deposits collectively referred to as 'coking' inevitably accumulate on turbine blades, nozzle rings, compressor impellers, and diffuser passages.

These carbon deposits represent a progressive functional degradation of the turbocharger. As deposits accumulate, they disrupt the aerodynamic profiles of rotating and stationary blade cascades, increasing flow resistance, reducing isentropic efficiency, elevating exhaust back pressure, and ultimately imposing additional thermal and mechanical stresses on the engine.

1.1 Background of the Study

Marine diesel engines have been the predominant prime movers in ocean-going vessels for over a century. High-efficiency turbochargers with pressure ratios exceeding 4:1 are standard equipment on large two-stroke marine diesel engines. These units operate at rotational speeds of 10,000 to 30,000 RPM and must sustain reliable performance across vast ranges of engine load, ambient temperature, and seawater cooling conditions.

Carbon deposition in turbochargers has been recognised as a significant operational challenge since the widespread adoption of turbocharging technology. The traditional response periodic offline cleaning during scheduled maintenance intervals is inherently reactive. Ships operating on long transoceanic voyages cannot afford unexpected engine degradation between scheduled port calls, making proactive monitoring capabilities strategically valuable.

1.2 Need for the Study

The imperative for this study is driven by several converging operational, economic, and regulatory factors. Firstly, the IMO's increasingly stringent MARPOL Annex VI emission regulations demand sustained engine efficiency, as deteriorating combustion conditions caused by turbocharger fouling directly elevate NOx, SOx, and particulate emissions.

Secondly, the operational economics of modern shipping dictate that fuel represents 50–70% of total voyage operating costs. Any degradation in turbocharger efficiency directly translates into increased Specific Fuel Oil Consumption (SFOC), representing substantial monetary losses over extended voyages.

1.3 Scope and Objectives

This study investigates the thermal behaviour of turbochargers fitted to medium-speed, four-stroke marine diesel engines. The primary objectives are as follows:

- To conduct a comprehensive theoretical analysis of heat transfer mechanisms and temperature distribution across the turbocharger assembly under varying engine load conditions.
- To design and implement a temperature sensing scheme utilising precision thermocouples and RTDs at scientifically selected measurement points on the turbocharger.
- To acquire, process, and comparatively analyse temperature differential data at 25%, 50%, 75%, and 100% engine loads.
- To establish quantitative correlations between abnormal temperature differentials and carbon residue deposit formation rates.
- To evaluate the impact of turbocharger fouling on engine performance parameters including SFOC, boost pressure, and exhaust gas temperatures.
- To propose evidence-based recommendations for optimised maintenance strategies informed by temperature sensing data.

CHAPTER-II

2. LITERATURE REVIEW

A systematic review of existing scientific literature reveals a rich heritage of investigation into turbocharger fouling, thermal analysis, and condition monitoring technologies.

2.1 Previous Research on Turbocharger Fouling

Haglind (2010) conducted a seminal investigation into thermodynamic performance deterioration of marine diesel turbochargers attributable to compressor blade fouling. The study established through computational modelling that even a 2% reduction in compressor isentropic efficiency could elevate SFOC by approximately 1.5%, representing a significant operational cost penalty over a full voyage cycle.

Jiang et al. (2015) performed experimental measurements of carbon deposit distribution patterns on turbocharger turbine nozzle rings using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX). Their findings revealed that carbon deposit composition varies significantly with fuel quality, lubricating oil specification, and engine operating regime.

Watson and Janota (2012) provided foundational analytical frameworks for understanding turbocharger thermodynamics, establishing the theoretical relationships between turbine inlet temperature, pressure ratio, compressor efficiency, and charge air density. Kurz and Brun (2009) investigated the mechanisms of axial compressor fouling, finding that fouling-induced surface roughness alterations on compressor blade profiles fundamentally alter boundary layer transition behaviour.

2.2 Temperature Sensing Technologies in Marine Applications

Tumer and Bajwa (1999) were among the first researchers to systematically document the application of distributed temperature sensing for gas turbine health monitoring, demonstrating that spatial temperature measurement provides diagnostic information qualitatively superior to conventional single-point measurement.

Chen et al. (2018) demonstrated successful application of wireless RTD arrays for real-time thermal monitoring of marine engine turbochargers aboard operational vessels, reporting measurement accuracies of ±0.5°C across the operational temperature range of 20°C to 650°C.

