

Predictive Maintenance of a Marine Diesel Engine Cooling System Using Thermo-Hydraulic Operating Relationships

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الصيانة التنبؤية لمنظومة تبريد محرك ديزل بحري باستخدام العلاقات الحرارية الهيدروليكية التشغيلية

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Abstract

This study investigates the cooling system of an MTU marine diesel engine as one of the critical subsystems responsible for maintaining the engine's thermal stability and ensuring operation within safe design limits specified by the manufacturer. The study adopts an analytical–applied methodology combining theoretical analysis based on heat transfer and fluid mechanics principles, with practical implementation using Arduino UNO for data acquisition and monitoring of cooling parameters.

The research focuses on the relationships between Cooling Temperature (CT), Cooling Pressure (CP), and Cooling Flow Rate (CF), as the most representative indicators of the cooling system's operational condition. The results indicate that deviations in these variables can serve as early indicators of faults such as pump inefficiency, heat exchanger fouling, or air entrainment in the circuit.

The study confirms that analyzing the graphical relationships between these parameters provides a practical framework for implementing predictive maintenance strategies in marine diesel engines and enhances operational reliability while reducing unexpected failures.

Keywords: Predictive maintenance; Marine diesel engine; Cooling system; Thermo-hydraulic behaviour; Condition monitoring; Fault diagnosis.

المخلص

تهدف هذه الدراسة إلى تحليل منظومة التبريد لمحرك ديزل بحري من نوع MTU، باعتبارها إحدى المنظومات الحيوية المسؤولة عن الحفاظ على الاستقرار الحراري للمحرك وضمان عمله ضمن الحدود التشغيلية الآمنة المحددة من قبل الشركة المصنعة. تعتمد الدراسة على منهجية (تحليلية، تطبيقية) تجمع بين التحليل النظري المعتمد على مراجع علمية متخصصة في انتقال الحرارة وميكانيكا الموائع والتطبيق العملي باستخدام منصة Arduino UNO لمراقبة وجمع بيانات منظومة التبريد وتحليل سلوكها التشغيلي.

تركز الدراسة على تحليل العلاقات بين درجة حرارة سائل التبريد (CT) Cooling Temperature، وضغط سائل التبريد (CP) Cooling Pressure، ومعدل تدفق سائل التبريد (CF) Cooling Flow Rate، باعتبارها المؤشرات الأكثر تمثيلاً للحالة التشغيلية لمنظومة التبريد. وقد أظهرت النتائج أن الانحرافات في هذه المتغيرات يمكن أن تمثل مؤشرات مبكرة لأعطال محتملة مثل ضعف أداء المضخة، انسداد أو اتساخ المبادل الحراري، أو وجود هواء داخل الدائرة. كما تؤكد الدراسة أن تحليل العلاقات البيانية بين هذه المتغيرات يوفر إطاراً عملياً لتطبيق استراتيجيات الصيانة التنبؤية في المحركات البحرية، بما يساهم في تحسين موثوقية التشغيل وتقليل الأعطال المفاجئة.

الكلمات المفتاحية: الصيانة التنبؤية، محرك ديزل بحري، منظومة التبريد، السلوك الحراري-الهيدروليكي، مراقبة الحالة، تشخيص الأعطال.

Introduction

Marine diesel engines are widely utilized in marine vessels due to their high efficiency, operational reliability, and capability to withstand harsh environmental conditions (Heywood,2018). During operation, these engines are exposed to significant thermal loads generated by combustion processes and mechanical friction, making thermal regulation essential for maintaining safe and stable operating conditions within the manufacturer's specified limits (Heywood,2018;Stone,2012).

Among the critical subsystems of marine diesel engines, the cooling system plays a fundamental role in controlling engine temperature and preventing overheating phenomena that may lead to lubricant degradation, excessive thermal stresses, and reduced engine performance (Stone,2012). This role becomes increasingly important in high-power marine engines such as MTU propulsion systems used in naval and patrol vessels, where precise temperature management is directly associated with operational safety and long-term reliability (MTU Friedrichafen GmbH, 1982).

Modern marine cooling systems typically operate using a dual-circuit configuration composed of a closed freshwater circuit and an open seawater circuit. Heat generated inside the engine is transferred from the freshwater coolant to seawater through a heat exchanger before being discharged overboard. The operational performance of this system is primarily characterized by three important parameters: Cooling Temperature (CT), Cooling Pressure (CP), and Cooling Flow Rate (CF), which collectively reflect the thermal and hydraulic efficiency of the engine cooling process (MTU Friedrichafen GmbH, 1982; Lazakis et al., 2016).

Recent studies have highlighted the importance of Predictive Maintenance (PdM) and intelligent condition monitoring techniques in marine diesel engine applications through continuous analysis of thermal and hydraulic operating parameters. Monitoring variations in CT, CP, and CF can significantly improve early fault detection capability, reduce unexpected failures, and enhance system reliability under varying operating conditions (Lazakis et al., 2016; Jardine et al., 2006). In previous research conducted by the authors on the same MTU marine diesel propulsion system installed on a Libyan marine patrol vessel, a maintenance system design was proposed to improve machinery reliability, operational continuity, and fault prevention through structured maintenance planning and monitoring methodologies. The outcomes of that work provided a practical foundation for extending predictive maintenance approaches toward real-time thermo-hydraulic condition monitoring of critical subsystems such as the engine cooling system (Al-Rashidi et al., 2024).

Previous research on MTU marine diesel engines also confirmed the effectiveness of predictive maintenance methodologies using lubrication analysis and intelligent monitoring approaches. The study demonstrated that the analysis of thermal and hydraulic parameters contributes significantly to improving fault diagnosis accuracy and enhancing operational reliability during engine operation (Al-Rashidi & Eshoul, 2026).

Furthermore, advanced diagnostic methods based on artificial neural networks, machine learning algorithms, and data-driven monitoring techniques have demonstrated high effectiveness in identifying abnormal operating conditions and predicting system failures before severe degradation occurs (Gharib & Kovács, 2023; Zhu et al., 2023; Liu et al., 2023).

2. Research Objectives:

This study aims to:

- Analyze the operational behavior of the MTU marine diesel engine cooling system.
- Investigate the relationships between Cooling Temperature (CT), Cooling Pressure (CP), and Cooling Flow Rate (CF).

- Evaluate the effectiveness of thermal and hydraulic parameter monitoring for early fault detection.
- Support predictive maintenance applications to improve operational reliability and minimize unexpected failures.

3. Operating Principle of the MTU Marine Diesel Cooling System:

The MTU cooling system is based on two separate circuits: a closed freshwater cooling circuit and an open seawater cooling circuit. This configuration ensures effective heat dissipation while minimizing corrosion and scaling caused by seawater exposure to engine components (Stone, 2012; MTU Friedrichshafen GmbH, 1982).

3.1. Closed Freshwater Cooling Circuit:

The closed circuit begins at the freshwater pump, which circulates coolant through passages inside the engine block and cylinder heads. As the coolant flows, it absorbs heat generated by combustion and mechanical friction, and the temperature rise reflects the engine's thermal load (Heywood, 2018; MTU Friedrichshafen GmbH, 1982).

The heated coolant then passes through a thermostatic valve that regulates the flow depending on temperature. At low temperatures, the valve recirculates coolant back to the engine, while at higher temperatures it directs the coolant toward the heat exchanger for heat rejection (Stone, 2012; MTU Friedrichshafen GmbH, 1982).

An expansion tank maintains pressure stability and compensates for volume changes due to thermal expansion while preventing air entry into the circuit, which could reduce heat transfer efficiency and affect pump performance (MTU Friedrichshafen GmbH, 1982; Jardine et al., 2006).

3.2. Open Seawater Cooling Circuit:

Seawater enters through the sea cock, passes through strainers, and flows to the plate heat exchanger where heat is transferred from the freshwater coolant without mixing. Plate heat exchangers are widely used in marine applications due to their high efficiency and ease of maintenance (Stone, 2012; Kakaç et al., 2012).

The heated seawater is then discharged overboard, completing the cooling cycle (MTU Friedrichshafen GmbH, 1982).

3.3. Integration Between the Two Circuits:

Figure (1) illustrates the integration between the freshwater and seawater cooling circuits in the marine diesel engine cooling system. The figure demonstrates the heat transfer process through the heat exchanger and highlights the interaction between major components including the seawater pump, thermostat, expansion tank, and freshwater circulation path. This integrated operation ensures stable thermal regulation and efficient cooling performance under normal operating conditions (MTU Friedrichshafen GmbH, 1982; Lazakis et al., 2016).

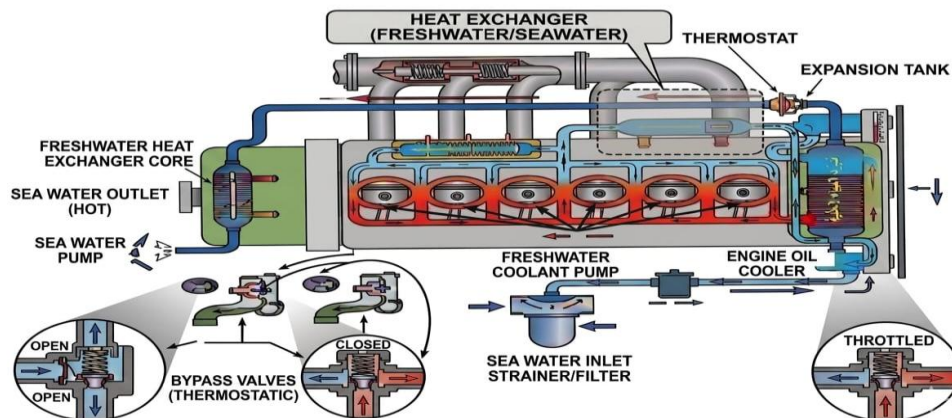


Figure (1) Schematic diagram of the cooling system for an MTU marine diesel engine (MTU Friedrichshafen GmbH, 1982).

4 .Methodology Adopted for Studying the Cooling System of the MTU Marine Diesel Engine:

This study adopts an analytical–applied methodology to investigate the operational behavior of the cooling system of an MTU marine diesel engine. The methodology combines theoretical analysis based on manufacturer documentation and scientific references with practical simulation using Arduino UNO to monitor the cooling parameters and analyze their relationships (MTU Friedrichshafen GmbH, 1982; Lazakis et al., 2016).

4.1.Technical Data Sources and Reference Criteria:

The primary source of technical data for this study is the official MTU technical documentation and operating manuals, which provide the design limits, system layout, and nominal operating conditions of the cooling system (MTU Friedrichshafen GmbH, 1982). These documents serve as the reference framework to ensure that the analysis is performed within the correct design boundaries.

Additional support is provided by scientific references related to heat transfer and fluid flow behavior in engine cooling systems (Heywood, 2018; Stone, 2012; Incropera et al., 2011).

4.2.Identification of Key Operational Variables:

Based on the manufacturer documentation and relevant scientific studies, the following variables were selected as the most representative indicators of cooling system performance:

Cooling Temperature (CT)

Cooling Pressure (CP)

Cooling Flow Rate (CF)

These variables directly reflect the thermal and hydraulic behavior of the cooling circuit and are widely used in predictive maintenance applications for marine systems (MTU Friedrichshafen GmbH, 1982; Lazakis et al., 2016; Kakaç et al., 2012).

4.3.Experimental Simulation Model and Measurement Points:

An experimental simulation model was developed using Arduino UNO to emulate the operational behavior of the cooling system. Measurement points for CT, CP, and CF were selected along the freshwater circuit to represent real operational conditions consistent with the MTU system layout shown in Figure (1) (MTU Friedrichshafen GmbH, 1982).

The selected measurement points allow detection of common cooling system issues such as pump inefficiency, flow disturbances, and pressure drops due to partial blockage or leakage (MTU Friedrichshafen GmbH, 1982; Jardine et al., 2006; Michala & Lazakis, 2015).

4.4.Measurement Tools and Data Quality Considerations:

Sensors and measurement tools were selected to ensure accuracy, stability, and suitable measurement ranges for each variable. Data quality was treated as a critical factor, as unstable readings could affect the reliability of graphical analysis and predictive interpretation (Jardine et al., 2006; Maio et al., 2024).

To improve reliability, readings were taken under stabilized conditions, and multiple measurements were recorded for each operating point to reduce random error (Jardine et al., 2006; Maio et al., 2024).

4.5.Data Collection and Validation Procedure:

The data collection process followed these steps:

- 1.Stabilizing operating conditions before recording data.
- 2.Recording multiple readings for each condition.
- 3.Using the average value for analysis.
- 4.Discarding abnormal readings caused by temporary disturbances.

These procedures are consistent with best practices in condition monitoring and predictive diagnostics (Jardine et al., 2006; Maio et al., 2024).

4.6.Graphical Analysis of Operational Relationships:

Figure (2) presents the Arduino UNO-based experimental test bench used to simulate, monitor, and record the operational parameters of the marine diesel engine cooling system.

The setup integrates sensors, data acquisition components, and computer-based monitoring software to measure Cooling Temperature (CT), Cooling Pressure (CP), and Cooling Flow Rate (CF) under different operating conditions. This configuration provides a practical platform for graphical analysis and predictive maintenance applications (MTU Friedrichshafen GmbH, 1982; Jardine et al., 2006).

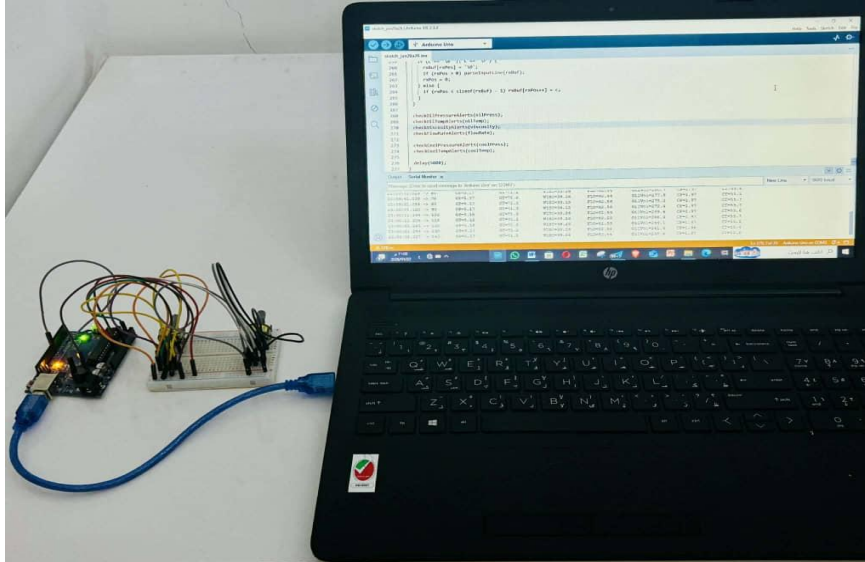


Figure (2) Arduino UNO test-bench used to simulate and measure marine diesel engine cooling system parameters.

5. Governing Physical Equations of the Marine Diesel Engine Cooling System:

The physical analysis of the cooling system in marine diesel engines is based on an accurate description of heat transfer mechanisms and fluid flow behavior within the cooling circuits. Understanding these governing equations is essential for interpreting the operational relationships between Cooling Temperature (CT), Cooling Pressure (CP), and Cooling Flow Rate (CF) observed in this study. These equations are widely adopted in the analysis of diesel engine cooling systems and similar industrial thermal applications (Incropera et al., 2011; Çengel & Ghajar, 2015; White, 2016).