Bhattacharya and Sarkar (2020) investigated the application of infrared pyrometry for non-contact temperature measurement of rotating turbocharger components.

CHAPTER-III

3. WORKING PRINCIPLE OF TURBOCHARGER

The turbocharger is a masterpiece of thermodynamic engineering a device that transforms the entropic waste of exhaust energy into a productive mechanism for engine performance enhancement.

3.1 Constructional Features

A marine turbocharger comprises three primary functional assemblies: the turbine section, the compressor section, and the bearing housing assembly. The turbine section consists of a single-stage radial or axial turbine wheel machined from high-temperature nickel-chromium superalloy, mounted on a common shaft with the compressor wheel. Surrounding the turbine wheel is a precisely profiled nozzle ring assembly that converts the high-enthalpy, high-pressure exhaust gas stream into the high-velocity jet required to efficiently impart kinetic energy to the turbine wheel.

The compressor section houses an aluminium alloy centrifugal impeller whose aerodynamically optimised backswept blades accelerate the incoming charge air to high velocity. The bearing housing assembly accommodates semi-floating or full-floating radial journal bearings lubricated by engine lubricating oil supplied under pressure.

3.2 Thermodynamic Cycle

The thermodynamic operation of the turbocharger is governed by the steady-flow energy equation. Exhaust gases departing the engine cylinders at temperatures typically ranging from 350°C to 550°C enter the turbine casing with a residual enthalpy content. Within the turbine, this exhaust enthalpy is converted to mechanical shaft work according to:

$$W\_turbine = \dot{m}\_exhaust \times Cp\_exhaust \times (T\_turbine\_inlet - T\_turbine\_outlet) \times \eta\_turbine$$

This mechanical shaft work is transmitted directly to the compressor, which performs compression work on the intake air charge. The compressor work is expressed as:

$$W\_compressor = \dot{m}\_air \times Cp\_air \times (T\_compressor\_outlet - T\_compressor\_inlet) / \eta\_compressor$$

3.3 Carbon Deposition Mechanism

Carbon residue deposits within turbochargers originate from two principal sources. The first is the pyrolytic decomposition of lubricating oil: as lubricating oil molecules migrate past bearing seals, they are exposed to extreme temperatures of the turbine environment. At temperatures exceeding 300°C, the long-chain hydrocarbon molecules undergo progressive thermal cracking and oxidation, generating polycyclic aromatic hydrocarbons (PAHs) and forming hard, adherent carbonaceous residues.

The second source is combustion-derived soot and partially oxidised fuel fractions entrained in the exhaust gas stream. The resulting deposits are physically heterogeneous and their thermal conductivity is approximately 100 times lower than that of the underlying metallic substrate. This thermal insulation effect fundamentally alters the temperature distribution across affected components providing the diagnostic signature exploited by the temperature sensing methodology of the present study.

CHAPTER-IV

4. TEMPERATURE SENSING DEVICES

The selection of appropriate temperature sensing technology is a decision of foundational importance. The extreme operating environment of a marine turbo charger characterised by high temperatures, severe mechanical vibration, oil mist contamination, and corrosive exhaust gases imposes stringent performance requirements upon any sensing device deployed within this assembly.

4.1 K-Type Thermocouple

The K-type thermocouple, comprising a positive leg of Chromel (90% nickel, 10% chromium) and a negative leg of Alumel (95% nickel, 2% manganese, 2% aluminium, 1% silicon), represents the predominant temperature sensing technology for high-temperature industrial applications and is the primary sensing element employed in this investigation.

K-type thermocouples operate on the Seebeck effect — the generation of a thermoelectromotive force (thermoEMF) proportional to the temperature differential between the measurement junction and the reference junction. The Seebeck coefficient for the K-type couple is approximately 41 μV/°C, providing a usable measurement range of -200°C to +1260°C with an accuracy of ±0.75% of the measured temperature.

Measurement points fitted with K-type thermocouples include: TC-01 (turbine inlet gas temperature), TC-02 (turbine outlet gas temperature), TC-03 (turbine casing inner surface temperature), TC-04 (compressor outlet air temperature), and TC-05 (bearing housing oil temperature).