5.1. Energy Balance of the Coolant Inside the Engine:

$$Q = \dot{m} \cdot C_p \cdot (T_{out} - T_{in}) \quad (1)$$

This equation represents the fundamental thermal relationship between the engine and the coolant flowing through the cooling passages. As the coolant absorbs heat from the engine block and cylinder heads, its temperature increases proportionally to the mass flow rate and the specific heat capacity of the coolant. This relationship directly explains the interaction between coolant temperature and coolant flow rate in diesel engine cooling analysis (Incropera et al., 2011; Çengel & Ghajar, 2015).

Definitions:

Q : Heat transferred from the engine to the coolant (W).

\dot{m} : Coolant mass flow rate (kg/s).

C_p : Specific heat capacity of the coolant at constant pressure (J/kg·K).

T_{in} : Coolant inlet temperature to the engine (C°)

T_{out} : Coolant outlet temperature from the engine (C°)

5.2. Heat Transfer in the Heat Exchanger:

$$Q = U \cdot A \cdot \Delta T_{lm} \quad (2)$$

After absorbing heat inside the engine, the coolant transfers this heat to seawater through the plate heat exchanger. This equation describes the rate of heat transfer based on the overall heat transfer coefficient, the effective heat transfer area, and the logarithmic mean temperature difference. It is fundamental for evaluating the performance of marine plate heat exchangers (Kakaç et al., 2012; Incropera et al., 2011).

Definitions:

Q : Heat transfer rate in the heat exchanger (W).

U : Overall heat transfer coefficient (W/m²·K).

A : Effective heat transfer area (m²).

ΔT_{lm} : Logarithmic Mean Temperature Difference (C°).

5.3. Logarithmic Mean Temperature Difference (LMTD):

$$\Delta T_{lm} = (\Delta T1 - \Delta T2) / \ln(\Delta T1 / \Delta T2) \quad (3)$$

The LMTD represents the effective thermal driving force for heat transfer between the two fluids inside the heat exchanger. It accounts for the varying temperature difference along the exchanger length and is widely used in the thermal design and analysis of marine heat exchangers (Incropera et al., 2011; Çengel & Ghajar, 2015).

Definitions:

$\Delta T1$: Temperature difference at one end of the heat exchanger (C°).

$\Delta T2$: Temperature difference at the other end of the heat exchanger (C°).

ln : Natural logarithm

5.4. Pressure Loss in Cooling Pipes (Darcy–Weisbach Equation):

$$\Delta P_f = f \cdot (L / D) \cdot (\rho \cdot v^2 / 2) \quad (4)$$

This equation describes the pressure loss due to friction as the coolant flows through the pipes of the cooling circuit. It explains the direct relationship between cooling pressure and flow rate and is essential for diagnosing abnormal pressure drops caused by partial blockage, increased flow resistance, or pump performance degradation (White, 2016).

Definitions:

ΔP_f : Pressure loss due to friction inside the pipe (Pa).

f : Friction factor (dimensionless).

L : Pipe length (m).

D : Internal pipe diameter (m).

ρ : Coolant density (kg/m³).

v : Average flow velocity (m/s).

6. Results and Discussion:

6.1. Introduction:

This section presents the operational results obtained from the simulation of the cooling system of an MTU marine diesel engine using the Arduino UNO platform. The analysis focuses on the behavior of the three principal operating variables of the cooling circuit:

Coolant Temperature (CT)

Cooling Pressure (CP)

Cooling Flow Rate (CF)

The objective is first to establish the normal reference operating behavior of the system under stable conditions. This reference behavior is then used to interpret deviations caused by different fault conditions, forming the basis for predictive maintenance applications in marine diesel engines (Heywood, 2018; Lazakis et al., 2016).

6.2. Normal Operating Behaviour of the Cooling System:

Before analyzing abnormal conditions, it is essential to define the natural thermo-hydraulic behavior of the cooling circuit at steady operation. The reference condition adopted in this study is:

$$CT = 75C^\circ$$

At this temperature, the influence of thermal variation on fluid properties is minimized, allowing the hydraulic relationships inside the circuit to be clearly observed (Stone, 2012; White, 2016).

Under this condition, three fundamental relationships govern the performance of the cooling system:

1. CP–CF relationship.
2. CT–CP relationship.
3. CT–CF relationship.

These relationships represent the baseline operational signature of the cooling system in healthy condition.

6.3. Relationship Between Cooling Pressure (CP) and Flow Rate (CF): at Constant Coolant Temperature.

The operating zones observed within the pressure range of 0.70–3.00 bar are classified as:

- Normal operating zone.
- Warning zone 1.
- Warning zone 2.
- Critical operating zone.
- Shutdown zone.

Figure (3) illustrates the direct relationship between cooling pressure (CP) and cooling flow rate (CF) within the marine diesel engine cooling system while maintaining a constant coolant temperature of 75°C, which represents the normal operating temperature specified for the studied marine engine. The obtained curve demonstrates that increasing cooling pressure leads to a proportional increase in coolant flow rate due to the improved hydraulic energy supplied by the centrifugal pump to overcome internal flow resistance within pipes, engine jackets, and the heat exchanger (Stone, 2012; White, 2016).

At the normal operating condition (CT = 75°C), the system operates within the stable pressure range of approximately 0.80–3.00 bar, where the cooling flow rate increases gradually from nearly 52.28 L/min at 0.70 bar to approximately 60.00 L/min at 3.00 bar. This behavior reflects proper hydraulic equilibrium between pump performance and system resistance characteristics inside the cooling network.

The figure further identifies multiple operational safety regions. The pressure range between 0.60 and 0.80 bar represents Warning Zone 1, indicating the beginning of hydraulic performance degradation and possible reduction in coolant circulation efficiency. When the cooling pressure decreases further to the range between 0.50 and 0.60 bar (Warning Zone 2), the system approaches unstable operating conditions associated with insufficient coolant flow and reduced heat transfer capability.

At pressures below 0.50 bar, the system enters the critical and shutdown operating zones where the cooling flow rate becomes inadequate for maintaining proper engine thermal regulation. Under such conditions, several faults may occur, including centrifugal pump degradation, internal leakage, cavitation effects, partial blockage inside the heat exchanger, excessive pipe resistance, or thermostat malfunction. Continued operation under these abnormal conditions may eventually result in engine overheating and severe thermal stress on cooling system components (Lazakis et al., 2016; Jardine et al., 2006; Michala & Lazakis, 2015).

These observations confirm that monitoring the relationship between CP and CF provides an effective diagnostic indicator for evaluating hydraulic stability, cooling efficiency, and predictive maintenance conditions in marine diesel engine cooling systems. The obtained results are consistent with previous studies on marine cooling system behavior and condition monitoring applications (Stone, 2012; Lazakis et al., 2016; Jardine et al., 2006; Michala & Lazakis, 2015; White, 2016).

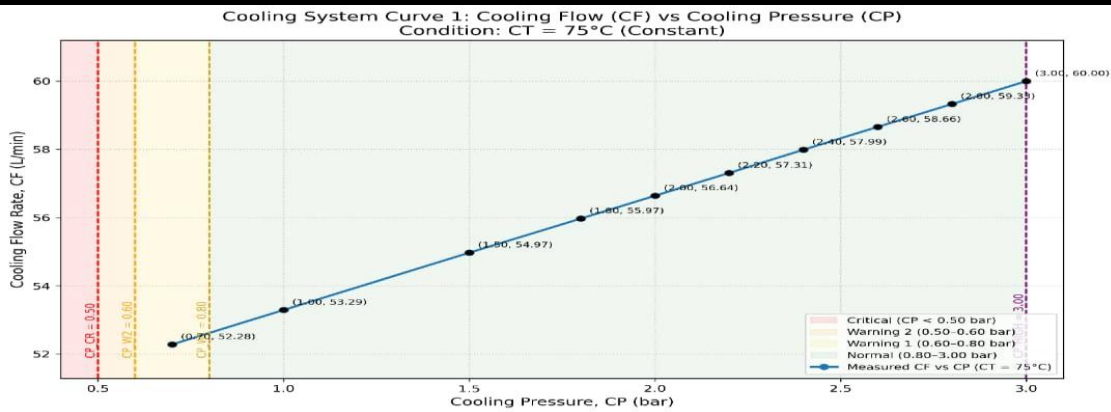


Figure (3) Relationship between Cooling Pressure and Cooling Flow Rate at CT = 75°C°.

6.3.1. Physical Interpretation of the (CP–CF) Relationship:

The cooling circuit relies on a centrifugal pump to circulate coolant through pipes, engine jackets, and the heat exchanger. The cooling pressure represents the hydraulic energy required to overcome internal resistance.

According to the Darcy–Weisbach equation, pressure losses are proportional to the square of the flow velocity. Therefore, increasing flow rate requires higher pressure from the pump to overcome frictional losses (White, 2016).

By fixing the temperature at , the effect of viscosity and density variation is eliminated, allowing this curve to represent the pure hydraulic behavior of the system (Stone, 2012).

6.4. Relationship Between Coolant Temperature (CT) and Cooling Pressure (CP):

Figure (4) illustrates the inverse relationship between coolant temperature (CT) and cooling pressure (CP) within the marine diesel engine cooling system. The obtained curve demonstrates that increasing coolant temperature causes a gradual reduction in cooling pressure despite unchanged pump operating conditions. This behavior is primarily attributed to the influence of temperature on coolant viscosity, hydraulic resistance, and pump operating characteristics within the circulation network (Stone, 2012; White, 2016).

At the normal operating condition of 75°C, the cooling pressure is approximately 1.92 bar, representing stable hydraulic equilibrium and efficient heat transfer inside the cooling circuit. As coolant temperature increases above the reference operating point, the cooling pressure progressively decreases due to reduced fluid viscosity and increasing thermal loading within the system.

The figure further shows that at 85°C, the system enters the near-critical warning zone where the cooling pressure decreases to nearly 1.47 bar, indicating the beginning of thermal and hydraulic instability. At 90°C, the pressure drops further to approximately 1.25 bar, reflecting deterioration in cooling effectiveness and increased thermal stress on system components.

When coolant temperature reaches 95°C, the system approaches the critical operating zone with cooling pressure around 1.02 bar. Under these conditions, the probability of overheating, pump performance degradation, cavitation effects, and reduced heat exchanger efficiency becomes significantly higher. Finally, at 100°C, the cooling pressure decreases to approximately 0.80 bar, representing the shutdown zone where safe engine operation can no longer be maintained.

These observations confirm that coolant temperature has a direct influence on the hydraulic performance and thermal stability of the marine cooling system. Continuous monitoring of CT and CP parameters therefore provides an effective basis for predictive maintenance and early fault detection in marine diesel engine cooling applications (Lazakis et al., 2016; Jardine et al., 2006; Michala & Lazakis, 2015).

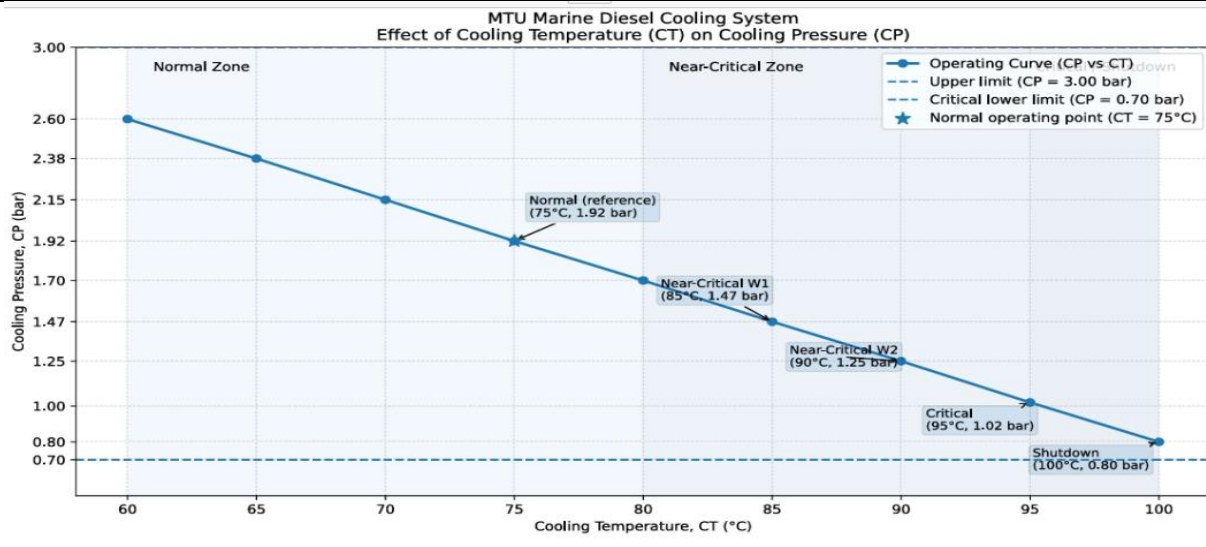


Figure (4) Inverse relationship between Coolant Temperature (CT) and Cooling Pressure (CP), showing the effect of increasing coolant temperature on the reduction of cooling pressure and the transition from normal operation to critical and shutdown zones.

6.4.1. Physical Interpretation of the (CT–CP) Relationship:

An increase in temperature reduces coolant viscosity and alters density, which modifies the frictional characteristics of the flow and shifts the operating point between the pump curve and the system curve.

This results in a measurable reduction in effective pressure inside the cooling circuit at higher temperatures (White, 2016).

6.5. Relationship Between Coolant Temperature (CT) and Cooling Flow Rate (CF):

Figure (5) illustrates the inverse relationship between coolant temperature (CT) and cooling flow rate (CF) in the marine diesel engine cooling system. The experimental results show that increasing coolant temperature leads to a gradual reduction in the achievable cooling flow rate, even though the pump speed and system configuration remain unchanged. This behavior reflects the thermal influence on coolant hydraulic properties and the overall flow stability inside the cooling circuit.

The normal operating condition was observed at $CT = 75^{\circ}C$, where the cooling flow rate reached approximately $CF = 55.00$ L/min. At this condition, the cooling system maintains balanced thermal regulation and stable coolant circulation through the engine jackets and heat exchanger. This operating point represents the recommended thermal condition for the studied marine diesel engine according to the manufacturer's operational limits and marine engine cooling practices (Stone, 2012; MTU Friedrichshafen GmbH, 1982).

As coolant temperature increased beyond the normal operating range, the cooling flow rate progressively decreased. At $CT = 85^{\circ}C$, the system entered the first near-critical warning zone, where the flow rate dropped to approximately $CF = 51.00$ L/min. This reduction indicates increasing hydraulic instability and rising thermal stress within the cooling circuit. Such behavior may result from partial blockage inside the heat exchanger, increased internal pipe resistance, or reduced cooling efficiency caused by deposit accumulation and localized overheating (Kakaç et al., 2012; Çengel & Ghajar, 2015; White, 2016).

A second near-critical operating condition was observed at $CT = 90^{\circ}C$, where the flow rate further decreased to approximately $CF = 49.00$ L/min. At this stage, the cooling system becomes more sensitive to disturbances, and coolant circulation efficiency begins to deteriorate significantly. Continued operation under these conditions may accelerate thermal fatigue, reduce lubrication effectiveness, and increase the probability of cavitation and pump performance degradation (Lazakis et al., 2016; Jardine et al., 2006; Michala & Lazakis, 2015).