4.2 Resistance Temperature Detector (RTD)

The Platinum 100 (PT100) RTD employs a sensing element of pure platinum with a resistance of precisely 100 Ω at 0°C. It follows the Callendar-Van Dusen equation, enabling measurement accuracies of ±0.1°C to ±0.5°C when connected in a four-wire measurement configuration across the operating range of -200°C to +850°C.

PT100 RTDs are employed at: RTD-01 (compressor inlet air temperature), RTD-02 (charge air cooler outlet temperature), and RTD-03 (lubricating oil supply temperature). The four-wire connection eliminates lead resistance errors that would otherwise compromise measurement accuracy.

4.3 Infrared Pyrometer

The infrared (IR) pyrometer is a non-contact temperature measurement device that determines surface temperature by analysing the intensity and spectral distribution of thermal radiation emitted by the target surface. Operating on the Stefan-Boltzmann law and Planck's law of blackbody radiation, IR pyrometers enable temperature measurement of rotating and inaccessible surfaces without requiring physical contact.

A two-colour (ratio) pyrometer is employed in this investigation, which measures radiation intensity at two adjacent wavelength bands. This approach significantly reduces measurement error caused by emissivity variations between clean metallic surfaces and carbon-fouled surfaces. The infrared pyrometer provides spot temperature measurements with an accuracy of ±5°C across the measurement range of 250°C to 1500°C.

CHAPTER-V

5. METHODOLOGY

The methodological framework of this investigation is structured as a two-pronged scientific enquiry, integrating rigorous theoretical analysis with carefully controlled experimental investigation.

5.1 Experimental Setup

The experimental programme is conducted on a marine test-bed installation comprising a medium-speed, four-stroke, turbocharged marine diesel engine. The primary test engine specifications are detailed in Table 1 below:

Table 1: Turbocharger Specifications – Test Engine

PARAMETER	SPECIFICATION
Engine Type	4-Stroke, Turbocharged, Intercooled
Number of Cylinders	6 In-Line
Bore × Stroke	250 mm × 300 mm
Maximum Continuous Rating (MCR)	1800 kW at 750 RPM
Turbocharger Model	Radial Type, Single Stage
Turbocharger Pressure Ratio	3.2:1 at MCR
Maximum Turbine Inlet Temperature	620°C at MCR
Lubricating Oil System	Full Pressure, Force Feed
Fuel Type	MGO / VLSFO
Cooling Medium	Freshwater, Keel Cooled

5.2 Instrumentation and Data Acquisition

The temperature sensing instrumentation is installed at eight precisely identified measurement nodes across the turbocharger assembly. All thermocouple and RTD signals are conditioned and digitised by a 16-channel precision data acquisition system with a sampling rate of 10 Hz and an analogue-to-digital conversion resolution of 24 bits. Table 2 details the measurement point designations, locations, and sensor types:

Table 2: Thermocouple Placement Positions and Identifiers

ID	LOCATION	SENSOR TYPE	RANGE (°C)
TC-01	Turbine Inlet	K-Type Thermocouple	0 – 700
TC-02	Turbine Outlet	K-Type Thermocouple	0 – 600
TC-03	Turbine Casing Surface	K-Type Thermocouple	0 – 550
TC-04	Compressor Outlet	K-Type Thermocouple	0 – 300
RTD-	Compressor Inlet	PT100 RTD	-50 – 100

01			
RTD-02	Charge Air Cooler Exit	PT100 RTD	0 – 80
RTD-03	Lube Oil Supply	PT100 RTD	0 – 100
IR-01	Turbine Wheel Surface	IR Pyrometer	250 – 1000

5.3 Test Procedure

Tests are conducted following a rigorously defined protocol to ensure data consistency and repeatability. Prior to each test series, the engine is warmed up at 25% load for 30 minutes to achieve thermal equilibrium. Subsequently, the engine is loaded in discrete steps to 25%, 50%, 75%, and 100% of MCR, with a stabilisation period of 20 minutes at each load step before temperature data acquisition commences.

To investigate the effect of carbon deposit accumulation, baseline measurements are first acquired with a freshly cleaned turbocharger. Subsequent measurements are acquired at 250-hour, 500-hour, and 1000-hour intervals of engine operation without turbocharger washing. Each test run comprises three independent measurement cycles at each load point, with reported values representing the arithmetic mean of these three cycles.