When the coolant temperature reached $CT = 95^{\circ}\text{C}$, the system approached the critical operating zone, where the flow rate decreased to approximately $CF = 47.00$ L/min. This condition indicates insufficient heat removal capability and unstable thermal equilibrium inside the engine cooling network. Persistent operation near this region may lead to severe overheating, thermal expansion problems, and possible damage to engine components such as cylinder liners and head gaskets (Heywood, 2018; Stone, 2012; Çengel & Ghajar, 2015).

At $CT = 100^{\circ}\text{C}$, the system reached the shutdown condition, where the cooling flow rate decreased to approximately $CF = 45.00$ L/min. This operating state represents a dangerous thermal condition in which the cooling circuit can no longer maintain adequate heat dissipation. Emergency shutdown procedures are therefore required to prevent catastrophic engine failure and protect the cooling system components from irreversible thermal damage (MTU Friedrichshafen GmbH, 1982; Lazakis et al., 2016).

The obtained results demonstrate that coolant temperature has a direct influence on the hydraulic efficiency and flow stability of the marine cooling system. The observed inverse CT – CF relationship agrees with established principles of heat transfer, fluid mechanics, and marine engine cooling behavior reported in previous studies (Stone, 2012; Jardine et al., 2006; Kakaç et al., 2012; White, 2016).

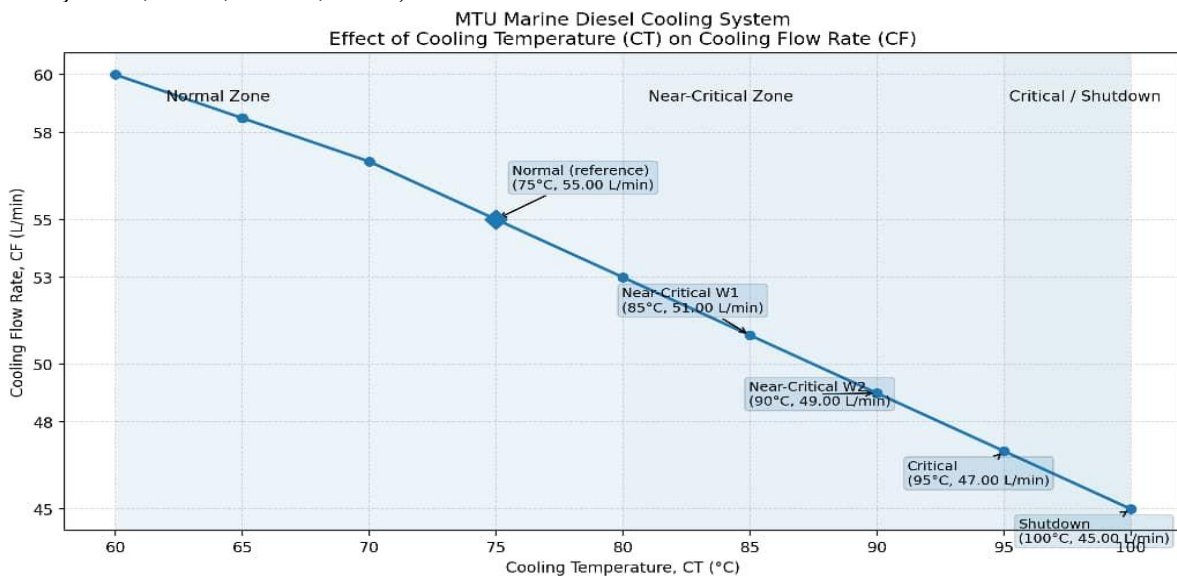


Figure (5) Inverse relationship between Coolant Temperature (CT) and Cooling Flow Rate (CF), illustrating the reduction of achievable flow rate as coolant temperature increases.

6.5.1. Physical Interpretation of the (CT–CF) Relationship:

Higher temperatures affect the hydraulic efficiency of the cooling system and disturb the stability of the flow inside the network.

These effects reduce the effective flow rate delivered through the cooling circuit, especially near higher temperature limits where the system becomes more sensitive to disturbances (Jardine et al., 2006; White, 2016).

6.6. Fault Curve Analysis of the Cooling System:

After establishing the normal reference operating curve of the cooling system at $CT = 75^{\circ}\text{C}$, the deviation patterns caused by different fault conditions can be analyzed and compared with the reference curve.

6.6.1. Fault 1 – Weak Cooling Pump:

Figure (6) illustrates the deviation of the CP – CF relationship under the condition of cooling pump degradation at nearly constant coolant temperature.

Under normal operating conditions at approximately $CT = 75^{\circ}\text{C}$, the reference curve demonstrates a stable linear hydraulic relationship between coolant pressure (CP) and coolant flow rate (CF). At this operating point, the measured coolant pressure is approximately 1.92

bar, indicating that the cooling pump is capable of maintaining the required hydraulic head and stable coolant circulation throughout the cooling circuit.

However, under weak pump conditions, the generated hydraulic head decreases due to pump performance degradation. As a result, the coolant velocity inside the piping system decreases, leading to a direct reduction in both coolant pressure and volumetric flow rate. This behavior causes the fault curve to shift downward relative to the reference curve while maintaining nearly the same slope.

According to the Darcy–Weisbach equation (Eq. 4), pressure losses are directly related to flow velocity. Therefore, any reduction in coolant velocity produces a corresponding decrease in the measured pressure values. Furthermore, the continuity equation confirms that the reduction in volumetric velocity leads directly to a reduction in the overall coolant flow rate (White, 2016).

The obtained results show that the deviation begins gradually from the normal operating region and increases as pump degradation progresses. For example, the normal operating condition at $CT \approx 75^\circ\text{C}$ corresponds to $CP \approx 1.92$ bar, whereas the weak pump condition produces lower pressure readings at comparable flow conditions. This deviation represents a clear hydraulic imbalance inside the cooling circuit.

The downward parallel displacement of the fault curve without a major change in slope represents a characteristic signature of cooling pump degradation. This behavior distinguishes weak pump faults from other cooling system faults such as heat exchanger fouling or air entrainment, where the curve shape and slope usually change differently (Lazakis et al., 2016; Jardine et al., 2006).

If the degradation continues, insufficient coolant circulation may occur, resulting in localized overheating, unstable thermal distribution, reduced cooling efficiency, and possible thermal stress on critical engine components. Therefore, continuous monitoring of the CP–CF relationship can provide an effective predictive maintenance indicator for early detection of cooling pump deterioration before reaching critical operating conditions.

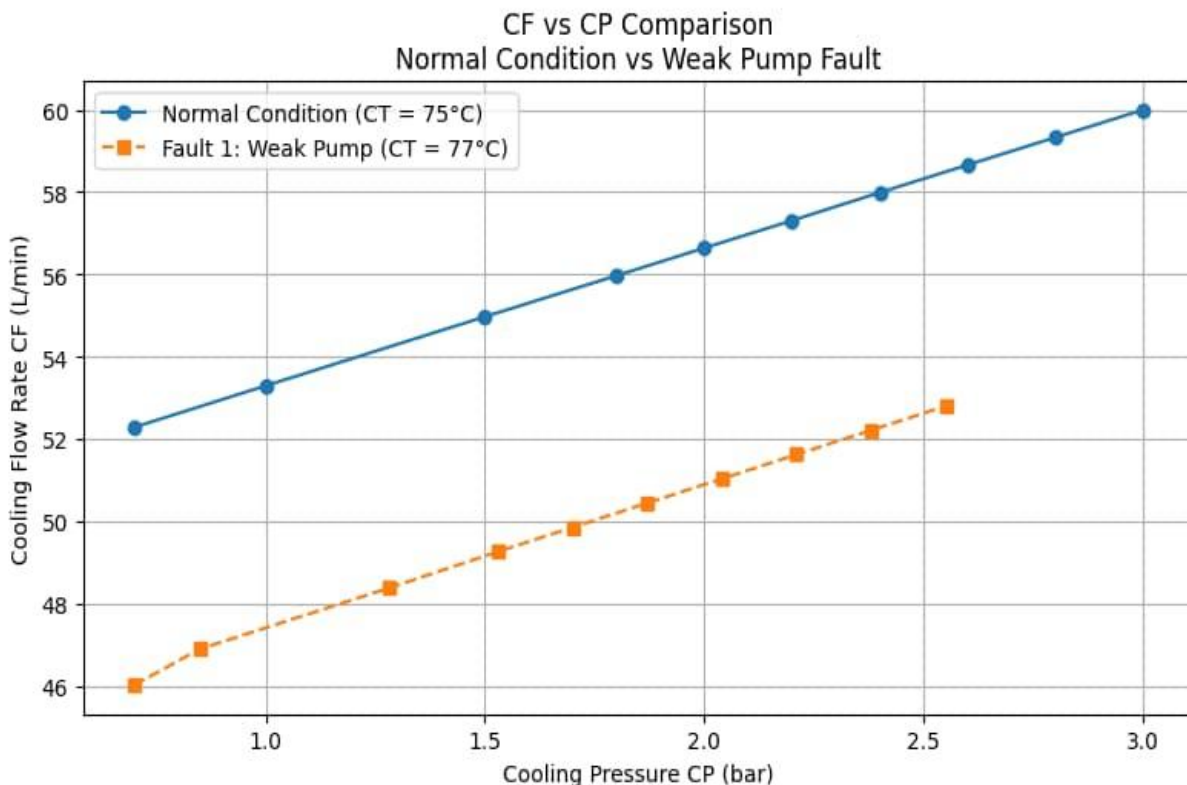


Figure (6) Deviation of the CP–CF relationship under pump degradation condition at $CT = 75^\circ\text{C}$.

6.6.2 Fault 2 – Heat Exchanger Fouling and Flow Restriction:

Figure (7) illustrates the deviation of the Cooling Pressure–Cooling Flow Rate (CP–CF) relationship under heat exchanger fouling conditions in the MTU marine diesel engine cooling system. Compared with the normal operating condition, the cooling system requires higher cooling pressure to maintain approximately the same coolant flow rate. This behavior is caused by the accumulation of deposits and fouling layers inside the heat exchanger tubes, which increase both hydraulic resistance and thermal resistance within the cooling circuit.

The fouling phenomenon directly affects coolant circulation stability and reduces the overall heat transfer efficiency of the marine cooling system. As deposits accumulate on the internal surfaces of the heat exchanger, the effective flow area decreases, resulting in higher friction losses and pressure drop across the cooling circuit. Consequently, the cooling pump operates farther from its optimal hydraulic efficiency region, leading to abnormal CP–CF behavior and degraded thermal regulation performance.

This behavior can be explained using:

- Energy balance equation (Eq. 1)
- LMTD equation (Eq. 3)
- Darcy–Weisbach equation (Eq. 4)

The increase in thermal resistance due to fouling reduces the heat exchanger effectiveness, while the increase in friction factor causes additional hydraulic losses. Therefore, for a given cooling flow rate, the system requires higher operating pressure compared with the clean heat exchanger condition. This agrees with established principles of heat transfer and fluid mechanics in marine engine cooling systems (Kakaç et al., 2012; Incropera et al., 2011; Çengel & Ghajar, 2015; White, 2016).

Under the normal operating condition at coolant temperature $CT = 75^{\circ}\text{C}$, the cooling system demonstrates stable hydraulic behavior. At $CP = 0.5$ bar, the cooling flow rate was approximately $CF = 52.78$ L/min. As cooling pressure gradually increased to $CP = 3.0$ bar, the flow rate increased smoothly to approximately $CF = 60.00$ L/min. This operating trend represents the normal hydraulic response of the cooling circuit, where pressure increase enhances coolant circulation through the engine jackets and heat exchanger with minimal hydraulic resistance.

In contrast, under the fouling fault condition at approximately $CT = 79^{\circ}\text{C}$, the cooling flow rate decreased significantly for all pressure levels. At $CP = 0.5$ bar, the flow rate dropped to approximately $CF = 48.00$ L/min, indicating an early-stage reduction in coolant circulation efficiency caused by internal deposit accumulation. Although increasing the cooling pressure improved the flow rate gradually, the system remained below the normal operational performance line throughout the entire pressure range.

At $CP = 1.0$ bar, the fouled condition achieved only $CF = 49.00$ L/min compared with approximately $CF = 53.28$ L/min under normal conditions. This deviation indicates increasing internal resistance and partial obstruction inside the heat exchanger passages. The reduction in coolant velocity also contributes to lower convective heat transfer coefficients, reducing the capability of the cooling system to dissipate engine thermal loads effectively.

A more pronounced degradation was observed at $CP = 1.5$ – 2.0 bar, where the fouled system reached approximately $CF = 50.5$ – 52.0 L/min, while the normal condition maintained approximately $CF = 54.97$ – 56.21 L/min. At this stage, the cooling circuit begins to experience unstable thermal regulation, increased local temperature gradients, and reduced heat exchanger effectiveness. Such behavior may accelerate scaling formation and promote localized overheating inside the engine cooling jackets (Kakaç et al., 2012; Incropera et al., 2011).

At higher operating pressures, the deviation between normal and fouled conditions remained evident. At $CP = 2.5$ bar, the fouled condition reached approximately $CF = 53.2$ L/min, compared with $CF = 57.91$ L/min in the normal case. Finally, at $CP = 3.0$ bar, the system

achieved approximately $CF = 55.0$ L/min under fouling conditions, while the normal condition reached $CF = 60.0$ L/min.

These results indicate that increasing cooling pressure alone cannot fully compensate for the hydraulic and thermal degradation caused by heat exchanger fouling. Continued operation under such conditions may lead to:

1. Increased pump power consumption.
2. Reduced cooling efficiency.
3. Higher coolant outlet temperatures.
4. Increased thermal stress on cylinder liners and cylinder heads.
5. Greater probability of cavitation and pump degradation.
6. Accelerated engine component wear.

The obtained results demonstrate that heat exchanger fouling has a direct influence on both the hydraulic and thermal performance of the MTU marine diesel engine cooling system. The observed deviation in the CP–CF relationship agrees with previous studies related to fouling effects, pressure losses, and marine cooling system degradation mechanisms (Jardine et al., 2006; Kakaç et al., 2012; Incropera et al., 2011; Çengel & Ghajar, 2015; White, 2016).