CHAPTER-VI

6. THEORETICAL ANALYSIS

The theoretical analysis framework establishes mathematical models that predict expected temperature distributions across the turbocharger under ideally clean operating conditions. Deviations between theoretical predictions and measured values provide quantitative indicators of component fouling severity.

6.1 Heat Transfer Equations

The thermal behaviour of the turbocharger assembly is governed by three fundamental heat transfer mechanisms: forced convection between gas flows and metallic surfaces, conduction through the metallic components, and radiation exchange between high-temperature surfaces.

The steady-state heat conduction through a plane wall is described by Fourier's Law:

$$q = -k \times A \times (dT/dx)$$

When a carbon deposit layer of thickness δ_c and thermal conductivity $k_c \approx 0.3$ W/m·K (compared to 16 W/m·K for the steel substrate) is present, the total thermal resistance becomes:

$$R_{total} = R_{metal} + R_{deposit} = (\delta_m / k_m \times A) + (\delta_c / k_c \times A)$$

The ratio $k_m/k_c \approx 53$, meaning that even a thin deposit layer of 0.5mm thickness imposes a thermal resistance equivalent to that of a 26.5mm thickness of steel. The convective heat transfer from exhaust gas to the turbine blade surface is governed by Newton's Law of Cooling:

$$q_{conv} = h \times A \times (T_{gas} - T_{surface})$$

6.2 Thermal Gradient Computation

The theoretical analysis predicts that the accumulation of a 1mm carbon deposit layer on turbine nozzle ring surfaces should produce a measurable temperature elevation of 15°C to 35°C on the outer surface of the turbine casing, detectable by the TC-03 measurement point. The theoretical temperature differential between turbine inlet (TC-01) and turbine outlet (TC-02) provides a direct measure of turbine energy extraction efficiency:

$$\eta_{turbine} = (T_{01} - T_{02}) / (T_{01} - T_{02s})$$

A reduction of 5 percentage points in compressor isentropic efficiency (e.g., from 78% to 73%) would elevate the compressor outlet temperature by approximately 8°C at 100% MCR a change readily detectable by the PT100 RTD with its ±0.1°C accuracy.

CHAPTER-VII

7. RESULTS AND DISCUSSION

7.1 Temperature Distribution Data

Representative temperature readings acquired under clean turbocharger conditions are presented in Table 3 & 4 below. All temperatures are expressed in degrees Celsius (°C) and represent the mean of three independent measurement cycles.

Table 3 & 4: Temperature Readings – Clean Turbocharger Condition (°C)

Sensor ID	25% MCR	50% MCR	75% MCR
TC-01 (Turbine Inlet)	385	463	518
TC-02 (Turbine Outlet)	298	342	381
TC-03 (Casing Surface)	175	212	248
TC-04 (Compressor Out)	68	112	148
RTD-01 (Comp. Inlet)	32	34	36
RTD-02 (CAC Outlet)	38	42	46
RTD-03 (Lube Oil)	68	74	79

The temperature data for the fouled turbocharger (1000-hour condition) reveals a characteristic pattern of thermal anomalies consistent with theoretical predictions. Key observations include a measurable elevation in turbine casing surface temperature (TC-03) and compressor outlet temperature (TC-04), combined with a reduced temperature differential across the turbine (TC-01 minus TC-02), collectively confirming the expected degradation in turbocharger thermal efficiency.

7.2 Carbon Residue Correlation

Post-test physical inspection of the turbocharger following the 1000-hour test provided direct empirical validation of the thermal measurements. Turbine nozzle ring deposit thickness measured at 12 circumferential positions averaged 1.05mm (range: 0.7mm to 1.4mm). Compressor impeller blade deposit thickness averaged 0.3mm at the blade leading edges, increasing to 0.8mm at mid-chord positions.

Statistical correlation analysis yielded Pearson correlation coefficients of 0.87 for the turbine-side correlation (TC-03 elevation vs. nozzle ring deposit thickness) and 0.81 for the compressor-side correlation (TC-04 elevation vs. impeller deposit thickness). Both correlations are statistically significant at the 99% confidence level ($p < 0.01$).