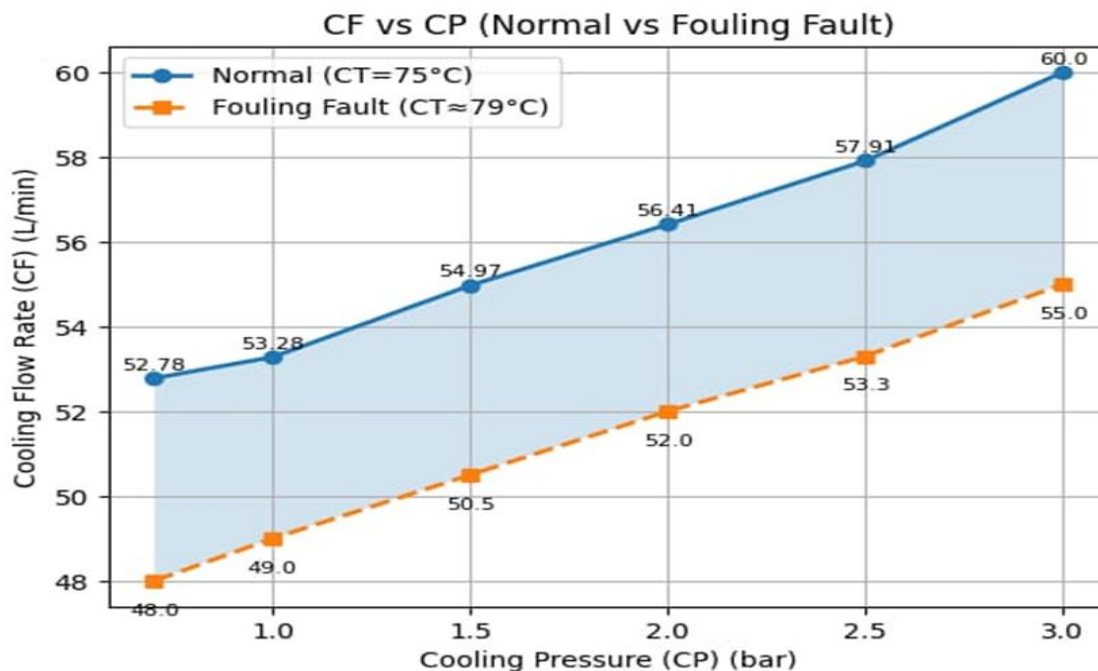


Figure (7) Deviation of the CP–CF relationship due to heat exchanger fouling at $CT = 75^{\circ}\text{C}$.

6.6.3. Fault 3 – Air in Cooling Circuit:

The presence of air inside the marine diesel engine cooling circuit causes unstable coolant circulation and significantly reduces heat transfer efficiency. Unlike normal operating conditions, entrained air bubbles disturb the hydraulic continuity of coolant flow, resulting in irregular variations in the Cooling Pressure–Cooling Flow Rate (CP,CF) relationship.

Figure (8) illustrates the abnormal CP,CF behavior when air is present inside the cooling circuit at $CT = 75^{\circ}\text{C}$. Under this condition, the coolant flow no longer follows the stable and nearly linear hydraulic response observed during normal operation. Instead, the curve exhibits fluctuating and irregular behavior caused by localized compressibility effects of trapped air pockets and intermittent obstruction within coolant passages.

Air bubbles inside the cooling system reduce the effective density of the coolant and introduce hydraulic instability throughout the circulation paths. This phenomenon alters the internal pressure distribution within the cooling circuit and weakens the ability of the cooling

pump to maintain continuous and stable coolant delivery. Consequently, the cooling system becomes increasingly sensitive to pressure fluctuations and transient thermal disturbances (Heywood, 2018; Lazakis et al., 2016; White, 2016).

This behavior can be interpreted using:

- Continuity equation.
- Bernoulli equation.
- Darcy–Weisbach equation (Eq. 4).
- Cavitation and two-phase flow principles.

Under normal operating conditions, increasing cooling pressure produces a smooth and proportional increase in coolant flow rate. However, when air enters the cooling circuit, part of the effective hydraulic energy generated by the pump is consumed in compressing and transporting entrained air bubbles rather than maintaining efficient coolant circulation. As a result, the hydraulic efficiency and volumetric stability of the cooling pump decrease, causing the CP,CF relationship to deviate from its normal stable behavior.

At the initial fault condition, approximately at $CP = 0.7$ bar, the cooling flow rate dropped to nearly $CF = 47.0$ L/min. This operating point represents the first indication of air entrainment inside the cooling circuit. The reduction in flow rate at relatively low pressure indicates unstable coolant movement and partial interruption of coolant continuity caused by dispersed air pockets within the circulation system.

As the cooling pressure increased toward $CP \approx 1.6$ bar, the flow rate gradually increased to approximately $CF = 51.0$ L/min. Although the system exhibited partial hydraulic recovery, the flow behavior remained irregular compared with the normal operating condition. This intermediate operating region reflects unstable internal circulation in which migrating air bubbles continuously disturb local pressure gradients and transient flow behavior inside the cooling passages.

The maximum measured operating condition occurred at approximately $CP = 2.40$ bar and $CF = 54.00$ L/min. Despite the increase in cooling pressure, the achieved flow rate remained lower than the expected normal cooling performance. This indicates that pressure increase alone cannot completely eliminate the hydraulic disturbances associated with air entrainment inside the cooling circuit.

The irregular shape of the CP,CF curve represents a characteristic diagnostic signature of air presence within the marine cooling system. Unlike heat exchanger fouling faults, which generally produce smoother and more predictable deviations, air-related faults generate unstable and non-uniform hydraulic behavior due to the dynamic movement, expansion, and compression of trapped air bubbles within the coolant flow.

Continued operation under these conditions may lead to:

1. Reduced heat transfer efficiency.
2. Localized overheating inside engine cooling jackets.
3. Increased cavitation probability near the pump impeller.
4. Pump vibration and unstable hydraulic operation.
5. Increased thermal stress on cylinder liners and cylinder heads.
6. Reduced lubrication efficiency caused by elevated engine temperatures.

Furthermore, persistent air accumulation inside the cooling circuit may accelerate oxidation, corrosion, and degradation of cooling system components. Under severe operating conditions, the reduction in coolant circulation stability may eventually result in critical thermal imbalance and progressive engine overheating (Heywood, 2018; Lazakis et al., 2016; Incropera et al., 2011; White, 2016).

The obtained results demonstrate that air entrainment directly affects both the hydraulic stability and thermal efficiency of the MTU marine diesel engine cooling system. The observed irregular CP,CF behavior is consistent with established principles of fluid mechanics, cavitation theory, two-phase flow behavior, and marine engine cooling system

diagnostics reported in previous studies (Heywood, 2018; Lazakis et al., 2016; Çengel & Ghajar, 2015; White, 2016).

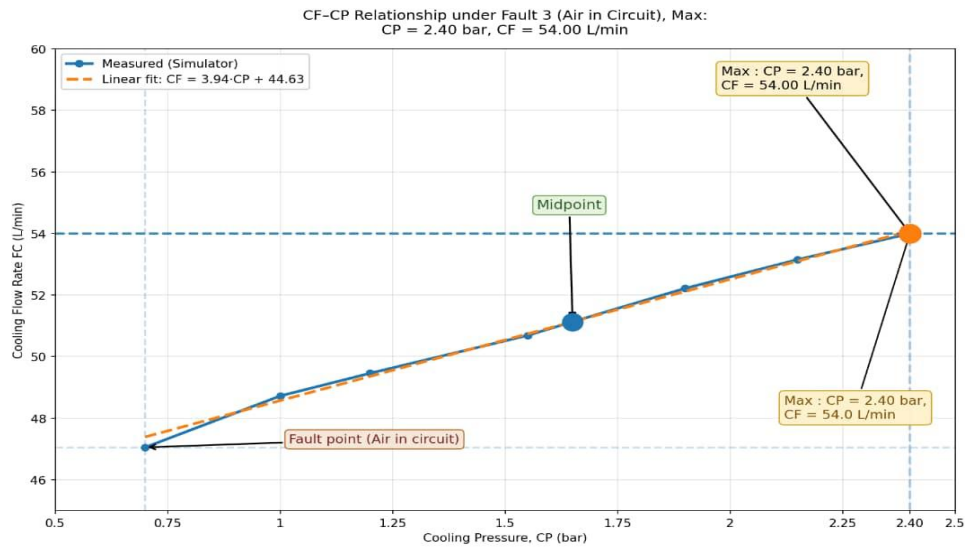


Figure (8) Irregular CP–CF behaviour caused by air presence inside the cooling circuit at $CT = 75^{\circ}C$.

6.7. Comparative Analysis Between Fault Curves and Normal Condition:

Figure (9) presents a comparative analysis of the CP–CF characteristics under normal operating conditions and the three investigated fault conditions at $CT = 75^{\circ}C$ in the MTU marine diesel engine cooling system. The comparison demonstrates that each fault condition produces a distinct hydraulic response and a characteristic deviation pattern relative to the normal operating curve.

Under normal operating conditions, the CP–CF relationship exhibits a stable and nearly linear increase in cooling flow rate with increasing cooling pressure, indicating balanced hydraulic performance, stable coolant circulation, and efficient heat removal throughout the cooling circuit.

Fault 1 (Pump Degradation) produces an approximately parallel downward shift of the CP–CF curve relative to the normal condition. This deviation indicates a reduction in pump hydraulic efficiency and coolant delivery capability while preserving a similar overall flow trend. The observed behavior reflects weakened pressure generation and progressive deterioration in pump performance (MTU Friedrichshafen GmbH, 1982; Lazakis et al., 2016).

Fault 2 (Heat Exchanger Fouling and Partial Blockage) produces a noticeable change in curve slope caused by increased hydraulic resistance, partial coolant flow restriction, and reduced heat transfer efficiency inside the heat exchanger. The accumulation of deposits and internal obstruction within the cooling passages increases friction losses and reduces effective coolant circulation. Consequently, the cooling system requires higher cooling pressure to maintain comparable flow rates relative to the normal operating condition (Kakaç et al., 2012; Incropera et al., 2011; Çengel & Ghajar, 2015).

Fault 3 (Air in Cooling Circuit) exhibits the most irregular hydraulic behavior among all investigated faults. The presence of entrained air bubbles introduces localized compressibility effects, unstable pressure distribution, and transient flow disturbances, leading to a fluctuating and non-uniform CP–CF response. This unstable hydraulic behavior represents a characteristic diagnostic signature of air entrainment inside the cooling system (Heywood, 2018; Lazakis et al., 2016; White, 2016).

The comparison further indicates that the separation between the normal operating curve and the fault curves becomes progressively larger at elevated operating pressures, particularly beyond $CP \approx 2.0$ bar. This behavior demonstrates the increasing influence of hydraulic degradation and coolant circulation instability under higher thermal and hydraulic loading conditions.

Furthermore, the critical lower operating limit observed near $CP = 0.70$ bar represents a sensitive diagnostic region where the cooling system becomes highly vulnerable to flow instability and thermal imbalance. Continuous operation near this region may accelerate fault progression and increase the probability of overheating, cavitation, and cooling system component degradation.

The clear differences in curve shape, slope, and hydraulic response provide a reliable diagnostic fingerprint for distinguishing between cooling system faults in marine diesel engines. These characteristic deviations can be effectively utilized in predictive maintenance and condition monitoring systems for early fault detection before reaching critical or shutdown operating conditions (Incropera et al., 2011; Michala & Lazakis, 2015).

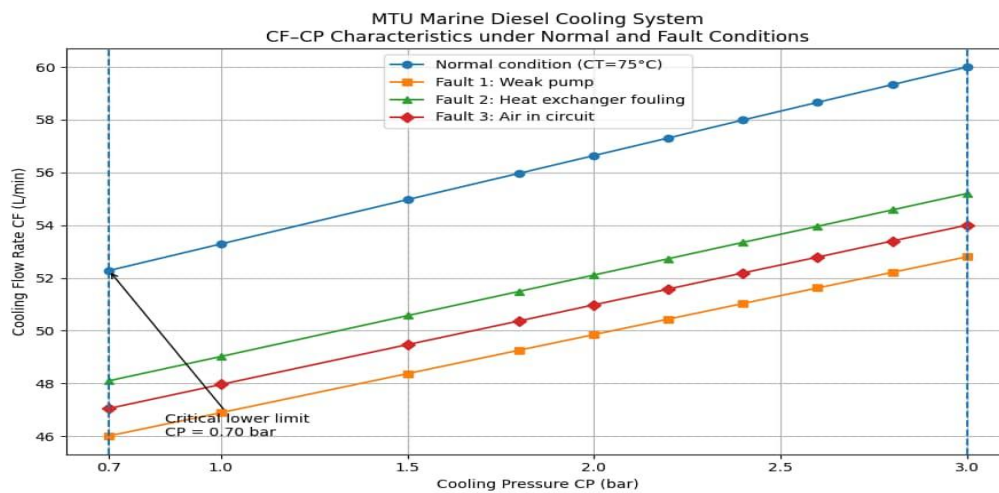


Figure (9) CF-CP characteristics under normal and fault conditions at $CT = 75^\circ\text{C}$ for the MTU marine diesel engine cooling system.

6.8. Integration of the Three Operating Relationships:

The behavior of the marine diesel engine cooling system cannot be accurately interpreted by observing a single operating parameter independently. The interaction between coolant temperature (CT), cooling pressure (CP), and cooling flow rate (CF) forms an integrated thermo-hydraulic operating framework that governs the stability and efficiency of the cooling circuit.

The obtained results demonstrate that increasing coolant temperature leads to:

1. Reduction in effective cooling pressure (CP).
2. Decrease in achievable cooling flow rate (CF).
3. Progressive shift of the operating condition from normal operation toward warning, critical, and shutdown regions.

This thermo-hydraulic integration explains the behavior of both normal and fault operating curves and provides a reliable basis for cooling system diagnostics and predictive maintenance applications (Stone, 2012; Michala & Lazakis, 2015).

6.9. Practical Significance for Predictive Maintenance:

The continuous monitoring of coolant temperature (CT), cooling pressure (CP), and cooling flow rate (CF), together with the analysis of their operating relationships, provides an effective framework for predictive maintenance in marine diesel engine cooling systems.

The obtained CP–CF and CT-related characteristics allow early detection of abnormal operating conditions associated with:

- Pump degradation
- Heat exchanger fouling and partial blockage
- Air entrainment inside the cooling circuit

Each fault condition produces a distinct hydraulic deviation pattern that can be used as a diagnostic indicator before reaching critical thermal or hydraulic failure conditions (Lazakis et al., 2016; Jardine et al., 2006).

The proposed methodology improves fault diagnosis capability, supports condition-based maintenance strategies, and contributes to reducing unexpected operational failures and maintenance costs in marine propulsion systems.

Conclusion

This study established a comprehensive operational analysis of the marine diesel engine cooling system by investigating the relationships between coolant temperature (CT), cooling pressure (CP), and cooling flow rate (CF) under normal and faulty operating conditions.

The experimental results demonstrated that the cooling system possesses stable hydraulic behavior at the reference operating condition of approximately $CT = 75^{\circ}\text{C}$, where balanced thermal regulation and efficient coolant circulation are achieved. Under constant coolant temperature conditions, a direct relationship between cooling pressure and cooling flow rate was observed, indicating that increasing hydraulic pressure improves coolant circulation and overall heat removal capability.

In contrast, increasing coolant temperature produced inverse effects on both cooling pressure and cooling flow rate. As coolant temperature increased beyond the normal operating range, gradual reductions in (CP) and (CF) were recorded due to changes in coolant viscosity, increased thermal loading, and deterioration of hydraulic stability inside the cooling circuit. The system progressively transitioned from normal operation into warning, near-critical, critical, and shutdown zones.

The obtained operating curves successfully defined the baseline hydraulic signature of the cooling system and provided a practical reference for condition monitoring and fault diagnosis.

Deviation analysis under fault conditions revealed that different cooling system faults generate distinguishable changes in the (CP,CF) relationship. Weak cooling pump conditions resulted in reduced hydraulic performance and lower achievable flow rates. Heat exchanger fouling increased hydraulic resistance and pressure losses due to internal deposit accumulation. Air entrainment inside the cooling circuit caused unstable circulation behavior and reduced system stability. These deviations confirmed that cooling system degradation can be identified through continuous monitoring of the operational curves.

Overall, the study confirms that the combined analysis of (CT), (CP), and (CF) parameters provides an effective approach for evaluating cooling system health, detecting early-stage faults, and supporting predictive maintenance strategies in marine diesel engine applications.

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