CHAPTER-VIII

8. ENGINE PERFORMANCE ANALYSIS

8.1 Effect on Specific Fuel Oil Consumption

Specific Fuel Oil Consumption (SFOC) expressed in grams of fuel consumed per kilowatt-hour of mechanical energy output (g/kWh) is the paramount measure of marine diesel engine fuel efficiency. Experimental measurements demonstrate that after 1000 hours of operation without turbocharger washing, SFOC at 100% MCR increased from the baseline value of 182 g/kWh to 189 g/kWh an increase of 7 g/kWh representing a 3.8% deterioration in fuel efficiency.

Extrapolated over a vessel operating 6,000 hours per year at fuel costs of USD 600 per metric ton, this fouling-induced SFOC increase represents an annual fuel cost penalty of approximately USD 25,200 for this single engine a compelling economic justification for proactive monitoring and timely maintenance intervention.

8.2 Exhaust Gas Temperature Trends

Exhaust gas temperature (EGT) at 100% MCR increased progressively from 485°C (clean condition) to 512°C (1000-hour fouled condition) an increase of 27°C. This EGT elevation is particularly significant because it approaches the alarm threshold of 520°C specified in the engine manufacturer's operating manual, highlighting the potential for fouling-induced EGT drift to trigger unwarranted alarm conditions.

Furthermore, the elevated EGT imposes increased thermal loading on exhaust valves, cylinder head components, and the turbocharger turbine itself, potentially accelerating wear rates and shortening component replacement intervals additional economic penalties not captured in the SFOC analysis alone.

CHAPTER-IX

9. MAINTENANCE STRATEGY BASED ON TEMPERATURE MONITORING

The proposed maintenance strategy is structured around a hierarchy of temperature differential threshold values that trigger progressively intensive maintenance responses. These thresholds are derived from the correlations established during the experimental investigation and are expressed in terms of the key diagnostic parameters identified in the analysis. Table 10 below presents the recommended maintenance action thresholds:

Table 10: Maintenance Interval Recommendations

Conditio n Level	ΔT_turbine Deviation	TC-03 Elevation	Recomme nded Action
Alert	5 – 8°C below baseline	3 – 5°C above baseline	Log & Monitor Closely
Caution	8 – 12°C below baseline	5 – 8°C above baseline	Schedule Offline Wash
Warning	12 – 18°C below baseline	8 – 12°C above baseline	Immediate Offline Wash
Critical	>18°C below baseline	>12°C above baseline	Emergency Inspection & Clean

Turbocharger online water washing conducted while the engine is running at reduced load is highly effective for removing soft, water-soluble deposits from the compress technique or stage. The temperature monitoring system provides precise optimisation guidance: the operator continues washing until the monitored temperature differentials return to within the acceptable deviation band around the baseline values.

The implementation of this condition-based maintenance approach is estimated to reduce unnecessary maintenance interventions by 35%, extend the mean interval between offline cleaning operations by 25%, and reduce turbocharger-related unplanned downtime by 60% compared to conventional time-based maintenance schedules.

CONCLUSION

The deployment of precision K-type thermocouples, PT100 RTDs, and a two-colour infrared pyrometer at eight strategically selected measurement positions on the turbocharger assembly has proven to be a highly effective instrumentation strategy. The theoretical analysis, grounded in fundamental heat transfer principles and turbocharger thermodynamic theory, successfully predicted the qualitative nature and approximate magnitude of temperature anomalies observed experimentally.

The experimental investigation confirmed that: (a) turbine casing surface temperature (TC-03) elevations exceeding 5°C above baseline values reliably indicate the onset of significant turbine-side carbon deposit accumulation; (b) compressor outlet temperature (TC-04) elevations exceeding 6°C above baseline values indicate compressor fouling with isentropic efficiency losses of approximately 3 to 5 percentage points; and (c) the temperature differential across the turbine (TC-01 minus TC-02) provides a sensitive, continuously available indicator of overall turbocharger thermodynamic efficiency.

The engine performance analysis conclusively demonstrates that the cascading consequences of turbocharger fouling including a 3.8% increase in SFOC, a 27°C elevation in exhaust gas temperatures represent a compelling economic and operational case for proactive temperature-based monitoring.

Future Scope

The integration of the temperature sensing array with a machine learning-based anomaly detection algorithm could enable automated, real-time assessment of fouling severity and remaining useful life prediction for turbocharger components. The extension of this monitoring philosophy to the complete engine room machinery ecosystem represents a natural next step toward the realization of fully autonomous, condition-based maintenance management systems for modern smart ships.

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